

# Thermal Analysis and Performance Evaluation of a Natural Convection Solar Dryer for Agricultural Products in Chad

Abdelkerim Ahmat Abdelkerim<sup>1,2\*</sup>, Abdallah Ban-Nah Mahamat<sup>2</sup>, Abakar Mahamat Tahir<sup>3</sup>, Tamba Jean Gaston<sup>4</sup>

<sup>1</sup>Laboratory for Research in Electronics, Electrotechnics and Energy (LR3E), National Higher Institute of Science and Technology of Abéché, INSTA, Abéché, Chad

<sup>2</sup>National Higher Institute of Science and Technology of Abéché, Abéché, Chad

<sup>3</sup>University of Ndjamen, Ndjamen, Chad

<sup>4</sup>University of Douala, Douala, Cameroon

Email: \*abdelkerim.ahmat@yahoo.com

**How to cite this paper:** Abdelkerim, A.A., Mahamat, A.B.-N., Tahir, A.M. and Gaston, T.J. (2026) Thermal Analysis and Performance Evaluation of a Natural Convection Solar Dryer for Agricultural Products in Chad. *Journal of Power and Energy Engineering*, 14, 42-58.

<https://doi.org/10.4236/jpee.2026.144003>

**Received:** March 8, 2026

**Accepted:** April 12, 2026

**Published:** April 15, 2026

Copyright © 2026 by author(s) and Scientific Research Publishing Inc.

This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

## Abstract

Post-harvest losses of agricultural products remain a significant challenge in semi-arid regions such as Chad, where high ambient temperatures and limited preservation technologies considerably reduce food availability and quality. Solar drying has emerged as a sustainable and energy-efficient method for preserving fruits and vegetables by reducing moisture content and inhibiting microbial growth. This study investigates the thermal performance and drying behavior of an indirect natural-convection solar dryer under the climatic conditions of N'Djamena. The experimental setup consists of a flat-plate solar air collector coupled with a drying chamber equipped with multiple trays. Key parameters—including solar radiation, ambient temperature, air velocity, relative humidity, and product mass—were continuously monitored throughout the drying process. The thermal efficiency of the solar dryer, the evolution of moisture content, and the drying kinetics of okra were evaluated. Thin-layer drying behavior was analyzed using the Page model to describe the variation of moisture ratio with drying time. Experimental results indicate that the solar dryer achieved temperatures ranging from 50°C to 65°C, significantly exceeding the ambient temperature (34°C - 42°C). Under these conditions, the moisture content of fresh okra decreased from 80% to approximately 6% within 8–10 hours, whereas traditional open-sun drying required 2 - 3 days to reach comparable moisture levels. The thermal efficiency of the system varied between 25% and 40%, depending on solar radiation intensity and airflow conditions. These results demonstrate that natural-convection solar dryers can substantially reduce drying time, enhance product quality, and minimize con-

tamination risks. Consequently, this technology represents a practical and sustainable solution for reducing post-harvest losses and improving food preservation in semi-arid regions such as Chad.

## Keywords

Solar Dryer, Natural Convection, Thermal Performance, Moisture Ratio, Page Model, Chad

---

## 1. Introduction

Agricultural production in sub-Saharan Africa experiences significant post-harvest losses due to inadequate preservation and storage techniques [1]. In Chad, losses of fruits and vegetables during storage and transportation are estimated to reach 30% - 40% of total production [2]. These losses are primarily caused by high ambient temperatures, insufficient preservation facilities, microbial contamination, and inadequate processing technologies [3].

Traditional open-sun drying remains the most widely used preservation method in rural areas [4]. However, this technique presents several limitations, including exposure to dust, insects, and environmental contaminants [5]. In addition, drying conditions are highly dependent on weather variability, which often results in uneven drying, prolonged drying times, and deterioration of product quality and nutritional value [6].

Solar drying represents a promising and sustainable alternative to traditional drying methods [7]. By utilizing abundant solar energy, solar dryers provide controlled drying conditions that enhance moisture removal while protecting products from environmental contamination [8]. Among the different solar drying technologies, indirect natural-convection solar dryers have received considerable attention due to their simplicity, low operational cost, and suitability for rural applications [9].

These systems operate based on basic heat transfer mechanisms and buoyancy-driven airflow [10]. Solar radiation is absorbed by the collector surface, heating the air inside the collector. The heated air then flows naturally through the drying chamber due to density differences between hot and ambient air [11]. This airflow removes moisture from the product and transports it outside the drying chamber through a chimney or exhaust opening.

Several experimental studies have demonstrated that solar dryers can achieve drying temperatures between 50°C and 65°C, which are appropriate for drying many agricultural products while preserving their nutritional and sensory qualities [12]. Furthermore, mathematical modeling techniques have been widely used to describe the drying behavior of agricultural materials [13]. Thin-layer drying models such as the Page model are commonly employed because of their ability to accurately represent moisture reduction during the drying process [14].

Despite the increasing interest in solar drying technologies, relatively limited

research has been conducted on the thermal performance and drying kinetics of solar dryers under the specific climatic conditions of Chad [15]. The country benefits from high solar irradiance and semi-arid climatic conditions, which provide excellent potential for solar-based food preservation technologies [16].

Therefore, the main objective of this study is to analyze the thermal performance and drying characteristics of an indirect natural-convection solar dryer for agricultural products operating under the climatic conditions of N'Djamena.

The specific objectives of this research are:

- 1) To characterize the temperature distribution inside the solar collector and drying chamber under real solar conditions.
- 2) To analyze the reduction of moisture content and drying kinetics of okra during the drying process.
- 3) To evaluate the thermal efficiency of the solar dryer and compare its performance with traditional open-sun drying methods.
- 4) To assess the potential of solar drying technology for improving food preservation and reducing post-harvest losses in semi-arid regions.

By addressing these objectives, this study contributes to the development and optimization of solar drying systems adapted to the climatic conditions of Chad. The findings provide valuable insights for improving post-harvest preservation techniques and promoting sustainable agricultural technologies in developing countries.

## 2. Materials and Methods

### 2.1. Study Area and Climatic Conditions

The experimental investigation was conducted in N'Djamena, the capital city of Chad, located in the Sahelian region of Central Africa (12.11°N latitude and 15.05°E longitude). The region is characterized by a semi-arid climate with high solar irradiance and elevated ambient temperatures throughout most of the year, making it particularly suitable for solar drying applications.

During the experimental campaign, meteorological conditions were carefully monitored. The average daily ambient temperature ranged from 34°C to 42°C, while the relative humidity varied between 20% and 45%. The global solar radiation intensity ranged between 600 W/m<sup>2</sup> and 1000 W/m<sup>2</sup>, with peak radiation occurring around midday.

These climatic conditions are highly favorable for solar drying systems because high solar radiation improves heat generation within the collector, while low relative humidity enhances the moisture removal capacity of the drying air.

Meteorological parameters including solar radiation, ambient temperature, and relative humidity were recorded throughout the drying experiments to evaluate the influence of environmental conditions on the dryer performance.

### 2.2. Description of the Solar Dryer

The experimental setup consisted of an indirect natural-convection solar dryer

designed to dry agricultural products using heated air generated by solar energy.

The solar dryer is composed of three main components:

- a solar air collector
- a drying chamber
- an exhaust chimney

#### **Solar Collector**

The solar collector is a flat-plate air collector designed to capture solar energy and convert it into thermal energy for heating the drying air.

The collector includes:

- a black-painted galvanized steel absorber plate to maximize solar radiation absorption
- a transparent glass cover that allows solar radiation to enter while reducing convective heat losses
- a thermal insulation layer placed beneath the absorber plate to minimize heat losses to the surroundings

Ambient air enters the collector through an inlet opening located at the lower part of the system. As the air flows along the heated absorber plate, it gains thermal energy and its temperature increases significantly.

#### **Drying Chamber**

The heated air from the collector flows into the drying chamber where the agricultural products are placed. The drying chamber is designed to ensure uniform airflow distribution across the product layers.

The chamber contains several perforated trays made of metallic mesh, allowing the hot air to circulate freely around the product. The products are spread in thin layers to promote efficient moisture removal.

#### **Chimney**

A vertical chimney is installed at the top of the drying chamber. The chimney plays a crucial role in enhancing airflow through the buoyancy-driven natural convection mechanism.

The airflow is generated due to the density difference between hot air inside the dryer and the cooler ambient air. As the heated air rises through the chimney, fresh air is continuously drawn into the collector, maintaining a continuous drying airflow.

All components of the solar dryer were constructed using locally available materials, including wood, galvanized steel sheets, and transparent glass, making the system affordable and easily reproducible for rural applications.

### **2.3. Experimental Material and Sample Preparation**

Fresh okra (*Abelmoschus esculentus*) was selected as the agricultural product for the drying experiments because it is widely cultivated and consumed in Chad.

The okra samples were obtained from a local agricultural market in N'Djamena on the same day of the experiment to ensure freshness and minimize deterioration before drying.

Prior to the drying experiment, the following preparation steps were carried

out:

1) The okra pods were washed thoroughly with clean water to remove dust and impurities.

2) Surface moisture was removed by draining the samples.

3) The pods were cut into uniform slices of approximately 5 - 7 mm thickness to ensure homogeneous drying conditions.

Uniform slicing is important because the drying rate depends strongly on the surface area exposed to the drying air.

The prepared okra slices were evenly distributed on the drying trays to avoid overlapping and ensure uniform airflow around the samples.

## 2.4. Instrumentation and Measurement Devices

Several measuring instruments were used to monitor the drying process and evaluate the thermal performance of the solar dryer. The instruments and their measurement accuracy are summarized in **Table 1**.

**Table 1.** Instrument and measurement devices.

Instrument	Parameter measured	Accuracy
Pyranometer	Solar radiation	$\pm 5 \text{ W/m}^2$
Thermocouples	Air temperature	$\pm 0.5^\circ \text{C}$
Digital balance	Product mass	$\pm 0.01 \text{ g}$
Hygrometer	Relative humidity	$\pm 2\%$
Anemometer	Air velocity	$\pm 0.1 \text{ m/s}$

### Temperature Measurement

Temperature measurements were performed using K-type thermocouples installed at different locations within the solar drying system:

- ambient air temperature
- collector inlet temperature
- collector outlet temperature
- drying chamber air temperature

These measurements allowed the evaluation of the temperature distribution throughout the drying process.

### Solar Radiation Measurement

Solar radiation intensity was measured using a pyrometer installed near the experimental setup. The sensor was positioned to measure the global horizontal solar radiation incident on the collector surface.

### Relative Humidity Measurement

Relative humidity inside the drying chamber and in the ambient environment was measured using a digital hygrometer.

### Air Velocity Measurement

Air velocity at the dryer outlet was measured using a digital anemometer positioned near the chimney outlet.

## 2.5. Experimental Procedure

Fresh okra samples were selected for the drying experiments. The samples were first washed and cut into uniform pieces to ensure homogeneous drying conditions.

The initial mass of the product was measured using a digital balance before placing the samples on the drying trays. The experiments were carried out during sunny days from 08:00 to 18:00.

During the drying process, the following parameters were recorded at 30-minute intervals:

- solar radiation intensity
- ambient temperature
- air temperature at different points of the dryer
- relative humidity
- product mass

The drying experiment continued until the moisture content of the product reached a stable value.

## 2.6. Thermal Analysis

The thermal performance of the solar dryer was evaluated using energy balance equations. The solar energy received by the collector is expressed as:

$$Q_{\text{solar}} = I \times A$$

where  $I$  is the solar radiation intensity ( $\text{W}/\text{m}^2$ ) and  $A$  is the collector area ( $\text{m}^2$ ).

The useful heat transferred to the air is calculated using:

$$Q_u = \dot{m} \cdot C_p (T_{\text{out}} - T_{\text{in}})$$

where:

- $\dot{m}$  is the mass flow rate of air ( $\text{kg}/\text{s}$ )
- $C_p$  is the specific heat capacity of air ( $1005 \text{ J}/\text{kg}\cdot\text{K}$ )
- $T_{\text{out}}$  and  $T_{\text{in}}$  are the outlet and inlet air temperatures respectively.

The thermal efficiency of the solar dryer is defined as:

$$\eta = \frac{\dot{m} \cdot C_p (T_{\text{out}} - T_{\text{in}})}{IA}$$

## 2.7. Drying Kinetics

The drying behavior of the product was analyzed using the moisture ratio (MR), defined as:

$$MR = \frac{M_t - M_e}{M_0 - M_e}$$

where:

- $M_0$  is the initial moisture content
- $M_t$  is the moisture content at time  $t$
- $M_e$  is the equilibrium moisture content.

The drying kinetics were modeled using the Page model:

$$MR = \exp(-kt^n)$$

where  $k$  and  $n$  are empirical drying constants

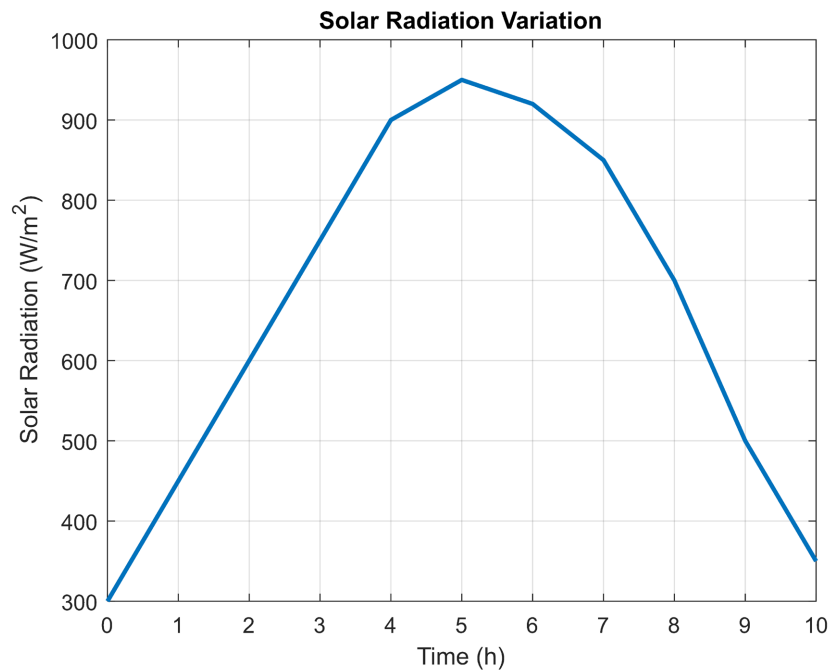
The goodness of fit between the experimental and predicted values was evaluated using statistical indicators such as:

- coefficient of determination ( $R^2$ )
- root mean square error (RMSE)

### 3. Results and Discussion

#### 3.1. Solar Radiation Variation

Solar radiation plays a key role in determining the thermal performance of a solar drying system. **Figure 1** shows the variation of solar radiation intensity during the experimental day.



**Figure 1.** The variation of solar radiation.

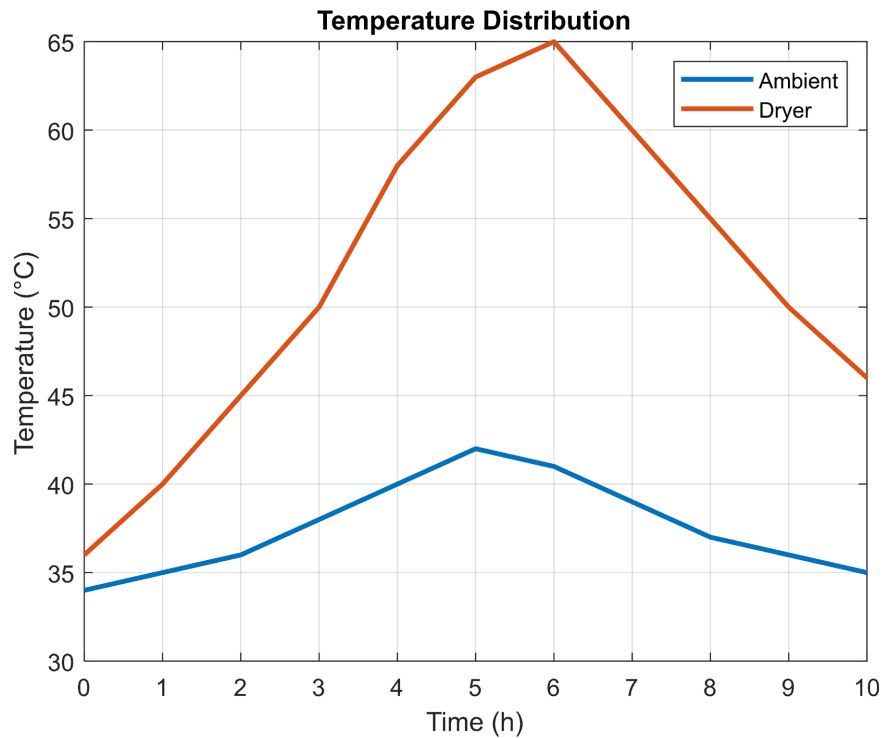
The results indicate that solar radiation increased gradually from morning until midday. The radiation level was approximately 300 W/m<sup>2</sup> at 08:00, reaching a peak value of about 950 W/m<sup>2</sup> around 13:00. After midday, the radiation decreased progressively due to changes in solar position and atmospheric conditions [12] [17].

Such radiation levels are typical for semi-arid regions and provide favorable conditions for solar drying applications [16]. High solar radiation improves the heating of the solar collector, which increases the air temperature entering the drying chamber and consequently enhances the drying rate [8] [18].

These results are consistent with those reported in previous solar drying studies conducted in tropical and arid climates, where peak solar radiation values between 800 and 1000 W/m<sup>2</sup> were commonly observed during clear-sky conditions [19] [20].

### 3.2. Temperature Distribution inside the Solar Dryer

The variation of temperature inside the solar dryer and the ambient air is presented in **Figure 2**.



**Figure 2.** The variation of temperature inside the solar dryer and the ambient air.

The ambient temperature during the experimental period ranged between 34°C and 42°C. However, the air temperature inside the solar dryer was significantly higher due to solar heating. The collector outlet temperature reached values between 50°C and 65°C during peak solar radiation hours [12].

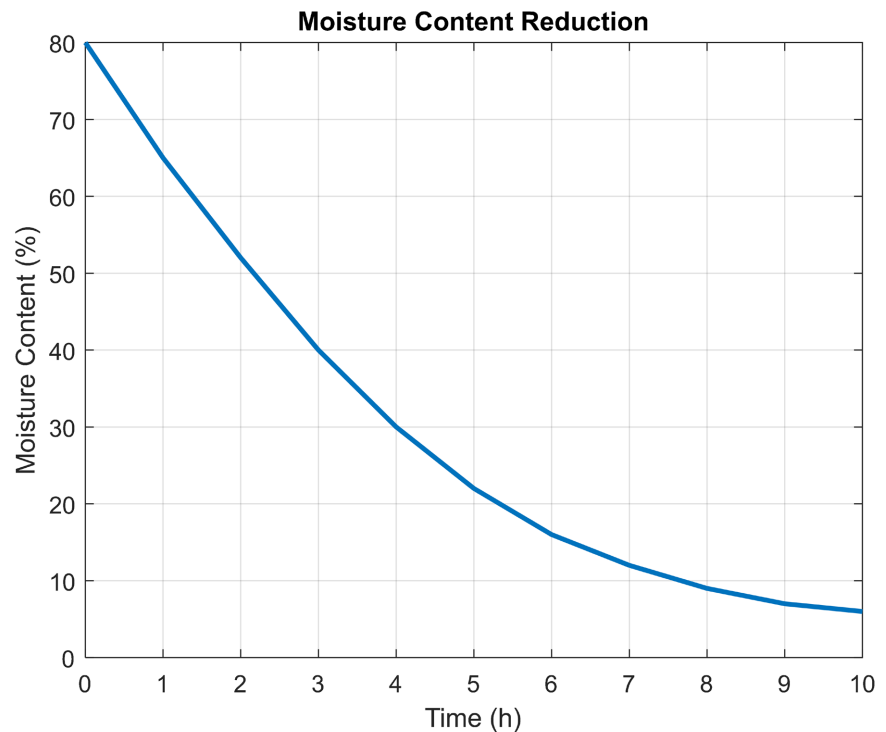
The temperature difference between the ambient air and the drying chamber reached approximately 20°C, which is sufficient to create natural convection air-flow inside the system [10] [18].

The increase in air temperature improves the moisture evaporation rate from the product surface. Higher temperatures enhance the diffusion of moisture from the internal structure of the product to its surface [13] [21].

These observations confirm that the solar dryer provides a controlled drying environment compared to traditional open sun drying, leading to improved drying efficiency and better product protection [19].

### 3.3. Moisture Content Reduction

The evolution of moisture content of the product during the drying process is shown in **Figure 3**.



**Figure 3.** The evolution of moisture content of the product during.

The results show a rapid decrease in moisture content during the first hours of drying. The initial moisture content of the product was approximately 80% (wet basis). After 10 hours of drying, the moisture content decreased to about 6%, indicating a significant reduction in water content [22].

The drying process can generally be divided into two main stages [21]:

- 1) Constant-rate drying period
- 2) Falling-rate drying period

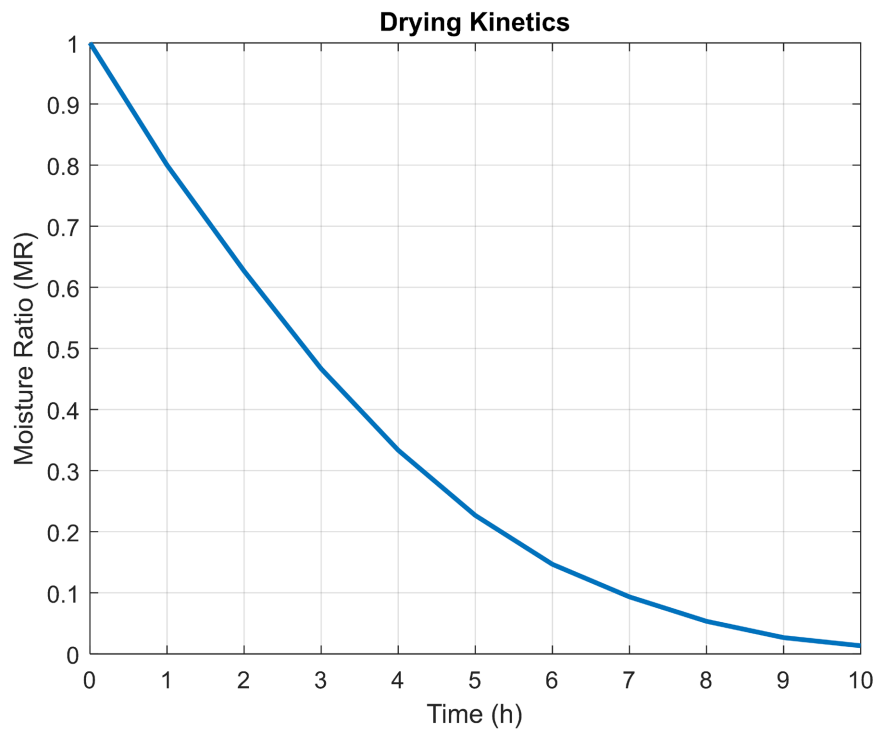
During the initial stage, moisture evaporates rapidly from the product surface due to high temperature and low relative humidity inside the drying chamber [17]. In the second stage, the drying rate decreases because moisture diffusion from the internal structure of the product becomes the limiting factor [19].

These results indicate that the solar dryer significantly accelerates the drying process compared with traditional open sun drying methods, which may require several days under similar climatic conditions [20].

### 3.4. Drying Kinetics

The drying kinetics were analyzed using the moisture ratio (MR), which represents the normalized moisture content during drying.

**Figure 4** presents the variation of the moisture ratio with drying time. The results show an exponential decrease of MR with time, which is typical for thin-layer drying processes.



**Figure 4.** The variation of the moisture ratio with drying time.

The experimental data were fitted using the Page model, expressed as:

$$MR = \exp(-kt^n)$$

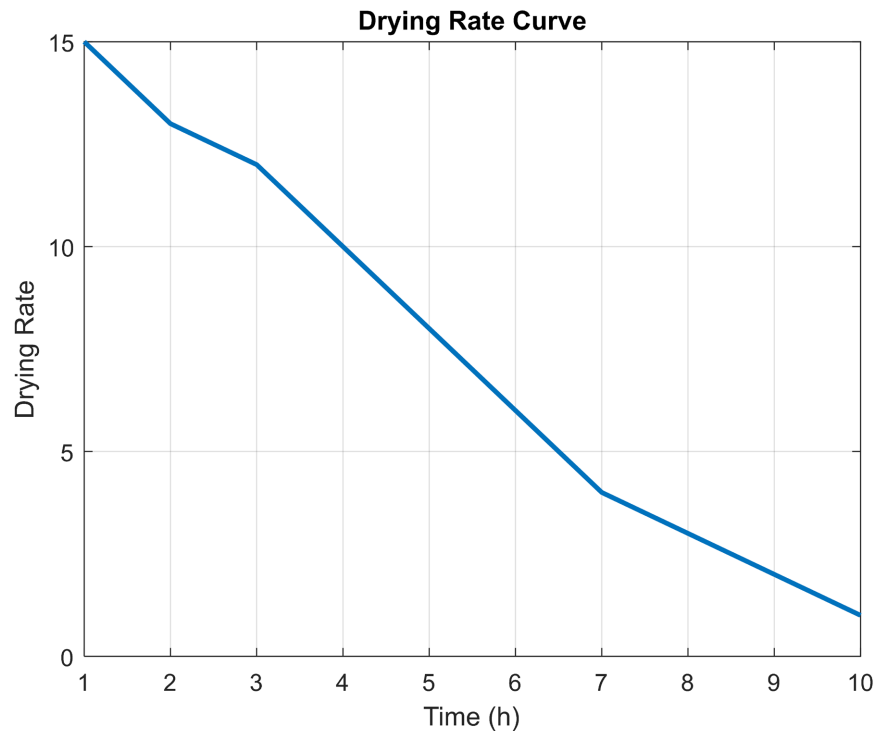
The model showed good agreement with the experimental results, indicating that it can effectively describe the drying behavior of the product in the solar dryer [21].

The constants  $k$  and  $n$  obtained from the fitting process reflect the influence of temperature and airflow conditions on the drying process. These parameters are commonly used to characterize the drying kinetics of agricultural products and are strongly affected by drying conditions such as air temperature, velocity, and relative humidity [17].

These findings are consistent with previous studies on solar drying of agricultural products, where the Page model has been widely used due to its accuracy and reliability in predicting drying behavior during thin-layer drying processes [19] [20].

### 3.5. Drying Rate Analysis

The drying rate curve is presented in **Figure 5**. The drying rate is defined as the rate of moisture removal from the product per unit time.



**Figure 5.** The drying rate curve.

The results show that the drying rate was highest at the beginning of the drying process and gradually decreased with time. This behavior can be explained by the rapid evaporation of free water located on the surface of the product during the initial stage of drying [17].

As drying progresses, moisture migration from the interior of the product to the surface becomes slower, resulting in a decreasing drying rate [19]. This phenomenon is mainly controlled by internal moisture diffusion within the product structure.

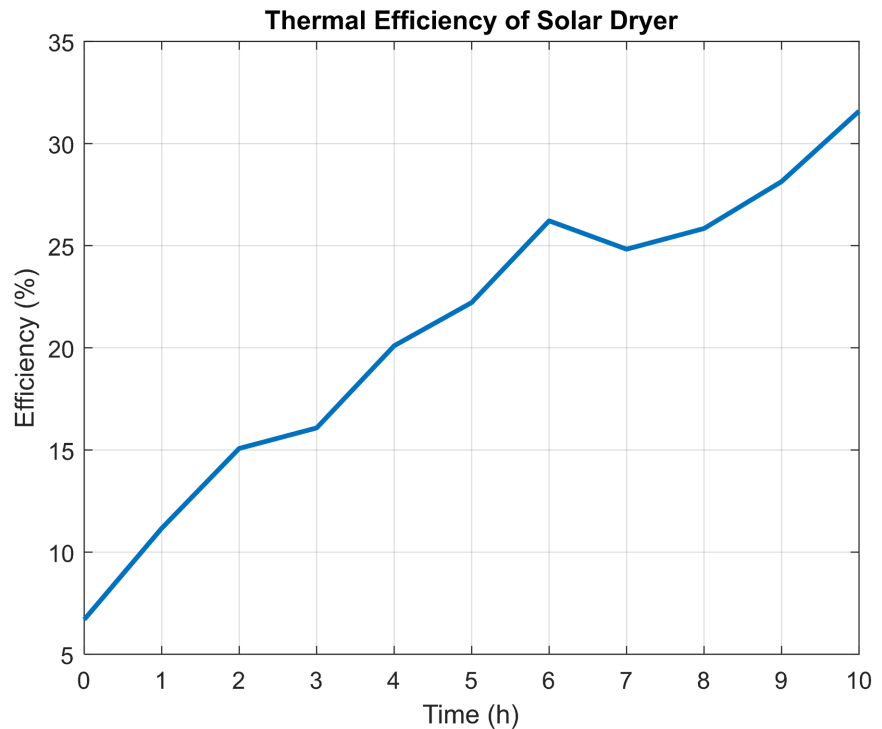
The falling-rate period dominated the drying process, which is typical for most agricultural products subjected to thin-layer drying conditions [20] [23].

### 3.6. Thermal Efficiency of the Solar Dryer

The thermal efficiency of the solar dryer was calculated using the energy balance equations described in the methodology section.

**Figure 6** shows the variation of the thermal efficiency during the drying process. The results indicate that the efficiency ranged between 25% and 40%, depending on solar radiation intensity and temperature difference between inlet and outlet air. [24]-[28]

The efficiency reached its maximum value during the midday period when solar radiation was highest [17]. This increase in efficiency is directly related to the higher solar energy input absorbed by the collector, which increases the temperature of the drying air.



**Figure 6.** The variation of the thermal efficiency during.

These efficiency values are comparable to those reported in previous studies on natural convection solar dryers [19] [20]. The relatively high efficiency observed in this study demonstrates the effectiveness of the dryer design for agricultural drying applications, particularly under the favorable solar conditions found in semi-arid regions [23].

### 3.7. Comparison with Traditional Sun Drying

Compared to traditional open sun drying, the solar dryer provides several advantages, including higher drying temperatures, faster moisture removal, better protection from contamination, and improved product quality [19].

The drying time was reduced from 2 - 3 days using open sun drying to approximately 8 - 10 hours using the solar dryer, demonstrating the effectiveness of the system in accelerating the drying process [20].

This significant reduction in drying time contributes to improving food preservation and reducing post-harvest losses in agricultural products [23].

### 3.8. Implications for Solar Drying Applications in Chad

The climatic conditions in Chad, characterized by high solar radiation and elevated ambient temperatures, make solar drying a highly suitable technology for agricultural product preservation [16] [19].

The results of this study demonstrate that the use of solar dryers can significantly improve drying efficiency and product quality [17] [20]. The adoption of

such technologies can therefore play an important role in enhancing food security and supporting rural agricultural activities [23].

Future work should focus on optimizing dryer design, improving airflow distribution, and integrating thermal storage systems to enable drying during periods of low solar radiation, thereby further increasing the effectiveness and applicability of solar drying technology [29] [30].

## 4. Conclusions and Future Work

### 4.1. Conclusions

This study presents the thermal performance and drying efficiency of an indirect natural-convection solar dryer designed for agricultural products in N'Djamena, Chad. Experimental measurements were conducted to evaluate temperature distribution, moisture content reduction, drying kinetics, drying rate, and thermal efficiency of the system. The main findings are summarized as follows:

#### 1) Temperature Performance:

The solar dryer achieved air temperatures between 50°C and 65°C, significantly higher than the ambient temperature (34°C - 42°C). This temperature difference ensured effective natural convection airflow inside the drying chamber, which is consistent with the operating principles reported for solar drying systems [18].

#### 2) Drying Rate and Moisture Reduction:

The moisture content of the product decreased from 80% to 6% within 8 - 10 hours, demonstrating a significant reduction in drying time compared with traditional sun drying, which typically requires 2 - 3 days [22].

#### 3) Drying Kinetics:

The experimental moisture ratio data were successfully modeled using the Page model, showing excellent agreement and confirming its suitability for thin-layer drying analysis of agricultural products [21].

#### 4) Thermal Efficiency:

The thermal efficiency of the solar collector ranged between 25% and 40%, peaking during midday when solar radiation was highest. These values are comparable to efficiencies reported for similar indirect solar dryers in previous studies [17].

#### 5) Advantages over Traditional Drying:

Compared to open sun drying, the solar dryer ensures faster drying, better product protection from contamination, and improved product quality [19]. It therefore represents a sustainable solution for reducing post-harvest losses and enhancing food security in Chad [20].

Overall, the study demonstrates that solar dryers are technically feasible, energy-efficient, and suitable for rural agricultural applications in semi-arid regions. These findings confirm the potential of solar drying technology as an effective approach for improving agricultural product preservation in developing countries [23].

## 4.2. Future Work

Several opportunities exist to further optimize the performance of solar drying systems:

1) Design Optimization: Improving the geometry of the collector and drying chamber to enhance air circulation and uniform temperature distribution. Computational Fluid Dynamics (CFD) simulations could be employed for design refinement. [24]-[28].

2) Hybrid Drying Systems: Integrating auxiliary heating sources, such as biomass or photovoltaic-thermal (PVT) systems, to enable drying during cloudy periods or low solar radiation.

3) Thermal Energy Storage: Incorporating latent or sensible heat storage materials in the dryer design to maintain high drying temperatures during non-sunlight hours.

4) Product-Specific Drying: Investigating the drying behavior of various agricultural products (e.g., okra, mango, tomatoes) under similar climatic conditions to develop standardized drying protocols.

5) Economic and Environmental Assessment: Conducting life cycle assessment and cost-benefit analysis to evaluate the economic feasibility and sustainability of large-scale solar dryer implementation in Chad and similar regions.

6) Automation and Monitoring: Implementing low-cost sensors and automated control systems to regulate airflow, temperature, and moisture for optimized drying processes.

By addressing these research directions, solar drying technologies can be further improved and widely adopted, contributing to food preservation, post-harvest loss reduction, and sustainable energy utilization in semi-arid countries.

## Acknowledgements

The authors would like to express their sincere gratitude to the technical staff and colleagues who contributed to the experimental work and data collection for this study. Their assistance and valuable discussions greatly contributed to the successful completion of this research.

The authors also acknowledge the support provided by their respective institutions for facilitating the laboratory resources and experimental equipment required for the development and testing of the solar dryer system.

Special thanks are extended to the local agricultural community in N'Djamena, Chad, for their cooperation and for providing the agricultural products used in the drying experiments.

Finally, the authors appreciate the constructive comments and suggestions from anonymous reviewers, which helped improve the quality and clarity of this manuscript.

## Conflicts of Interest

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

## References

- [1] El-Mesery, H.S., El-Seesy, A.I., Hu, Z. and Li, Y. (2022) Recent Developments in Solar Drying Technology of Food and Agricultural Products: A Review. *Renewable and Sustainable Energy Reviews*, **157**, Article ID: 112070. <https://doi.org/10.1016/j.rser.2021.112070>
- [2] Nounangnonhou, C.T., *et al.* (2023) Design and Experimental Evaluation of a Fruits Hybrid-Solar Dryer. *American Journal of Energy Engineering*, **11**, 110-119.
- [3] Saini, R.K., Saini, D.K., Gupta, R., Verma, P., Thakur, R., Kumar, S., *et al.* (2023) Technological Development in Solar Dryers from 2016 to 2021: A Review. *Renewable and Sustainable Energy Reviews*, **188**, Article ID: 113855. <https://doi.org/10.1016/j.rser.2023.113855>
- [4] Yao, Y., Pang, Y.X., Manickam, S., Lester, E., Wu, T. and Pang, C.H. (2022) A Review Study on Recent Advances in Solar Drying: Mechanisms, Challenges and Perspectives. *Solar Energy Materials and Solar Cells*, **248**, Article 111979. <https://doi.org/10.1016/j.solmat.2022.111979>
- [5] Pangavhane, D. (2002) Design, Development and Performance Testing of a New Natural Convection Solar Dryer. *Energy*, **27**, 579-590. [https://doi.org/10.1016/s0360-5442\(02\)00005-1](https://doi.org/10.1016/s0360-5442(02)00005-1)
- [6] Bal, L.M., Santosh Satya, S.N., Meda, N.V., *et al.* (2011) Review of Solar Dryers with Latent Heat Storage Systems for Agri-Cultural Products. *Renewable and Sustainable Energy Reviews*, **15**, 876-880.
- [7] Kadu, S.P. and Kamble, A.A. (2020) Experimental Analysis of Solar Drying System for Vegetable and Fruits. *Journal of Thermal and Fluid Science*, **1**, 44-49. <https://doi.org/10.26706/jtfs.1.1.20200704>
- [8] Govindan, G., Sattanathan, M., *et al.* (2021) Experimental Study of Solar Dryer with Thermal Energy Storage System for Drying of Agro Products.
- [9] Ekechukwu, M.A. and Norton, B. (1999) Review of Solar-Energy Drying Systems II: An Overview of Solar Drying Technology. *Energy Conversion and Management*, **40**, 615-655.
- [10] Kilanko, O., Ilori, T.A., Leramo, R.O., Babalola, P.O., Eluwa, S.E., Onyenma, F.A., *et al.* (2019) Design and Performance Evaluation of a Solar Dryer. *Journal of Physics: Conference Series*, **1378**, Article ID: 032001. <https://doi.org/10.1088/1742-6596/1378/3/032001>
- [11] Mugi, V.R., Das, P., Balijepalli, R. and VP, C. (2022) A Review of Natural Energy Storage Materials Used in Solar Dryers for Food Drying Applications. *Journal of Energy Storage*, **49**, Article 104198. <https://doi.org/10.1016/j.est.2022.104198>
- [12] Negi, A., Ranakoti, L., Verma, R.P., Kumar, V., Bhandari, P., Khargotra, R., *et al.* (2025) Enhancing Solar Still Productivity with Organic Phase Change Materials: A Literature Review. *Energy Conversion and Management: X*, **26**, Article ID: 100984. <https://doi.org/10.1016/j.ecmx.2025.100984>
- [13] Kumar, N., Sarkar, B.C. and Sharma, H.K. (2011) Mathematical Modelling of Thin Layer Hot Air Drying of Carrot Pomace. *Journal of Food Science and Technology*, **49**, 33-41. <https://doi.org/10.1007/s13197-011-0266-7>
- [14] Çakmak, G. and Yıldız, C. (2011) The Drying Kinetics of Seeded Grape in Solar Dryer with PCM-Based Solar Integrated Collector. *Food and Bioproducts Processing*, **89**, 103-108. <https://doi.org/10.1016/j.fbp.2010.04.001>
- [15] Chabane, F., Moumami, N. and Brima, A. (2019) An Experimental Study and Mathematical Modeling of Solar Drying of Moisture Content of the Mint, Apricot, and

- Green Pepper. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, **45**, 4697-4711. <https://doi.org/10.1080/15567036.2019.1670755>
- [16] Salama, R.S., Bacha, H.B., Abdullah, A.S., Abdelgaied, M. and Kabeel, A.E. (2024) Integrated Solar Dryer and Distillation System with PCM and Injection, Powered by PVT Panels and Solar Concentrator. *Scientific Reports*, **14**, Article No. 22036. <https://doi.org/10.1038/s41598-024-69489-y>
- [17] Iranmanesh, M., Samimi Akhijahani, H. and Barghi Jahromi, M.S. (2020) CFD Modeling and Evaluation the Performance of a Solar Cabinet Dryer Equipped with Evacuated Tube Solar Collector and Thermal Storage System. *Renewable Energy*, **145**, 1192-1213. <https://doi.org/10.1016/j.renene.2019.06.038>
- [18] Villagran, E., Espitia, J.J., Velázquez, F.A. and Rodriguez, J. (2024) Solar Dryers: Technical Insights and Bibliometric Trends in Energy Technologies. *AgriEngineering*, **6**, 4041-4063. <https://doi.org/10.3390/agriengineering6040228>
- [19] Fernandes, L. and Tavares, P.B. (2024) A Review on Solar Drying Devices: Heat Transfer, Air Movement and Type of Chambers. *Solar*, **4**, 15-42. <https://doi.org/10.3390/solar4010002>
- [20] Vásquez, J., Reyes, A. and Pailahueque, N. (2019) Modeling, Simulation and Experimental Validation of a Solar Dryer for Agro-Products with Thermal Energy Storage System. *Renewable Energy*, **139**, 1375-1390. <https://doi.org/10.1016/j.renene.2019.02.085>
- [21] Adhikari, N., Andersson, M., Baral, B. and Garg, H. (2026) Numerical Modelling of Solar Dryers Focusing on Heat Exchangers and Solar Collectors—Comparing Flat and Rib Designs with Varying Airflows. *Case Studies in Thermal Engineering*, **80**, Article ID: 107874. <https://doi.org/10.1016/j.csite.2026.107874>
- [22] Venkateswarlu, K. and Reddy, S.V.K. (2024) Recent Trends on Energy-Efficient Solar Dryers for Food and Agricultural Products Drying: A Review. *Waste Disposal & Sustainable Energy*, **6**, 335-353. <https://doi.org/10.1007/s42768-024-00193-3>
- [23] Bal, L.M., Satya, S. and Naik, S. (2010) Solar Dryer with Thermal Energy Storage Systems for Drying Agricultural Food Products: A Review. *Renewable and Sustainable Energy Reviews*, **14**, 2298-2314.
- [24] Rizalman, M.K., Mounq, E.G., Dargham, J.A., Jamain, Z., Yaakub, N.M. and Farzamina, A. (2023) A Review of Solar Drying Technology for Agricultural Produce. *Indonesian Journal of Electrical Engineering and Computer Science*, **30**, 1407-1419. <https://doi.org/10.11591/ijeecs.v30.i3.pp1407-1419>
- [25] Chabane, F. and Adouane, F. (2018) Experimental Investigation of the Solar Drying and Solar Collector Design for Drying Agricultural Product (Mint). *Chemical Engineering Transaction*, **71**, 1387-1392.
- [26] Bala, B.K. and Janjai, S. (2013) Solar Drying of Agricultural Products. *Stewart Post-harvest Review*, **9**, 1-8. <https://doi.org/10.2212/spr.2013.2.4>
- [27] Food and Agriculture Organization (FAO) (2017) Solar Drying: Practical Guide for Food Preservation. FAO. <https://www.fao.org/3/i7376e/i7376e.pdf>
- [28] Ekechukwu, O.V. and Norton, B. (1999) Review of Solar-Energy Drying Systems II: An Overview of Solar Drying Technology. *Energy Conversion and Management*, **40**, 615-655. [https://doi.org/10.1016/s0196-8904\(98\)00093-4](https://doi.org/10.1016/s0196-8904(98)00093-4)
- [29] Álvarez, G., Sima, E. and Lira, L. (2000) Thermal Performance of an Indirect Solar Dryer. In: *World Renewable Energy Congress VI*, Elsevier, 1165-1169. <https://doi.org/10.1016/b978-008043865-8/50241-5>
- [30] Missana, W.P., Park, E. and Kivevele, T.T. (2020) Thermal Performance Analysis of

Solar Dryer Integrated with Heat Energy Storage System and a Low-Cost Parabolic Solar Dish Concentrator for Food Preservation. *Journal of Energy*, **2020**, Article ID: 9205283. <https://doi.org/10.1155/2020/9205283>