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RESEARCH ARTICLE

Optimizing the greenhouse solar drying conditions for banana slices using response surface methodology (RSM)

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Abstract

This study focuses on perfecting greenhouse solar drying conditions for banana slices using Response Surface Methodology (RSM). Experiments were conducted across a temperature range of 40-60 °C and a drying period of 20-40 hours, employing a Central Composite Design to investigate their effects on three critical quality parameters: moisture content, color change (ΔE), and vitamin C retention. The developed quadratic regression models showed excellent prediction power with R^2 values from 95.2% to 97.8%. The moisture content was found to be in the range of 12.50% to 16.83%, color change 22.0 to 35.8 and vitamin C content 3.25 to 8.85 mg/100 g. Optimal drying conditions were determined to be 52.15 °C for 31.66 hours, which yielded balanced product quality with moisture content of 14.45%, color change of 29.55 and vitamin C content of 5.41 mg/100 g. The results presented here show that the optimized solar drying process is capable of high-quality production of dehydrated banana slices with retention of the nutritional contents and efficient energy use. Designed to be compatible with commercial scale drying equipment, the developed predictive models can help to lower the post-harvest losses and ease food processing in rural and industrial settings in a more sustainable manner.

Keywords: ANOVA, moisture content, color, drying period, CCD

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1. Introduction

The potential of bananas in India is substantial due to favorable growing environments, significant domestic demand, and active involvement in export market [1]. With sustained support and investment, the banana industry is likely to grow rapidly and strengthen the nation's agricultural sector and economy. Presently, solar drying technology offers a lot of advantages for dehydrated banana slices such as nutrient preservation, longer shelf life, ease of use, cost-effectiveness, and revenue generation [2],[3],[4],[5]. Solar drying technology is an effective and environmentally friendly process for banana slice handling that enhances product value as well as expands the agricultural industry [6]the CBR augmented the Nusselt number around 8.25% over the FBR. When compared to the plain tube CBR SC, the CFT of minimum twist ratio (Y = 3,[7].This process is the very oldest as well as economical in the aspect of green circular economy [8],[9].The model of the green circular economy, which involves converting post-harvest agricultural residues into economically valuable products through the use of solar energy, is illustrated in Figure 1.

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Figure 1. Model of Green circular economy

A cabinet-type drying system was designed and developed to perfect the drying conditions using RSM. The drying temperature (40 to 70 °C) and wind velocity (1.30 to 1.65 m/s) were considered input variables. The combined impact of input variables on output responses (MC, vitamin C, and color change) was evaluated. The outcomes of this study indicate that the drying temperature (40°C) and airflow velocity (1.45 m/s) were achieved for maximization of vitamin C and minimization of MC [10]. A novel active indirect-type solar drying system was fabricated to optimize the drying parameters using an optimization method. Shape (square, rectangular, triangular, and circular), product thickness (4, 8, 12, 16, and 20 mm), and inlet air vent areas were taken as the independent variables. The results indicate that optimum outcomes observed were MC (11.98%), drying efficiency (34.51%), and drying rate (4.85g/hr) [11].Optimization of tray dryer process variables, including drying temperature (50 to 75°C), airflow velocity, and mass loading capacity, was recently evaluated for mushrooms using Response Surface Methodology (RSM). It proved effective moisture removal in high-density produce and focused only on MC without considering nutrient retention or color quality. The results revealed that the minimum moisture content (9.99% wb) was achieved under optimal conditions of 3 m/s airflow velocity and a drying temperature of 60°C [12]the drying of oyster mushrooms (P. ostreatus.A hybrid infrared/hot-IR drying system was designed, and Response Surface Methodology was used to optimize the drying process parameters, including infrared power and irradiation distance. This system shows high drying efficiency and energy efficiency. The results showed that the best conditions were achieved at a drying air temperature of 73°C, an infrared power of 720W, and an irradiation distance of 7 cm. The System complexity and energy input may reduce feasibility in rural/low-resource settings.[13]. Another study investigated the optimization of operating parameters for the dehydration of banana slices using RSM. The findings revealed that the optimal results were obtained at a moisture content of 7.5% db, a shrinkage factor of 69.54, and an energy utilization of 5.54 kW/h; these conditions corresponded to a temperature of 89.99°C, a mass of 240 g of banana slices, and a water flow rate of 14.0 L/hr [1]. A novel solar-assisted sorption-enhanced biomass gasification system has been proposed for combined electricity and hydrogen production. The system's performance was comprehensively evaluated through energy, exergy, economic, and emergy analyses. Using response surface method, researchers found best conditions: a steam-to-biomass ratio of 0.53 and a CO_2 capture efficiency of 65%. Under these conditions, the system achieved energy and exergy efficiencies of 67.2% and 71.89%, respectively, along with a levelized cost of energy of $7.87/MWh and a net power generation of 5.251 MW. Emergy analysis showed a renewability index of 0.22 and a sustainability index of 1.95, showing moderate sustainability and improved performance over conventional co-generation systems [14]. The drying behavior of Chilli pepper at different stages of maturity was investigated in a controlled hot-air cabinet dryer under different drying conditions. The central composite rotatable design (CCD) was used to evaluate the effects of three levels of drying temperatures (40 °C, 50 °C and 60 °C) and three levels of relative humidity (25%, 35%, and 45%) on drying time and quality attributes. The results showed that the deterioration of color increased as the temperature increased and 50 °C and 35% relative humidity were the best conditions for drying at all maturity stages. These conditions balanced drying efficiency and color retention, with red chili peppers showing favorable quality parameters, such as L* of 23.6 and ΔE* of 4.1. The resulting data are very useful for designing solar dryers to ensure the quality of dried chili peppers [15].

Solar drying techniques have been seen to be environmentally friendly and cost-effective methods of drying agricultural products, but the systematic optimization of greenhouse solar drying of banana slices is yet to be done. There are no methods available that consider significant quality parameters like the retention of vitamin C and color change, or that require extensive experimental trials.

Moreover, inconsistent drying conditions often lead to unreliable product quality. Therefore, a statistically optimized approach is needed to find suitable greenhouse drying conditions that minimize nutrient loss, preserve appearance, and efficiently reduce moisture content.

While RSM and CCD are set up tools for process optimization, the scientific novelty of this study lies in its integrated optimization of quality parameters (moisture content, vitamin C, and color change) under real greenhouse conditions rather than under lab-scale or hybrid systems commonly reported in the literature. To ensure the results are more practically translatable to off-grid setups, the study uses a custom-made greenhouse solar dryer that features a modified design that is better suited to the rural context, such as passive ventilation, polycarbonate glazing and variable solar input. Unlike many earlier studies, which are limited to one output parameter or to idealized environmental conditions, the current study considers multi-response optimization, real-time environmental changes, and confirms the results by experiment, with results in good agreement with the model predictions. In addition, a longer duration of drying (up to 40 hours) was considered in the study and an optimum drying window (52.15°C for 31.66 hrs.) was defined as a balance between nutrient retention and drying efficiency, a feature that was not well reported in previous drying RSM of bananas.

The structure of the paper is as follows: In Section 2, the materials and methods used in this study are described, which includes the experimental design and experimental setup. The results and their discussion are given in Section 3. The validation of models and investigation of process parameters are described in section 4. Lastly, Section 5 provides conclusions and recommendations for future work.

2. Materials and method

This section deals with the installation and fabrication of the experimental setup, the preparation of samples, and the mathematical modelling.

2.1. Greenhouse solar drying system

The Solar drying system, found on the rooftop of the Solar Energy Lab at Madhav Institute of Technology & Science, Gwalior, M.P., India (26° 13’ 47.388” N and 78° 10’ 24.132” E), is designed, fabricated, and tested. A photograph of the experimental setup is shown in Figure 2. The drying system consists of several components: a concrete floor, an even-span greenhouse, a centrifugal vent, a drying tray, and a thermoregulatory system. Volumetric dimensions of drying system are 3.14 m × 3.263 m × 3.14 m. The entire structure of the drying system was constructed using square mild steel channels; however, a 4mm-thick polycarbonate sheet was used as the covering material. A Centrifugal vent, an axial-type DC fan that runs at 220V and 1.2 Amp, allows a theoretical wind velocity of 1.2 m/sec. A digital-type anemometer was used to record the air velocity, and a no. of digital temperature sensors (range -140 to 1190°C, and accuracy: ± 0.1°C) were used to measure the temperature at different locations. Three evenly spaced drying trays are positioned within the drying region to accommodate the food samples. Throughout the drying process, moisture content, color change and vitamin C content of the samples are closely checked. The moisture content is calculated by weighing the sample periodically and the color changes are recorded and analyzed using standard colorimetric methods. Vitamin C content is found out using proper chemical assays, ensuring a comprehensive evaluation of drying effects on food samples [16]. Detailed specifications of the current research are given in Table 1. A schematic diagram and dried samples are shown in Figure 3.

Table 1. Detail specification

Area/Subject	Information
Specific area of research	Greenhouse solar drying system (GHSD)
Types of data value	Experimental data, Figures, Graphs, and Figures
Data presentation	Raw and analyzed data
How data were collected	Experimentation was conducted for GHSD of banana slices. Analytical modelling and optimization by using Design Expert-13 software.
Data collection region	Madhav Institute of Technology & Science, Gwalior, M.P India (26° 13’ 47.388” N and 78° 10’ 24.132” E)
Detail discussion of data collection	Banana slices were dehydrated using GHSD and the quality of the sample was in terms of color index and MC.

Figure 2. Actual view of experimental setup.

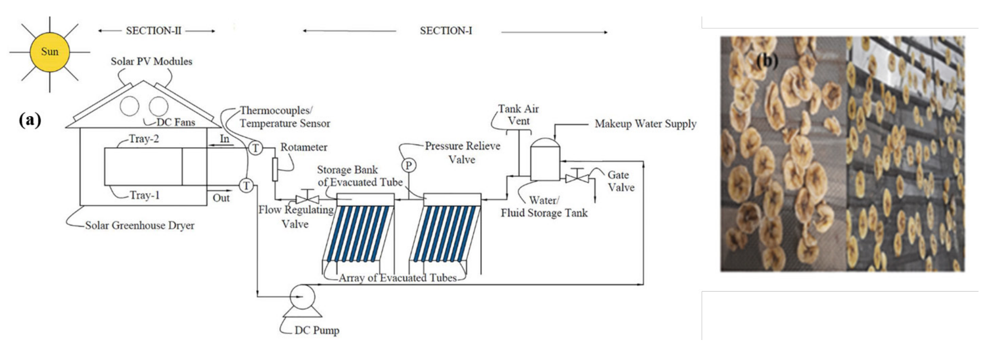

Figure 3. **(a)** Schematic diagram of GHSD, and **(b)** dried banana slices

2.2. Experimental setup and procedure

The experiments were conducted using a passive greenhouse solar dryer (GHSD) specifically designed and fabricated for this study. The dryer forms a semi-cylindrical drying chamber covered with polycarbonate, with natural ventilation and internally black-coated surfaces to enhance solar absorption. Fresh banana slices (5 mm thick) were evenly spread on stainless-steel mesh trays in the dryer. The drying experiments were carried out under different ambient conditions from 9 AM to 5 PM. Digital temperature and relative humidity sensors were used to collect data at 1-hour intervals. The samples were weighed periodically until we gained constant weight to check the endpoint of the drying process.

2.3. Preparation of sample and instrumentation

The fresh banana samples were bought from a local market in Gwalior, India. Before the drying process, the banana samples were carefully washed and peeled. The digital weighing machine was used to measure the weights of the prepared banana samples. The placement of banana samples to drying tray should not overlap between samples to ensure uniform drying. Samples collected from the drying tray and weighed at suitable time intervals. Experimental work was carried out from 07:00 to 18:00 hrs. per day during March 2024 to complete all the set of experiments. During the inquiry, the weather was mostly sunny with no precipitation. Air temperature, solar irradiance, relative humidity, drying-cabin temperature and sample weight were recorded during the experiment. A pyrometer was used to record solar radiation, and a digital thermo-hygrometer was used to record ambient relative humidity. The weight of the dried banana slices was periodically checked using a digital scale. The Detailed specifications of the measuring instruments are provided in Table 2.

Table 2. Detailed description of measuring devices

Instrument	Array	Precision	Measuring variable
K-types thermocouple (PT-100 &PT-1000 sensor)	-140 to 1190°C	±0.1°C	Temperature
Solar meter (PMV-210)	0-1800W/m^2	±2%	Solar irradiance
Pyrometer (Megger PVM 210)	0-2000W/m^2		Solar irradiance
Digital Hygrometer (MEXTECH TM-1)	5-85%	±2%	Relative humidity (RH)
Hot wire anemometer (Testo-405i)	0–30 m/s	0.2%	Air/wind velocity
Digital weighing Machine	0-35kg	0.1%	Dehydrated product

2.4. Experiment uncertainty analysis

The accuracy of data collection in experimental work is influenced by uncertainty and errors. Measurement uncertainty is influenced by various parameters, including instrument choice, calibration, environmental conditions, observational readings, and test planning (which encompasses fixed, systematic, and random errors). The overall uncertainty resulting from the interaction of different parameters can be calculated using the following equation:

$$U_R = \left[\left(\frac{\partial R}{\partial Z_1}U_1\right)^2(x_1) + \left(\frac{\partial R}{\partial Z_2}U_2\right)^2(x_2) + \ldots\ldots\ldots + \left(\frac{\partial R}{\partial Z_n}U_n\right)^2(x_n)\right]^{\frac{1}{2}} \quad (1)$$

Above can be written as, if

If $X_1, X_2 \ldots\ldots X_n$ are the independent parameters influencing the observed variables R, then the uncertainty in observed parameters U_R was computed by Equation.

The uncertainty analyses of various measured variables (air temperature, Rh, air velocity, MC, solar irradiance) and of the total uncertainty in the present study are shown in Table 3.

Table 3. Presentation of uncertainty analysis

Parameters	Uncertainty
Temperature	0.17
Relative Humidity (U_{Rh})	0.180
Air Velocity (X_{av})	0.180
Moisture content ($X_{moisture\ contenta.v}$)	0.100
Solar Intensity ($X_{solar\ intensity}$)	1.41
X_{total}	$\left[(0.17)^2 + (0.180)^2 + (0.180)^2 + (0.100)^2 + (1.41)^2\right]^{0.5}$ ±1.03

2.5. Moisture content (MC)

Moisture content (MC)in a sample is decided by the presence of equilibrium moisture, which serves as an important indicator of product quality and plays a key role in ensuring safe storage. Moisture in a product exists in two forms: surface moisture and internal(bound) moisture. The amount of moisture can be expressed using two methods: wet basis (w.b) and dry basis (d.b). In this study, moisture content was measured on a wet basis, with the primary aim of reducing it to a safe level suitable for long-term preservation. Moisture content of sample on a wet basis is evaluated [17],[18],[19],[20]:

$$M_t = \frac{W_t - W_d}{W_t} \quad (2)$$

where, W_t = weight of the sample at instantaneous time t, W_d = total weight of dry weight.

2.6. Color measurement

Color index assessment plays a crucial role in deciding the quality of dehydrated products and their recognition by end-users. A chromometer or a Hunter-type colorimeter is used to check the color of dehydrated and fresh banana samples. Measurements are carried out 5 times for each banana sample, and the average of all 5 measurement sets is used to be the sample color. Sample's color criteria are termed in Commission International Eclairage's chromaticity coordinates L_o, a_o, and b_o. Total Color difference (ΔE) was obtained using following relations [17]. Figure 4 schematically illustrates how experimental work was carried out. Overall, understanding color changes in dehydrated agricultural products helps ensure quality control, perfect harvesting, and keep nutritional value.

$$\Delta E = \sqrt{(\Delta L_o)^2 + (\Delta a_o)^2 + (\Delta b_o)^2} \quad (3)$$

where

$$\Delta L_o = (L_0 - L)$$
$$\Delta a_o = (a_o - a)$$
$$\Delta b_o = (b_o - b)$$

These factors have a major role in defining the color grouping in terms of huge angel(h), given in Eq.4:

$$h = \begin{cases} \tan^{-1}(b_o/a_o) & (\text{when } a_o > 0) \\ \text{[0.5em]}\ 180^\circ + \tan^{-1}(b_o/a_o) & (\text{when } a_o < 0) \end{cases} \quad (4)$$

where, is total color change difference, and are the corresponding value of fresh banana slices and dehydrated banana slices, respectively. The parameters moisture content, color change, and vitamin C (Table 4) content are used to assess the quality and characteristics of dried products. These parameters help to evaluate the quality, nutritional value, and consumer acceptance of food products during and after processing.

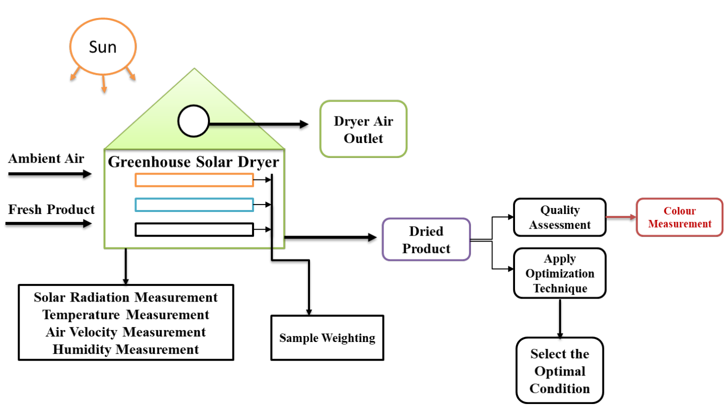

Figure 4. Investigation process

Table 4. Quality, nutritional value, and consumer acceptance parameters

Parameters	Methods to adopted
Moisture content	By analytical correlation
Color change	Chroma meter or colorimeter
Vitamin C content	DCPIP titration technique

2.7. Vitamin C assay methodology

Vitamin C content of the banana slices was decided by the 2,6-dichlorophenolindophenol (DCPIP) titration method, a standard redox titration technique for estimating ascorbic acid. The procedure involved the following steps:

Sample Preparation: A known weight of dried banana slices was homogenized in a 3% metaphosphoric acid solution to extract ascorbic acid and to prevent its oxidation.

Filtration: The mixture was filtered using Whatman No. 1 filter paper to get filtrate.

The filtrate was then titrated with a freshly prepared standard DCPIP solution (0.01%) and the end point was decided by the presence of persistent pink color after the reaction which showed the completion of the redox reaction.

Calculation: The vitamin C concentration (in mg/100g) was calculated based on the volume of DCPIP consumed, using the Eq:

$$\text{Vitamin C}\left(\frac{\text{mg}}{100\text{gm}}\right) = \left(\frac{V_1 \times C \times 100}{V_2 \times W}\right)$$

where:

V_1 is shows the volume of DCPIP used for titration (mL), the factors of C are the concentration of ascorbic acid standard (mg/mL), V_2 is shows the volume of sample extract taken for titration (mL), and W (g) is the mass of the sample.

The titration was carried out three times to get correct results for each sample, and the mean value was reported with standard deviation.

3. Result and discussion

The quality of banana slices is influenced by drying conditions, specifically, temperature and drying period, which in turn affect the response values. These conditions were perfected via response surface method (RSM).

3.1. Experimental design

In the current study, the influence of certain conditions was examined using a full factorial design. Response surface method (RSM) was applied to evaluate the effect of drying parameters [21]. In the Central Composite Design, temperature and drying period were treated as independent variables. The responses measured were moisture content, vitamin C, and color change. Temperature varied from 40°C to 60°C, while drying hours ranged from 20 to 40 hrs (Table 5). The CCD included 13 experiments: 4 factorial experiments, 4 axial experiments, and 5 center-point repetitions. The experimental design and data analysis were performed using Design-Expert software. The response factors were modelled as functions of the independent variables using a quadratic model, as expressed in Equation 6.

$$Y = \beta_0 + \sum_{i=1} \beta_i X_i i + \sum_{i=1} \beta_{ii} X_i^2 + \sum_{i=1} \sum_{j=i+1} \beta_{ij} X_{ij} \quad (6)$$

In the model, Y is the desired response value (Moisture content, Vitamin C, and color change) β_0 is defined as constant term, and β_i, β_{ii} and β_{ij} are the linear, quadratic, and cross-product coefficients, respetively. X_i and X_{ij} denote points of independent factors. Model accuracy was decided after considering predicted R^1 values and R^2 adjusted values. The precision, coefficient of variation, and prediction error sum of squares were computed using ANOVA. Figure 5 Sequential steps in the Response Surface Methodology (RSM)-based optimization process [1].

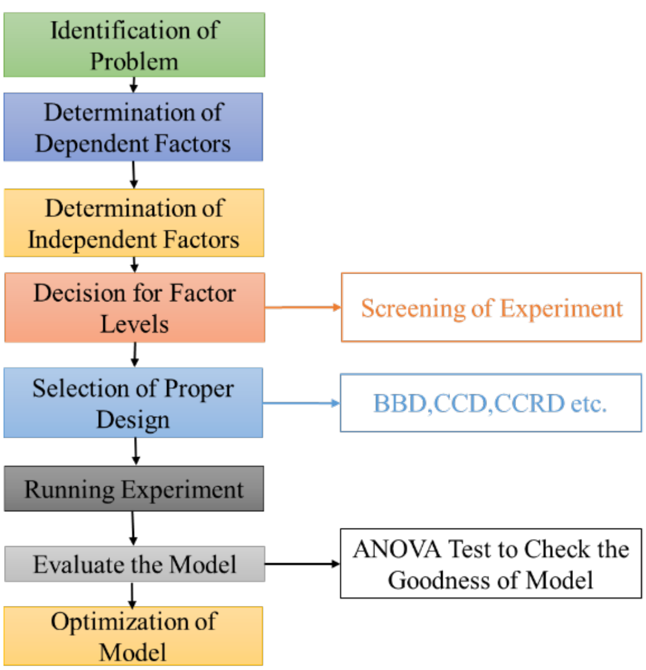

Figure 5. Steps followed during optimization process

To estimate overall desirability of model, individual desirability's of factors (d_i) were aggregated as follows:

$$\text{Desirability (D)} = (d_i \times d_{ii} \times d_{iii} \times \ldots\ldots\ldots \times d_n)^{\frac{1}{n}} \quad (7)$$

D is the overall desirability and the individual desirability for each response. Equal weights were assigned to all responses, reflecting their balanced importance in perfecting drying temperature and period. This approach allowed us to find the best drying conditions that maximize nutrient retention and product quality while minimizing moisture content and color degradation. This clarification has been incorporated to enhance the transparency of the optimization process.

3.2. Data description

The ranges and levels of control parameters investigated for solar drying are described in Table 5. The input variables, drying air temperature and drying period, each have 3 levels. The response of moisture content and color change was used to assess the impact of the investigational factors [10], [21]. Table 6 presents a detailed summary of the findings for 13 runs and 02 responses. Moisture content, Vitamin C content, and color change varied in the ranges of 12.50 to 16.83%, 3.25 to 8.85 mg/100gm, and 22.0 to 35.8, respectively. The precision of the output was used to examine the fit of the variance, as proved in Figure 6.

Table 5. Demonstration of investigation range and levels

Controlled Factors	Units	Symbols	Level 1	Level 2	Level 3
			Lower Range	Medium-Range	Higher-Range
Drying air temperatures	°C	A	40	50	60
Drying Period	hrs	B	20	30	40

The selected temperature ranges of 40-60 °C were based on earlier studies that showed that this interval effectively eases moisture removal while minimizing the thermal degradation of nutrients, such as vitamin C, in fruit products. Similarly, the drying time range of 20-40 hours was chosen to cover typical durations needed to achieve safe moisture levels in greenhouse solar drying systems under variable solar conditions.

Table 6. Design matrix

		Variable 1	Variable 2	Response 1	Response 2	Response 3
Std.	**Run**	**A: Drying Air Temperature (°C)**	**B: Drying Period (hrs)**	**Moisture Content (%)**	**Colour Change (ΔE)**	**Vitamin C (mg/100gm)**
		60	20	16.83	22	3.70
2	1	50	30	12.63	29.5	5.25
6	2	50	30	12.64	29.6	5.26
5	3	40	40	13.85	30.9	8.65
3	4	50	30	12.98	29.5	5.30
7	5	60	40	16.25	35.8	3.25
4	6	40	20	13.55	17.1	8.85
1	7	50	30	12.68	29.5	5.23
13	8	40	30	13.75	26.8	8.70
8	9	50	20	12.58	18.9	5.62
10	10	60	30	16.67	30.9	3.68
9	11	50	30	12.55	29.6	5.98
12	12	50	40	12.50	35.8	5.45

4. Evaluation and validation of RSM models

Both numerical and graphical optimization techniques were employed to adjust the independent variables, namely drying period and drying air temperature, to achieve best responses such as moisture content, Vitamin C, and color change. To enhance the drying procedure, specific constraints were set up for the parameters and responses, aiming to reduce moisture content and color change while maximizing Vitamin C across all experiments.

4.1 Model fitting

To find the best response state of the parameters under investigation, a regression analysis was conducted, as detailed in Table 7. The experimental data was fitted to a second order polynomial which was coded for two independent factors affecting the responses. The regression analysis showed that temperature and the drying period had significant effects on the responses with statistical significance of $p \leq 0.05$ for first order linear (A &B), second order quadratic (A^2 & B^2), and interaction effects (A*B). In particular, the findings showed the drying period had a positive linear coefficient and temperature had a negative linear coefficient. Based on these results, the moisture content with higher drying hours increased, while the moisture content with higher drying-air temperature decreased. The fitted quadratic polynomial equations for MC, vitamin C and color change were presented as well as analysis of variance (ANOVA) in table 5. The ANOVA tests show that quadratic regression models are highly significant and the F-value for lack of fit is not significant, showing that these regression models are a good fit and need further investigation. Several measures are tested to further decide the goodness of fit of the models: coefficient of determination (R^2), coefficient of variation (CV), adjusted coefficient of determination (adjusted R^2) and model accuracy. The R^2 values were 0.988 for MC, 0.973 for vitamin C, and 0.987 for color change, with adjusted R^2 values of 0.9779, 0.869, and 0.9788, respectively. The coefficient of determination (R^2), which shows the proportion of variance in the response variable explained by the model, was used to assess the model's predictive accuracy. Low CV values at replicated experimental data show high repeatability and precision. Furthermore, the precision values of the model are adequate in range from 6.45 to 21.47, showing that the model has a high signal-to-noise ratio.

4.2. Relationship between experimental and predicted data set

It is necessary to verify that the fitted model accurately is the actual data to avoid suboptimal or incorrect optimization outcomes. The adequacy of the model was assessed through fitted-line plots of projected vs. experimental data (Figure 6). These diagnostic plots show how well the data matches the expected data. All the points in Figure 6 are nearly on the regression line, and the points are plotted in Table 4, which shows that there is good agreement between the experimental points and the regression line. The plots of the fitted line show good agreement of the experimental points with the prediction. Further, high values of R^2 (0.988 for MC, 0.973 for vitamin C and 0.988 for color change) were obtained, showing that there was a high degree of compatibility between the model and the data. If the R^2 is 0.8 or higher, the model is generally regarded as having a good fit with the data, meaning that 80% or more of the variation in the response variable is accounted for by the model.

4.3. Impact of process parameters on outcomes

Effects of varying process conditions, including drying air temperature and drying periods, on three responses - MC, vitamin C content, and color change - in dried banana slices were analyzed. To explain the impact of these conditions, 3D contour plots of quadratic models were generated. These plots were designed to investigate the effect of one factor that was kept at its central level and the other factor that was manipulated between the experimental values. This method enabled a detailed examination of the influence of the modifications of process conditions on responses and insight into deviations from the reference points. Experimental data for the responses at the designed points are given in Table 5. The moisture content ranged from 12.50% to 16.83% with the highest of 16.83% moisture content obtained when the drying air temperature was 60°C and the drying time was 20 hrs. The change in color values ranged between 17.1 and 35.81 with the highest value (35.81) noted when drying at 50°C for 40 hrs. It was observed that the vitamin C content varied from 3.25 to 8.85mg / 100g in the samples (Figure 7) with the lowest content of 3.25mg / 100g in the sample dried at 40°C for 40 hrs. Results indicated that, for color change, the linear coefficient for temperature and the coefficient for drying hours were positive (Table 6). This suggests that color change values increase with rising temperature and drying period. This implies that vitamin C concentration increases with longer drying times and decreases with higher drying temperatures (Figure 7). Figure 6 illustrates a graphical representation of the models' performance, showing how the predicted responses compare with actual values, indicating the models' accuracy. To understand how variations affect responses, we created a response surface curve and contour plot based on statistically significant model, as shown in Figure 8. In the perturbation plot of Figure 8, the temperature curve is notably more pronounced than the curve for the dying period. This highlights temperature as a critical factor, revealing that moisture content is particularly sensitive to temperature.

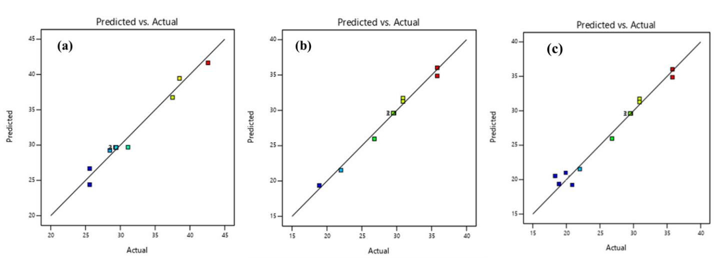

Figure 6. Predicted and experimental data for **(a)** MC, **(b)** color change, and **(c)** vitamin C content

The fitted line plot suggests the closeness b/w predicted and actual values for the coded equations; these equations and all expected responses are discussed in Table 6. With adjusted values of 0.9779 (97.7%) for moisture content and 0.9788 (97.8%) for colour change, the models were statistically valid.

Table 7. Coded equations with R values

Responses	$R^2_{(value)}$	$R^2_{(predicted)}$	$R^2_{(adjusted)}$
MC = + 29.66 - 3.52A - 8.62B + 2.23AB +3.56A² + 3.36B²	0.988	0.9590	0.9779
Colour Change(ΔE) = + 29.61 + 2.65A + 7.75B - 0.5032AB - 0.9874A² - 2.49B²	0.987	0.9529	0.9788
Vitamin C Content = + 6.02-2.53A+0.3105B 0.247AB + 1.01 + 2.75	0.973	.09510	0.9771

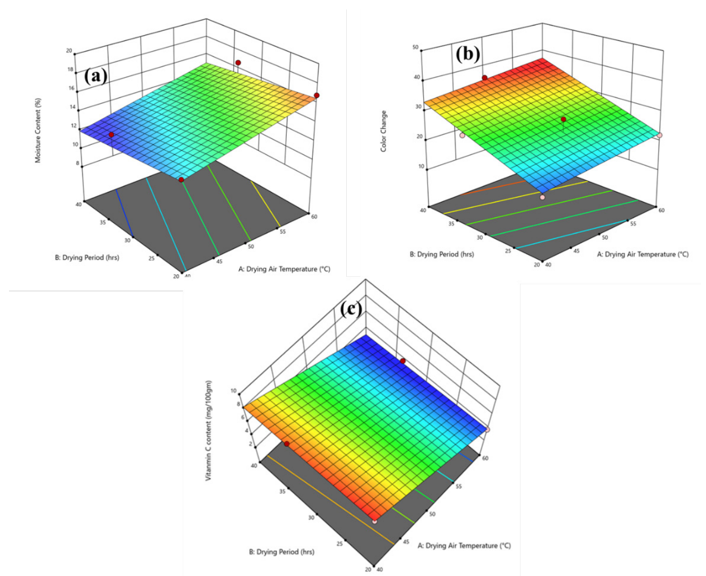

Figure 7. 3D contours plots for **(a)** moisture content, **(b)** color change, and **(c)** vitamin C content

Specifically, rising temperatures and longer drying times resulted in a noticeable reduction in moisture content and a reversal of color change. Tables 8–10 show how analysis of variance (ANOVA) was used to assess the statistical significance of the model.

Table 8. ANOVA results for moisture content

Variables	Sum of Square (SS)	Degree of Freedom (df)	Mean Square (MS)	F-value	P-value
A-Drying Air Temperature	39.09	1	39.09	60.69	0.0006
B-Drying Period	234.17	1	234.17	363.54	< 0.0001
Pure Error	0.0067	3	0.0022	-	-
Total SS	273.267	4	-	-	-

Table 9. ANOVA results for color change

Variables	Sum of Square (SS)	Degree of Freedom (df)	Mean Square (MS)	F-value	P-value
A-Drying Air Temperature	22.15	1	22.15	41.14	0.0014
B-Drying Period	189.25	1	189.25	351.51	< 0.0001
Pure Error	0.0117	3	0.0039	-	-
Total SS	211.4	4	211.4	-	-

Table 10. ANOVA results for vitamin C content

Variables	Sum of Square (SS)	Degree of Freedom (df)	Mean Square (MS)	F-value	P-value
A-Drying Air Temperature	25.71	1	13.04	135.35	0.0005
B-Drying Period	0.3149	1	25.71	266.85	< 0.0001
Pure Error	0.0092	3	0.0051	-	-
Total SS	252.12	4	252.12	-	-

The p-value plays a crucial role in deciding whether each coefficient is statistically significant (p-value < 0.05). Based on the findings, the drying period significantly influenced moisture content, while both temperature and the drying period affected color change value. However, various drying times were implemented to accommodate the duration of the working day. Results showed good agreement between the present and earlier study outcomes i.e. in the case of active indirect type solar drying system final MC was reached as 12.50% w.b [22,15]. In addition to reporting ANOVA results (Tables 8-10), diagnostic checks were performed to confirm the assumptions of the regression models. Normal probability plots of residuals, plots of residuals versus predicted values, and studentized residual plots were generated to examine the normality, homoscedasticity, and independence of residuals. The normal probability plots showed that the residuals approximately followed a straight line, confirming that the error terms were normally distributed. The residuals vs. predicted plots showed no discernible patterns, supporting the assumption of constant variance. No significant outliers or influential points were seen. 95% confidence intervals were also considered for the model coefficients, and they fell within acceptable bounds, showing reliable parameter estimates. The high R^2 and adjusted R^2 values (all above 0.95) further confirm that the models explain a substantial proportion of the response variability. Figures 8(a),8(b), and 8(c) show that the drying air temperature and drying period significantly affect the moisture content, color change, and vitamin C. An increase in air temperature results in reduced MC and increased color change.

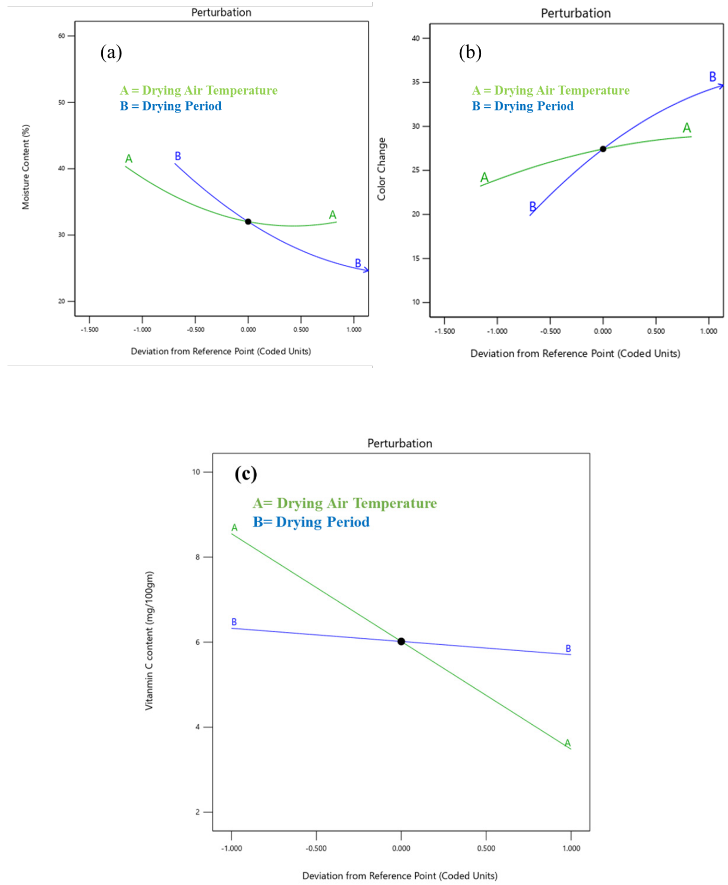

Figure 8. Impact of input variable on response **(a)** moisture content and, **(b)** color change, and **(c)** vitamin C

The design of the drying process and the characteristics of the samples could affect product quality variation. Additionally, the nutritional qualities of the food, such as protein, carbs, naturally occurring sugars, fibers, and potassium, may be influenced by the greenhouse solar-drying process. Under controlled conditions, solar drying within a greenhouse preserves the product's protein and carbohydrate levels. Concentration of the fruit during the drying process increases the final level of total sugars, even though naturally occurring sugars may undergo slight degradation. The greenhouse solar drying process has no impact on fiber and potassium content. From an energy perspective, the relative energy consumption of a greenhouse solar dryer and traditional drying methods (such as open-air, hot-air, freezing, and microwave) can vary depending on factors such as the specific drying technologies used, the scale of air-drying processes, and the local climate. The data recorded during drying methods forms the significant factors, i.e., drying period and drying air temperature. These variables can be used to perfect the drying process and provide useful data on its conditions. The final section underscores the value of data for contributing to scientific understanding, further research, and future investigations, especially those related to banana drying. It has proved that dry air temperatures of more than 52.15 °C and drying time of more than 31.66 hrs. must achieve proper MC range and the appearance of dried bananas. In terms of rural applications, greenhouse solar drying for commercial applications in remote areas has potential for increasing local economies, empowering farmers and improving sustainable farming practices [1], [13].

4.4. Optimal condition

Optimization is important in food engineering to ensure the process is customized for efficiency and increased production. The experiment aimed to evaluate the best process parameters which would influence vitamin C, MC and color change. These parameters were optimized using the desirability function by deciding the specific targets like minimizing moisture content, maximizing vitamin C content and limiting color change level in solar drying with green house. The desired conditions, as decided by this function, were 52.15°C and a drying period of 31.66 hrs. Table 10 presents the predicted values of the response variables under these ideal conditions, according to the quadratic model. Of the 13 runs designed using software one is considered the best solution for maximum drying. The red-colored points in Figure 9 show best conditions (drying air temperature and drying period), and best color change, moisture content, and Vitamin C content are shown as predicted values in Figure 10. The Desirability of the solution is 1, as proved in Figure 10. Table 10 shows the desired values for both independent and dependent variables resulting from the optimization technique. The best values of the control variables were 52.15°C (drying temperature) and 31.66 hrs (drying period). The best values of MC, vitamin C content, and color change for banana slices at these drying conditions were predicted as 14.45%, 5.41mg/100gm, and 29.55, respectively. Further, to set the benchmark for the precision of predicted outcomes using the RSM model, the experiments were repeated under optimized conditions, and the observed response data (MC and drying hours) were discussed in Table 11. It was noted that the errors b/w experimental outcomes and RSM predictions were 15.6%, 1.19%, and 7.12% for the minimum moisture content, color change, and vitamin C content, respectively. Furthermore, drying air temperature was seen to play a vital role in optimization.

Table 11. Optimum data

Method	Drying temperature (°C)	Drying Period (hrs)	Moisture Content on Wet basis (%)	Vitamin C (mg/100gm)	Colour change (ΔE)	Desirability
RSM Prediction	52.15	31.66	14.45	5.41	29.55	1.00
Experiment	-	-	12.50	5.05	29.20	-
Error (%)	-	-	15.6	7.12	1.19	-

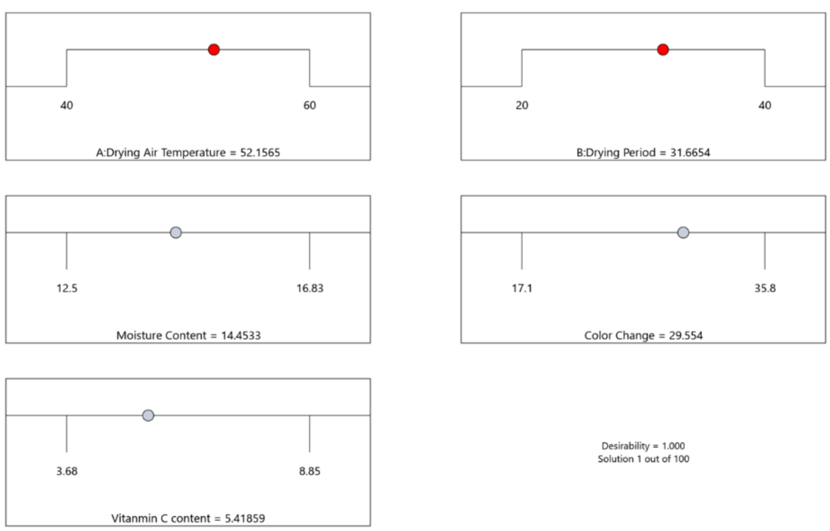

Figure 9. Optimum values of input variables

The observed percentage errors of 15.6% for moisture content, 7.12% for vitamin C, and 1.19% for color change may be attributed to experimental uncertainties, such as slight fluctuations in solar radiation and ambient conditions, and variability in material properties among banana slices. Further, although the RSM model can reproduce the major influences and interactions of important variables, it may not be able to capture all the real-world disturbances or nonlinearities that can also contribute to these discrepancies. The experimental/predicted values and 95% confidence bounds are shown in Figure 11.

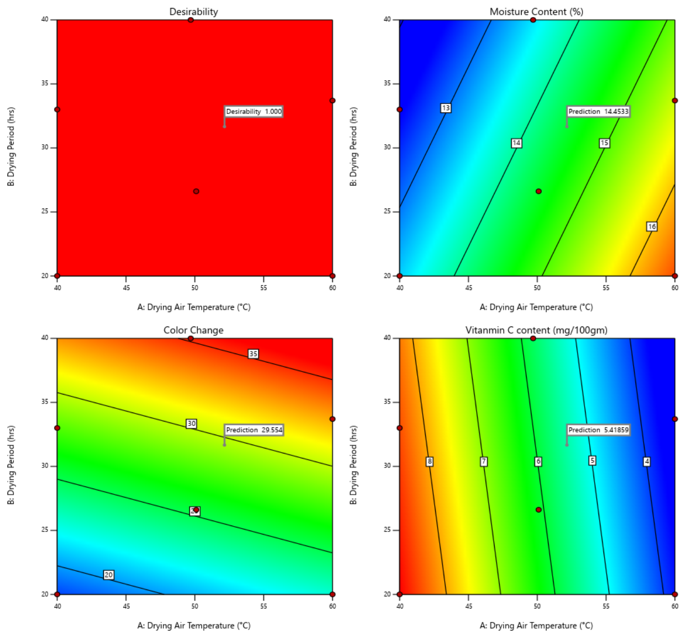

Figure 10. Optimum data of response with desirability

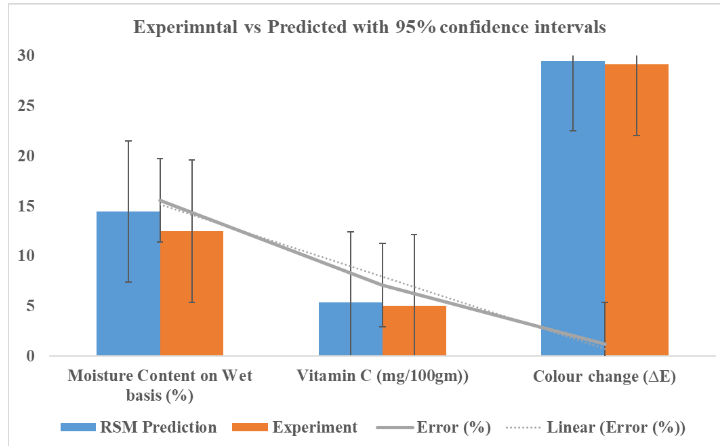

Figure 11. Experimental vs Predicted value

4.5. Comparison with conventional drying methods

Comparative data for the performance of the conventional drying methods: hot-air drying, open-sun drying, and infrared drying are summarized in Table 12 and used to give the context of the performance of the GHSD system. The methods vary in their ability to dry, to preserve nutrients, to use energy, and to make good products.

Table 12. Comparison analysis with conventional drying methods

Drying Method	Final MC (%)	Vitamin C (mg/100g)	Colour Change (ΔE)	Notable Characteristics
Greenhouse Solar Dryer (GHSD)	12.50 [15]	5.05	29.20	Sustainable, moderate nutrient retention
Hot Air Drying	9.99 [11]	3.8-4.2 [22]	32-36 [13]	Uniform drying, high energy use
Open Sun Drying	14-18 [22]	2.5-3.0	35-40	Inexpensive, high contamination risk
Infrared Drying	8.0-10.0	3.2-4.5 [12]	28-34	Fast drying, risk of surface overheating

4.6. Scalability and commercial potential

The greenhouse solar dryer (GHSD) provides energy efficient and low cost drying but has several problems which prevent its widespread use in rural areas. The outlay for first fabrication (~₹25,000) can be a financial constraint for small farmers without institutional support. Sunlight dependency restricts the operation around the year, particularly during monsoon season, and so results in hybrid or backup systems. Space on the roof or open land is needed, but this may not be available. In many remote areas, technical skills for fabrication, operation and maintenance are limited, affecting reliability and performance over time. Furthermore, lack of institutionalized market linkages about dried products decreases the economic benefit for adoption. Without automated controls, it is difficult to ensure a uniform quality of a product in rural areas where there is no centralized control. Community based models, skill development programs, policy incentives and the connection with rural food value chains are some of the key solutions that need to be applied to these challenges. The following steps will help make GHSD a practical and practical solution for sustainable post-harvest management in low resource areas. Table 13 shows sensory evaluation and consumer acceptability.

Table 13. Discussion of sensory evaluation and consumer acceptability

Sensory Attribute	Mean Score (± SD)	Interpretation
Appearance	8.1 ± 0.3	Liked very much
Texture	7.9 ± 0.4	Liked moderately to very much
Flavor	8.0 ± 0.2	Liked very much
Aroma	7.6 ± 0.5	Liked moderately
Overall Acceptability	8.0 ± 0.3	High consumer acceptability

4.6.1. Sustainability and economic feasibility

The proposed greenhouse solar drying system runs solely on solar energy, leading to substantial energy savings compared to conventional electric or fuel-based dryers. Comparisons of energy input show that the GHSD system eliminates approximately 5-6 kWh of electricity per 10 kg of dried **b**ananas that would otherwise be required by a hot-air dryer. This would equate to a saving of ₹ 35-48/batch, after considering maintenance and fixed costs, if local energy cost is assumed as ₹ 7-8/kWh. Furthermore, total CO_2 emissions are reduced by 4.2 kg/10 kg product to 5.0 kg/10 kg product for each ton of product produced when avoiding the use of energy derived from fossil fuels (assumed CO_2 emission factors 0.84 kg / kWh and 1.0 kg / kWh respectively). This corresponds to the mitigation of 400 – 500 kg CO_2 per season and small-scale rural unit (assumption 100 drying cycles per season). The cost of capital and operational costs of the GHSD unit is estimated to be ₹20,000-25,000(~$250 - 300 USD). Given an average seasonal output of 800–1,000 kg of dried bananas, the payback period is expected to be less than one year, particularly when local market prices for dried fruits and reduced post-harvest losses are considered. Table 14 presents a comparison of cost-benefit and sustainability.

Table 14. Demonstrate the cost-benefit and sustainability

Parameter	GHSD System	Hot Air Dryer	Open Sun Drying
Energy Source	Solar	Electricity (5–6 kWh)	None
Energy Cost (per 10 kg)	₹0	₹35–48	₹0
CO_2 Emissions (per 10 kg)	0 kg	4.2–5.0 kg	0 kg
Drying Time	30–40 hrs	8–12 hrs	2–3 days
Capital Cost (Est.)	₹25,000	₹60,000+	Minimal
Contamination Risk	Low	Very Low	High
Nutrient Retention	Moderate–High	Moderate	Low
Payback Period	< 1 year	2–3 years	N/A

4.7. Limitations and practical considerations

- The model assumes stable solar and environmental conditions, which may not hold in real field settings.
- Only two variables (temperature and time) were perfected; other key factors, such as airflow and slice thickness, were not considered.
- Results are dependent on the type of the system and may not be generalized to other dryer designs without testing.
- Still limited automation/scalability due to manual supervision.

5. Conclusion

This study perfected the greenhouse solar-drying process for banana slices through statistical modelling and experimental validation. Key findings are reported as:

- Response Surface Methodology has been used to successfully perfect the drying process of banana slices in the greenhouse with good predictive models ($R^2 > 0.979$) for the moisture content, vitamin C content and color change.
- Optimization of drying temperature (40-60°C) and drying time (20-40 hrs) were considered, which had significant effect on the response variables, moisture content and color change showed strong effect while vitamin C was less affected.
- The process has lowered the moisture content from 78% to 12.50% (w.b), which has resulted in higher quality products due to lower moisture and color changes and better retention of Vitamin C.
- The best drying condition was 51.15°C and 31.66 hrs, which gave predicted moisture content of 14.45%, vitamin C of 5.41 mg/100g and color change (ΔE) value of 29.55.
- The results of the validation experiments revealed good agreement between the predicted and observed values, with deviations of 15.6%, 1.19% and 7.12% for moisture, vitamin C and color change, respectively, which also proved the validity of the model.

The performance levels of the predictive models are good enough for their possible use in commercial drying processes, which could enhance the consistency of the processes and help to minimize post-harvest losses in banana processing. Further studies could focus on real-time monitoring and control systems for greenhouse solar drying to improve automation and efficiency.

Nomenclature

CCD	Central Composite Design
MC	Moisture content
GHSD	Greenhouse solar dryer
RSM	Response Surface Methodology
M	Mass of the banana slices
ΔE	Colour difference
T	Drying period (h)
d.b	Dry Basis (%)
w.b	Wet Basis (%)
β_0	Constant
Bi	Linear coefficient
Xi	Level of independent parameters
D	Overall desirability
d_i	Individual desirability

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Author contributions statement

Kamlesh Paswan: writing – original. Anand Kushwah: writing – review & editing. Kapil Kumar Gupta: formal analysis. Mohd. Ateeque: conceptualization. Supriya Raj: software. Manoj Kumar Gaur: supervision.

Data availability statement

All the actual data are presented in the manuscript.

Conflict of interest

Authors declare no competing interests.

Declaration of generative AI And AI-assisted technologies in the writing process

The authors used generative AI solely to improve the language and readability of the manuscript, and all scientific content was reviewed and approved by the authors.

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