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OPTIMIZATION OF HYBRID SOLAR DRYING OF OKRA BY USING RESPONSE SURFACE PLANES

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Abstract: This study employs the Response Surface Methodology (RSM) with a Central Composite Design (CCD) to optimize the hybrid solar drying process. Sixteen experimental runs were conducted based on three key input variables, leading to the formulation of a second-order regression model that explains the effects of these parameters on drying duration and energy consumption. Using data analysis via Minitab software, the optimal conditions were identified to achieve a final product moisture content of 15% (wet basis) while minimizing drying time and energy usage. The results revealed that energy demand increases with greater slice thickness, drying temperature, and air velocity, whereas drying time rises with slice thickness but decreases with increasing temperature and airflow. High agreement was found between the predictive models and experimental observations, with R^2 values of 99.3% for drying time and 99.8% for energy consumption. The optimal drying conditions were 40 °C air temperature, 11.5 mm slice thickness, and 1.02 m/s air velocity.

Keywords: Solar drying, Optimization, Response surface methodology, Drying duration

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1. Introduction

Okra (Abelmoschus esculentus) is a widely cultivated vegetable in Africa, known for its nutritional value, medicinal benefits, and culinary versatility. Containing approximately 87–90% water, okra is highly perishable, often resulting in post-harvest losses of up to 50% due to microbial activity. Traditional preservation techniques are insufficient in many developing countries, underscoring the need for more efficient and sustainable drying solutions.Drying is a widely accepted method for moisture reduction and microbial inhibition in agricultural products. However, conventional solar drying is limited by factors such as inconsistent solar intensity and inadequate process control. Hybrid solar dryers, which integrate auxiliary energy sources, offer a promising alternative by improving control and reducing drying times, though they may still incur high energy costs if not properly optimized.This research explores the optimization of a hybrid solar drying system for okra slices by minimizing drying time and energy usage. The study applies Response Surface Methodology (RSM) to examine the interaction of drying air temperature, slice thickness, and air velocity. A Central Composite Design (CCD) was used to structure the experimental approach and derive a mathematical model to define optimal conditions.

2. Materials and Methods

2.1. Experimental Setup and Materials

The experimental investigation was carried out using a custom-designed hybrid solar dryer, which combines solar energy with auxiliary electrical heating to maintain consistent drying conditions (see Figure 1). Fresh okra (Abelmoschus esculentus) used in the experiments was sourced from local markets in Brazzaville. The dryer was equipped with precise control instruments to monitor and regulate drying parameters.

Figure 1. Hybrid solar dryer.

Key measurement tools included:

- Solar Radiation Sensor: A digital pyranometer measured the solar radiation incident on the collector surface.
- Temperature Monitoring: Thermo-hygrometers were placed at the air inlet, outlet, and ambient environment to track temperature fluctuations.
- Weight Measurement: A precision digital balance with 0.001 g resolution was used to monitor mass loss during drying at 30-minute intervals.
- Power Consumption Tracker: An electricity meter recorded total electrical energy consumed by heaters and fans.

2.2. Determination of Moisture Content

Moisture content on a wet basis (X) was calculated using the following equation 1 (Benseddik et al., 2016):

$$X = (M_o - M_s)/M_s \quad (1)$$

where:

- M_0: Initial weight of the sample (g)
- M_s: Final dry weight of the sample (g)

Drying was considered complete when three consecutive weight readings showed no further change.

2.3. Experimental Conditions and Procedure

Drying experiments were conducted between December 5, 2020, and February 20, 2021, during daylight hours (07:00–18:00). Three independent variables were evaluated:

- Drying air temperature: 40°C, 50°C, 60°C
- Air velocity: 1.0 m/s, 1.5 m/s, 2.0 m/s
- Slice thickness: 10 mm, 15 mm, 20 mm

A total of 16 experiments were performed based on a Central Composite Design (CCD). At each trial, okra slices were weighed, and temperature and solar radiation readings were taken every 30 minutes.

2.4. Response Parameters

Two main response variables were analyzed:

- Drying Time (DS): Defined as the time required for the product to reach a final moisture content of 15% (wet basis). This value was obtained by plotting moisture loss over time and extrapolating with OriginPro 8 software. As shown in equation 2, drying time (DS) is modeled as a quadratic function of the input parameters.
- Energy Consumption (CE): Calculated as the total energy used by the system, including solar input, electrical heaters, and fans. The formula used: As presented in equations 2 and 3, energy consumption (CE) depends on both linear and interaction terms of the drying variables.

CE = Igt+ER+EV(kWh)
CE = I_{gt} + ER + EV \quad (\text{kWh}) (2)
CE= Igt+ER+EV(kWh)

In trials without solar input:

CE= ER+EV(kWh)
CE = ER + EV \quad (\text{kWh}) (3)
CE= ER+EV(kWh)

Where:

- IgtI_{gt}Igt: Solar energy input (kWh)
- ERERER: Electrical resistor consumption (kWh)
- EVEVEV: Fan energy use (kWh)

These values were also modeled and validated using OriginPro 8.

2.5. Selection of Parameters and Experimental Design

The primary objective of this study was to optimize the operating parameters of a hybrid solar drying system in order to minimize both energy consumption and drying time. Based on previous studies by Doymaz (2005), Seidilou et al. (2010), and Ndukuwu (2009), the most influential variables affecting the drying process were identified as drying air temperature, slice thickness, and air velocity.

Accordingly, a Central Composite Design (CCD) within the framework of Response Surface Methodology (RSM) was employed. The experimental design included three factors at three levels, resulting in a total of 16 experimental runs. Center points were replicated to enhance the precision and reliability of the results. The range and levels of the independent variables used in the experiments are summarized in Table 1.

Table 1. Experimental Factors and Their Ranges

Factor	Symbol	Low Level (-1)	High Level (+1)
Drying Air Temperature (°C)	X_1	40°C	60°C
Slice Thickness (mm)	X_2	10 mm	20 mm
Air Velocity (m/s)	X_3	1.0 m/s	2.0 m/s

2.6. Response Variables

Two primary response variables were evaluated in this study:

- Drying Time (DS): As shown in equation 2, drying time (DS) is modeled as a quadratic function of the input parameters.
- Drying time was defined as the duration required for the okra slices to reach a final moisture content of 15% (wet basis). This value was determined by analyzing the moisture content over time using OriginPro 8 software.
- Energy Consumption (CE): As presented in equation 3, energy consumption (CE) depends on both linear and interaction terms of the drying variables.
- Total energy consumption was calculated up to the point when the final moisture content was reached. This includes the combined energy from the solar collector, electrical heaters, and ventilation fans.

Both response variables were derived from experimental measurements and supported by simulation tools. The resulting data were then processed using Minitab software for modeling and optimization purposes.

2.7. Mathematical Modeling and Statistical Analysis

To analyze the influence of drying parameters, second-order polynomial regression models were developed. The general quadratic forms are (equations 4 and 5):

$$DS = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 + \varepsilon \quad (4)$$

$$CE = b'_0 + b'_1X_1 + b'_2X_2 + b'_3X_3 + b'_{11}X_1^2 + b'_{22}X_2^2 + b'_{33}X_3^2 + b'_{12}X_1X_2 + b'_{13}X_1X_3 + b'_{23}X_2X_3 + \varepsilon \quad (5)$$

Where:

- DS: Drying time (minutes)
- CE: Energy consumption (kWh)
- X_1, X_2, X_3: Coded values for temperature, thickness, air velocity
- b: Regression coefficients
- ε: Experimental error term

To analyze the influence of operating parameters and identify optimal drying conditions, a second-order polynomial regression model was developed based on the Central Composite Design (CCD) framework. This model captures both individual and interactive effects of drying air temperature (X_1), slice thickness (X_2), and air velocity (X_3) on two key responses: drying time (DS) and energy consumption (CE).

The general forms of the quadratic models are as follows equation 6:

$$\begin{aligned} DS &= b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 + b_{123}X_1X_2X_3 + \varepsilon \\ CE &= b'_0 + b'_1X_1 + b'_2X_2 + b'_3X_3 + b'_{11}X_1^2 + b'_{22}X_2^2 + b'_{33}X_3^2 + b'_{12}X_1X_2 + b'_{13}X_1X_3 + b'_{23}X_2X_3 + b'_{123}X_1X_2X_3 + \varepsilon \end{aligned} \quad (6)$$

Where:

- DS: Drying time (minutes)
- CE: Energy consumption (kWh)
- X_1, X_2, X_3: Coded values of temperature, thickness, and air velocity
- b_i, b_{ij}: Regression coefficients
- ε: Experimental error term

2.8. Model Fit and Significance

Statistical validation was performed using Minitab software. The coefficient of determination (R^2) was used to assess model accuracy. The models achieved excellent fits, with R^2=99.3% for drying time and R^2=99.8% for energy consumption, indicating that the models accurately reflect the experimental data.

Additionally, an Analysis of Variance (ANOVA) was conducted to test the significance of each regression coefficient using the Student's t-test. A p-value threshold of 0.05 was applied, meaning that any term with $P<0.05$ was considered statistically significant.

2.9. Lack of Fit Test

To ensure the adequacy of the models, a lack-of-fit test was performed. Results showed that the p-values for both responses were greater than 0.05 (Drying Time: p = 0.767; Energy Consumption: p = 0.717), confirming that the model does not significantly deviate from the experimental observations. As shown in equation 2, drying time (DS) is modeled as a quadratic function of the input parameters.

2.10. Estimated Model Coefficients and Final Regression Equations

Following statistical validation, the coefficients for the regression models were calculated to quantify the impact of each independent variable and their interactions on the drying time (DS) and energy consumption (CE). Tables summarizing the regression coefficients, standard errors, t-values, and p-values were generated using Minitab.

Drying Time (DS) Model – Significant Terms As shown in equation 2, drying time (DS) is modeled as a quadratic function of the input parameters.

Analysis of the regression output indicated that the following terms had statistically significant effects on drying time ($p < 0.05$):

• Positive influence: Slice thickness (X_2), square of thickness (X_2^2).

• Negative influence: Air velocity (X_3), square of air temperature (X_1^2), interaction terms X_1X_2 and X_1X_3.

Terms with p-values above 0.05, such as the linear effect of air temperature and the X_2X_3 interaction, were found to be statistically insignificant and excluded from the final empirical model.

Final Regression Equation for Drying Time: As shown in equation 7, drying time (DS) is modeled as a quadratic function of the input parameters.

$$DS = 399.88 + 44.20X_2 - 39.10X_3 - 50.07X_1^2 + 43.43X_2^2 - 20.62X_1X_2 - 37.63X_1X_3 \quad (7)$$

Where:

- DS: Drying time in minutes
- X_1: Drying air temperature (coded)
- X_2: Slice thickness (coded)
- X_3: Air velocity (coded)

Energy Consumption (CE) Model – Significant Terms As presented in equation 3, energy consumption (CE) depends on both linear and interaction terms of the drying variables.

For energy consumption, nearly all terms were statistically significant ($p < 0.05$), except for the square of air velocity (x_3^2), which was excluded.

Significant contributors included (equation 8):

- Positive influence: Drying temperature (X_1), slice thickness (X_2), air velocity (X_3), and square of slice thickness (x_2^2).
- Negative influence: Square of slice thickness (x_2^2), interactions X_1X_2, X_1X_3, and X_2X_3.
- Final regression equation for energy consumption:

$$
\begin{aligned}
CE = 8.3115 + 0.5593X_1 + 0.1135X_2 \\
+ 0.3539X_3 + 0.4297X_2^2 \\
- 0.3141X_2^2 - 0.1137X_1X_2 \\
- 0.1234X_1X_3 - 0.0542X_2X_3
\end{aligned} \quad (8)
$$

Where:

- CE: Energy consumption in kilowatt-hours (kWh).
- X_1, X_2, X_3: Coded values of temperature, thickness, and air velocity.

2.11. Desirability Analysis and Optimization of Drying Parameters

To identify the most favorable combination of operating parameters for hybrid solar drying, a desirability function approach was applied. This method transforms each response variable into a dimensionless desirability value ranging from 0 (completely undesirable) to 1 (fully desirable). The goal was to simultaneously minimize both drying time (DS) and energy consumption (CE) while maintaining a final moisture content of 15% (wet basis) to ensure microbiological stability.

Optimization Criteria:

- Objective for DS: Minimize
- Objective for CE: Minimize
- Target moisture content: 15% (wet basis), corresponding to water activity ≈ 0.6
- Overall desirability goal: Maximize

Optimal Solution and Operating Conditions:

Using the regression models developed in the previous section, numerical optimization was conducted. The optimal set of parameters was found to be:

- Drying air temperature: 40°C
- Slice thickness: 11.5 mm
- Air velocity: 1.02 m/s

These conditions yielded:

- Minimum drying time (DS): 318.29 minutes
- Minimum energy consumption (CE): 7.19 kWh
- Overall desirability index: 0.9029 (or 90.29%)

Table 2. Summary of variable effects on DS and CE

Run	X1 (°C)	Code	X2 (mm)	Code	X3 (m/s)	Code
1	40	-1	10	-1	1.0	-1
...	...	...	...	...	...	...

3. Results and Discussions

The desirability value exceeding 90% indicates a highly effective optimization, demonstrating that the selected drying conditions achieve a balanced trade-off between time efficiency and energy use, without compromising the final product's quality. Summary of variable effects are preset in Table 2.

These findings align with previous research (Kemmene Dapabko et al., 2021), which also suggested that moderate drying temperatures combined with thin slices and efficient airflow enhance both energy and drying efficiency.

Table 3. Summary of variable effects

Parameter	Drying Time (DS) Effect	Energy Consumption (CE) Effect
Temperature (X_1)	↓ Time as Temp ↑	↑ Energy as Temp ↑
Thickness (X_2)	↑ Time as Thickness ↑	↑ Energy as Thickness ↑
Air Velocity (X_3)	↓ Time as Velocity ↑	↑ Energy as Velocity ↑

↑= indicates increase, ↓= indicates decrease.

If a prediction profiler or 3D surface response graph is provided in the paper (e.g., Figure 2), it should be interpreted as follows:

The response surface graphs confirm that the lowest drying time and energy use occur at the lower end of the temperature scale, with reduced slice thickness and slightly above-average air velocity. This validates the regression model's predictive accuracy and confirms the robustness of the optimization process.

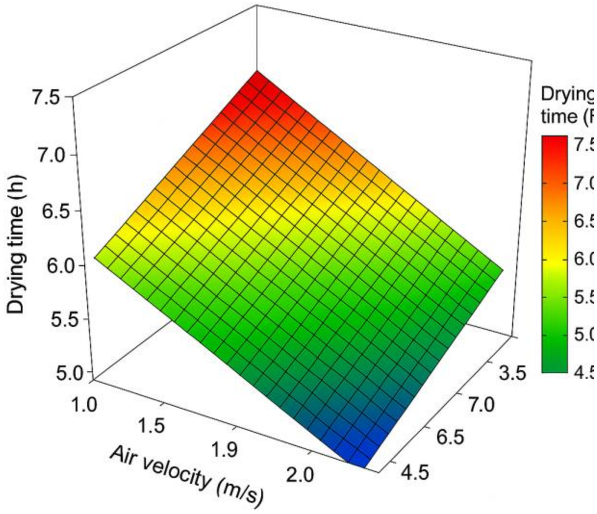

Figure 2. 3D surface response graph showing interactions.

3.1. Effects of Process Parameters on Drying Performance

This section analyzes how each individual process variable—drying air temperature, slice thickness, and air velocity—affects the two main responses: drying time (DS) and energy consumption (CE). These relationships are derived from both the regression models and the experimental data.

3.1.1. Effect of drying air temperature (X_1)

On drying time; Increasing the drying air temperature from 40°C to 60°C significantly reduced the drying time. This is attributed to the enhanced thermal gradient, which accelerates moisture diffusion from the interior to the surface of the okra slices. The drying time decreased from approximately 425 minutes at 40°C to 348 minutes at 60°C. Comparable results were reported by Doymaz (2005) and Jiokap et al. (2021). As shown in equation 2, drying time (DS) is modeled as a quadratic function of the input parameters.

On energy consumption; While higher temperatures reduce drying time, they also lead to a noticeable increase in energy demand. As temperature rises, the auxiliary heating system operates more frequently to maintain the setpoint, pushing energy consumption up from 8.14 kWh at 40°C to 9.27 kWh at 60°C. As presented in equation 3, energy consumption (CE) depends on both linear and interaction terms of the drying variables.

3.1.2. Effect of slice thickness (X_2)

On drying time; As shown in equation 2, drying time (DS) is modeled as a quadratic function of the input parameters.

Thicker slices increase the diffusion path for internal moisture, thus extending the drying time. Increasing thickness from 10 mm to 20 mm increased drying time from approx. 437 minutes to 398 minutes, due to higher internal resistance to moisture movement. These observations align with studies by Nguyen (2015) and Benseddik et al. (2016).

Increasing the drying air temperature from 40°C to 60°C significantly reduced the drying time. This is attributed to the enhanced thermal gradient, which accelerates moisture diffusion from the interior to the surface of the okra slices. The drying time decreased from approximately 425 minutes at 40°C to 348 minutes at 60°C. Comparable results were reported by Doymaz (2005) and Jiokap et al. (2021).

On energy consumption; As presented in equation 3, energy consumption (CE) depends on both linear and interaction terms of the drying variables.

As expected, thicker slices also resulted in higher energy usage. The system must work longer to remove moisture from deeper layers, leading to increased total energy input—from 8.12 kWh at 15 mm to 8.37 kWh at 20 mm.

3.1.3. Effect of air velocity (X_3)

On drying time; As shown in equation 2, drying time (DS) is modeled as a quadratic function of the input parameters.

Air velocity exhibited a strong inverse relationship with drying time. An increase from 1.0 m/s to 2.0 m/s significantly reduced drying time—from about 425 minutes to 324 minutes. The increased convective transfer enhances surface evaporation, thus speeding up drying.

Higher air velocity, while improving drying efficiency, also leads to increased energy demand, primarily due to higher fan power usage. Energy consumption rose from 8.00 kWh at 1.0 m/s to 8.72 kWh at 2.0 m/s, confirming the trade-off between speed and energy efficiency.

4. Conclusion and Practical Implications

This study successfully demonstrated the optimization of a hybrid solar drying system for okra slices using Response Surface Methodology (RSM). Through a series of 16 well-structured experiments under a Central Composite Design (CCD) framework, the effects of drying air temperature, slice thickness, and air velocity were systematically analyzed (Acquistucci et al., 2002).

- Drying time was found to be positively correlated with slice thickness, and negatively correlated with both temperature and air velocity.
- Energy consumption increased with all three variables—temperature, thickness, and air velocity—highlighting the trade-off between process speed and energy efficiency (Sawadogo et al., 2017).
- The models developed for both drying time and energy consumption showed excellent predictive capability with R^2 values of 99.3% and 99.8%, respectively.
- Optimal operating conditions were determined as:
  - Drying temperature: 40°C
  - Slice thickness: 11.5 mm
  - Air velocity: 1.02 m/s
  - Minimum drying time: 318.29 minutes
  - Minimum energy use: 7.19 kWh
  - Overall desirability: 90.29%

These findings validate the robustness and effectiveness of the RSM approach for optimizing complex drying systems (Sharma et al., 2007).

Practical Implications

The implementation of the optimized drying strategy presents multiple advantages:

- Enhanced product quality: The lower drying temperature reduces thermal degradation, preserving nutritional and sensory characteristics.
- Energy savings: Efficient use of hybrid energy sources contributes to reduced operational costs.
- Sustainability: Reduced reliance on fossil fuels supports environmental goals, making the system suitable for adoption in resource-limited regions.
- Scalability: The proposed approach can be adapted for other perishable crops, offering a generalizable framework for optimizing agro-food drying.

Future Research Directions (Hamon et al., 1997).

To further develop this technology and extend its applicability, future studies are encouraged to:

- Explore alternative renewable energy integrations (e.g., biomass, wind-assisted drying)
- Investigate infrared-assisted or vacuum-solar hybrid drying techniques
- Employ machine learning algorithms for predictive modeling of drying behavior
- Scale up the system for industrial-level applications in food processing facilities

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	H.D.	K.F.D.
C	10	10
D	100	
S		100
DCP	50	50
DAI	50	50
L		50
W	50	50
CR	50	50
SR	50	50
PM	50	50
FA	50	50

C= concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because there was no study on animals or humans.

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