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Shrinkage and drying kinetics effects of process variables of Bitter leaf (*Vernonia amygdalina*): An investigative study

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Abstract: *This study explores the drying characteristics of Vernonia amygdalina (bitter leaf) through the use of an electric cabinet dryer, focusing on the effects of air temperature (40–60°C), air velocity (2.6–4.6 m/s), and leaf size on drying kinetics and shrinkage. Leafy vegetables need carefully controlled drying conditions because of their high moisture content (80–90% w.b.) in order to maintain their nutritional value and their marketability. The Box-Behnken Design (BBD), a response surface methodology, was employed to evaluate the effects and interactions of process variables on moisture ratio (MR), drying rate, and shrinkage. The BBD technique enables efficient development of quadratic models with minimal experimental runs. The findings demonstrated that air temperature had a significant impact on drying rate ($F = 418.11$, $p < 0.0001$) and that shrinkage was affected by both linear and quadratic temperature terms ($F = 272.86$, $p < 0.0001$; $F = 55.75$, $p = 0.0001$). $R^2 = 0.9869$ for drying rate and $R^2 = 0.9864$ for shrinkage indicated high model accuracy. Optimal drying conditions were 52.36 °C, 2.6 m/s airflow, and a leaf area of 0.0028 m^2 and these yielded a drying rate of 3.53 g/h and shrinkage of 30.62%. Model reliability was confirmed by validation assessments that revealed small errors (1.40% and 3.38%). This study emphasizes how important temperature is for maximizing convective drying while preserving product quality. Further studies on the microstructural behaviour of different species using image analysis under varied pre-treatments and drying conditions are recommended. Adopted ASTM Standard: Modified ASTM D4442 for moisture content determination.*

Keywords: *Drying, Response Surface Methodology, Drying Rate, Shrinkage, Model Validation, Bitter leaf (Vernonia Amygdalina)*

INTRODUCTION

Crop drying is an established food preservation method that offers advantages such as extended shelf life, decreased weight, and enhanced efficiency in storage and transportation (Bhardwaj *et al.*, 2017). Heat transmission is essential during the drying process to remove moisture from the product matrix, resulting in significant energy consumption. In agriculture, vegetable drying is critical for enhancing profitability, stabilising prices, and assuring year-round availability. The process also provides access to foreign markets, which helps to drive local economic growth and employment creation. This process is influenced by the type of food, dryer design, and drying conditions (Nwakuba *et al*., 2021). Over 85% of industrial dryers employ convective processes, commonly utilised for hot air drying, yet they still demand significant energy (Sabarez, 2015). Energy efficiency may be enhanced through the application of various drying techniques, including microwave and radio frequency drying. Vegetables are essential for human health because they provide crucial nutrients such as vitamins, minerals, and carbohydrates while also improving immune function through bioactive components such as phytochemicals and antioxidants (Gupta, 2020). Despite these benefits, green leafy vegetables (GLVs) such as bitterleaf are inadequately utilised, particularly in rural African areas, due to a lack of awareness about their health benefits (Dada *et al*., 2021). However, these vegetables are important in nutrition and traditional medicine, and they provide economic prospects through production and commercialisation (Adeoye, 2020). They confront substantial storage and economic value issues in Nigeria due to their perishable nature and high moisture content (80 - 90% w.b).

Vernonia amygdalina (bitter leaf) drying behaviour has not been fully studied, particularly in electric cabinet dryers with various temperatures, air velocities, and leaf sizes. Ideal drying parameters, such as the optimal ratio of air temperature, air velocity, relative humidity, and product attributes (leaf size), can reduce energy consumption, enhance drying results, and ultimately affect the choice of the best kind of drying system and approach for enhanced product end-use. Literature over the past several years shows that efforts to optimise energy use as a means of enhancing the process variable of plant-based products have expanded globally. Traditional drying methods, such as sun drying, are frequently impacted by outside variables, which reduces their scalability and degrades their quality. On the other hand, artificial drying techniques, like hot air drying, offer more control over the drying environment, but they can also be costly and energy-intensive. More so, fruits and vegetables generally consist of internal water ranging between 80% to 90%, making them highly perishable and necessitating effective food preservation techniques. Their heterogeneous structure complicates the understanding of the physicochemical changes during drying. A common phenomenon during drying is shrinkage, which affects the textural quality and taste of dried products. This shrinkage is influenced by various factors, including material characteristics, microstructure, mechanical properties, and processing conditions (Mahiuddin *et al*., 2018). The porous and hygroscopic nature of these food materials contributes to significant volume changes as water is transported from cellular environments to the external surroundings, with this volume reduction typically referred to as material shrinkage (Mahiuddin *et al*., 2018; Khan & Karim, 2017). Understanding the factors that influence shrinkage is crucial for improving product quality, as it significantly impacts the mechanical and textural properties of fruits and vegetables. For example, research has shown that the torsional stiffness of apple samples varies with shrinkage (Mahiuddin *et al*., 2018). Moreover, shrinkage affects drying rates and kinetics, highlighting its importance in predicting heat and mass transfer during drying. Models that account for shrinkage provide a better fit with experimental data than those that do not. To combat these obstacles, adjustment of drying parameters can be applied to optimise the drying rate and percentage shrinkage of the bitterleaf samples. The modelling of drying behaviour promotes comprehension of the moisture removal process, sets drying duration, and assesses the influence of diverse drying parameters, including temperature, relative humidity, leaf area, and air velocity, on the drying rate and percentage shrinkage. By optimizing these variables, one can obtain a balance between energy requirements and product quality, guaranteeing that the dried bitter leaf keeps its key properties, including colour, flavour, and nutritional content. Interestingly, the interaction between drying kinetics and process variables of leafy vegetables has not been extensively explored, thereby serving as the drive for this investigation. Given the foregoing background, this study seeks to solve the research gap by evaluating the influence of drying variables on the drying kinetics and percentage shrinkage of bitter leaf samples. It seeks to develop a predictive model for calculating the drying rate and percentage shrinkage based on varying leaf areas, air temperatures, and airflow rates and to optimize the drying settings by applying the idea of the numerical desirability function to promote a more sustainable technique that improves its preservation, quality, and accessibility for local and commercial purposes at minimal energy demand. It also indicated the ideal convective drying settings for drying high-quality bitter leaves. The empirical results were investigated via a 3 by 3-treatment design through the Box-Behnken Design experimental technique.

MATERIALS AND METHODS

2.1 Leaf Samples Preparation

Table-1 summarises the items used in the course of this experimental study. Specifications and uses are briefly discussed.

Table-1 Materials utilized in the experimental tests.

S/N	Equipment	Uses
1	Electrical resistance wire (2500W)	Heating element
2	Wire-mesh rack	To hold samples in the dryer
3	1hp AC motor is paired with vanes	Mechanical agitation of heated air
4	HTC-1 Thermometer/hygrometer (AAA battery powered)	For temperature and relative humidity readings
5	Axial fan (0.75hp)	For moisture removal
6	NHT- 4000 Variable resistor (4000W)	To vary current to the 1hp AC fan
7	Digital professional mini weighing balance (500/±0.01g)	For weighing samples
8	Casio scientific calculator	For value calculation
9	Digital timer, stopwatch and alarm clock	For accurate timekeeping
10	Measuring cup	For material measurements
11	Aluminium Sheets	For lagging
12	Air flow meter	For air velocity measurement
13	Meter rule	For leaf length measurement

2.2.1 Preparation of Sample and Experimental Procedure

Samples of fresh bitter leaves were obtained at the vegetable market in the Nigerian State of Imo. After being divided into three (3) different size groups (0.0028 m^2 for small, 0.0044 m^2 for medium, and 0.0063 m^2 for big and tolerance range of ± 5%), the samples were cleaned to get rid of any dirt. After washing, the samples' initial mass was assessed to provide a baseline for monitoring moisture loss during the drying process, before being exposed to varied drying conditions according to the experimental plan.

2.2.2 Experimental Procedure

The drying experiment was designed utilising a full tool for experiment design, statistical analysis, and optimization. The software utilized was the Design-Expert® Statistical Package. The statistical software randomised the input values to decrease bias and experimental error (Table-2). Using the Box-Behnken Design technique, the drying trials were meticulously organised and the response surface was evaluated using the same. This decision was taken on purpose because it decreased the number of experimental runs needed while being notably effective at assessing the effects of numerous factors with three levels each. Under these circumstances, the Box–Behnken design type performs exceptionally well since it facilitates a rigorous examination of the experimental space.

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Table-2 Experiment design layout

Run	Temp	Air Vel	Leaf area	Drying rate	Shrinkage
	(℃)	(m/s)	(m^2)	(g/h)	(%)
1	50	4.6	M		
2	50	3.6	M		
3	40	4.6	S		
4	60	3.6	M		
5	60	2.6	S		
6	60	4.6	S		
7	50	3.6	B		
8	50	3.6	S		
9	50	2.6	M		
10	40	4.6	B		
11	60	2.6	B		
12	60	4.6	B		
13	40	3.6	M		
14	40	2.6	B		
15	50	3.6	M		
16	40	2.6	S		
17	60	3.6	S		

The observed responses, detailed in Table-2, include the drying rate (g/h) and per cent shrinkage (%). A total of 17 experimental runs were performed utilising prepared bitterleaf samples dispersed over thin layers on aluminium mesh trays (77.5 cm × 43.3 cm) for drying experiments. Three air temperature settings (40, 50, and 60°C) were utilised with the trays placed in the electric convective drier to ensure warm air flowed axially over the leaf samples. These temperature ranges were chosen to optimize drying while maintaining the vegetables' flavour and nutritional content. An assortment of characteristics was tested to evaluate the thermal performance of the cross-flow air cabinet drier, including relative humidity, cabinet relative humidity, ambient air velocity, ambient air temperature, and cabinet air velocity. Temperature and relative humidity were measured using an exceptionally sensitive thermometer/hygrometer, while air velocity was assessed with an air-flow meter. The selected air velocities (2.6, 3.6, and 4.6 m/s) were meant to correlate with actual ambient air flow rates, establishing effective drying without displacing the leaves, which might lower thermal efficiency and waste useable heat. A hybrid thermometer/hygrometer was deployed to detect relative humidity and ambient air temperature (Table 1). Different speed settings were achieved by combining a variable resistor (NHT-4000, built in China) with an airflow meter to supply particular voltages for the 1hp AC motor in the heating system, corresponding to speeds of 2.6 m/s (104V), 3.6 m/s (114V), and 4.6 m/s (143V).

Prior to experiments, a laboratory-scale electric convective drier equipped with controls for heat input and airflow rate was preheated for 35 minutes without any load to ensure homogeneous conditions within the drying chamber. The dryer's components are stated in Table 1. Drying studies were conducted at varied air temperatures (40, 50, and 60°C) and air velocities (2.6, 3.6, and 4.6 m/s), with an average ambient relative humidity of 29.7% for all samples. The dryer was initially set to the target air temperature and fan speed (40°C and 2.6 m/s). The heated air was directed tangentially onto the leaf samples to promote uniform drying. Moisture loss was observed every 10 minutes throughout the experiments. A thermo-hygrometer (HTC-1 Thermometer/Hygrometer) was utilised to monitor the relative humidity within the drying chamber. Each batch was halted after the target final moisture content was reached, and the drying time and total energy consumption were measured (Nwakuba *et al*., 2021). Changes in the physical characteristics of the bitterleaf samples, such as average mass and percentage shrinkage, were also documented. To decrease the likelihood of experimental mistakes, treatments were randomised. Two response variables (drying rate and percentage shrinkage) were evaluated alongside three input parameters (air temperature, air velocity, and leaf area), each at three levels. Systematic adjustments were applied to the input parameters: air temperature (40, 50, and 60°C), air velocity (2.6, 3.6, and 4.6m/s), and leaf area (0.0028 (S), 0.0044(M), and 0.0063m^2(B)), as these factors considerably influence the drying process (Nwakuba *et al*., 2021). The drying rate and percentage shrinkage were carefully measured and examined concurrently. Table-3 highlights the experimental parameters, with the variables and levels displayed in both actual and coded versions as −1, 0, and 1, corresponding to low, medium, and high levels, respectively.

Table-3 Arrangement of levels and experimental parameters

Input parameter	Coded symbol	Factor level	
		Actual	Coded
Temperature (^{o}C)	T	40	-1
		50	0
		60	1
Air velocity (ms^{-1})	V	2.6	-1
		3.6	0
		4.6	1
Leaf area (x10^{-3}m^2)	A	2.8	-1
		4.4	0
		6.3	1

2.2.2 Data Analysis and Optimization Process

Analysis of variance (ANOVA) was employed to analyse the data for statistically significant factors at $P < 0.05$. The adequacy of the quadratic polynomial model fitting the drying data of *Vernonia amygdalina* was assessed using ANOVA and regression analyses, which included metrics such as the coefficient of determination (R^2), adjusted R^2, predicted R^2, adequate precision, lack of fit, and coefficient of variation. Model terms for each response parameter were tested using p-values. Response surface methodology (RSM) with Design Expert statistical software was utilised to investigate the impact of various experimental factors on drying rate, and percentage shrinkage through 3-D plots. Additionally, Microsoft Excel was adopted to graph the moisture ratio against time for different combinations of air velocity and leaf area at 60°C. RSM optimization, specifically the Box-Behnken design, was employed to optimize and appraise the primary and combined effects of air velocity, drying air temperature, and leaf area at changing levels on the drying rate, and per cent shrinkage of bitter leaf samples. This strategy seeks to discover the optimal settings of input variables to maximize or minimize the response variable of interest by fitting mathematical models to experimental data. The numerical RSM optimization method tries to minimize percentage shrinkage while maximizing the rate of the drying process. This is evaluated using a desirability index (D_n) to quantitatively gauge how well each output variable fits the desired objectives. To validate the projected optimal parameters, further experimental runs were done in triplicate under comparable conditions, and the mean results of these trials were evaluated for correlation. The least squares multiple regression approach was used to evaluate the experimental data, with the response variable (V_r) defined using a second-order polynomial function, as indicated in Eq. (1).

$$V_r = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 AB + \beta_5 AC + \beta_6 BC + \beta_7 A^2 + \beta_8 B^2 + \beta_9 C^2 \quad (1)$$

Where: *A, B, and C* are the independent variables, which are air temperature (°C), air velocity (m/s), and sample area (m^2), respectively; β_0 denotes the model intercept; and V_r is the response variable, which includes drying rate in (g/h), and shrinkage (%). Regression coefficients include β_1, β_2, β_3, β_4, β_5, β_6, β_7, β_8, *and* β_9. The linear effects are represented *by* $\beta_1 A$, $\beta_2 B$, and $\beta_3 C$; the interaction or cross-product effects are represented by $\beta_4 AB$, $\beta_5 AC$, and $\beta_6 BC$; and the quadratic or curvature effects are represented by $\beta_7 A^2$, $\beta_8 B^2$, and $\beta_9 C^2$ (Nwakuba, 2019).

2.3 Basic Theory

2.3.1 Moisture Ratio (Dimensionless)

The moisture content data that has been calculated in the experiment will be converted into a humidity ratio. This will be used for model analysis and computation. The moisture ratio (MR) can be defined by Eq. (2) (Kusuma *et al.*, 2023) as:

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad (2)$$

Where; *MR = Moisture ratio,* M_t *= moisture content at time t (%),* M_o *= initial moisture content (%),* M_e *= equilibrium moisture content (%).*

However, the moisture ratio was calculated using Eq. (3) in place of Eq. (2) due to the continuous fluctuation in the relative humidity during the drying processes (Alara *et al.*, 2018b).

$$MR = \frac{M_t}{M_0} \quad (3)$$

Where; M_t *= moisture content at time t (%),* M_o *= initial moisture content (%).*

2.3.2 Drying Rate (D_R)

The drying rate was determined by measuring the amount of moisture removed from the bitter leaf sample over a specified time interval (h). The moisture loss (M_L) is represented in Eq. 4 as:

$$M_L = W_i - W_f \quad (4)$$

Where; W_i*= initial weight, and* W_f*= final weight.*

Consequently, the drying rate is represented by Eq. 5 as:

$$D_R(g/h) = \frac{M_L}{t} \quad (5)$$

2.3.3 Shrinkage Ratio

Shrinkage usually denotes sample volume change after/during drying to the initial volume (Mutuli *et al.*, 2020). In the conventional drying method (hot air drying), the changes in the shape of the sample are concentrated in length and breadth. The shrinkage ratio (SR) was measured in order to estimate the volume changes of the dried samples. SR of the dried sample was expressed in Eq. (6) (Huang and Zhang, 2016) as:

$$SR = \frac{L_i - L_f}{L_i} * 100 \quad (6)$$

Where; L_i *= initial length (cm), and* L_f *= final length (cm)*

RESULTS AND DISCUSSION

3.1 Drying Kinetics

Fig.1 demonstrates an exponential decrease of the Moisture Ratio (MR) over time for dried bitterleaf samples, suggesting consistent moisture transfer mechanisms from the stomata to the surface. The MR represents the fraction of moisture left in the bitterleaf as drying continues. Higher air velocities (4.6 m/s) resulted in faster moisture loss compared to lower velocities, indicating the considerable impact of air velocity on drying efficiency. The continual reduction in MR shows that internal mass transfer is driven by moisture diffusion. The drying curves reveal a typical pattern for vegetable drying (Nwakuba *et al.*, 2021), characterized by an initial rapid moisture removal phase followed by a gradual reduction, eventually nearing the equilibrium moisture ratio. Leaves with greater surface areas displayed faster moisture diffusion, leading to shorter drying times and greater energy conservation. Additionally, drying air temperature, as observed by Idlimam *et al.* (2007) for drying grenade peel, is a major factor influencing drying kinetics. Elevated air temperatures increased drying rates and reduced drying periods by increasing water migration within the bitter leaf and boosting the kinetic activity of water molecules.

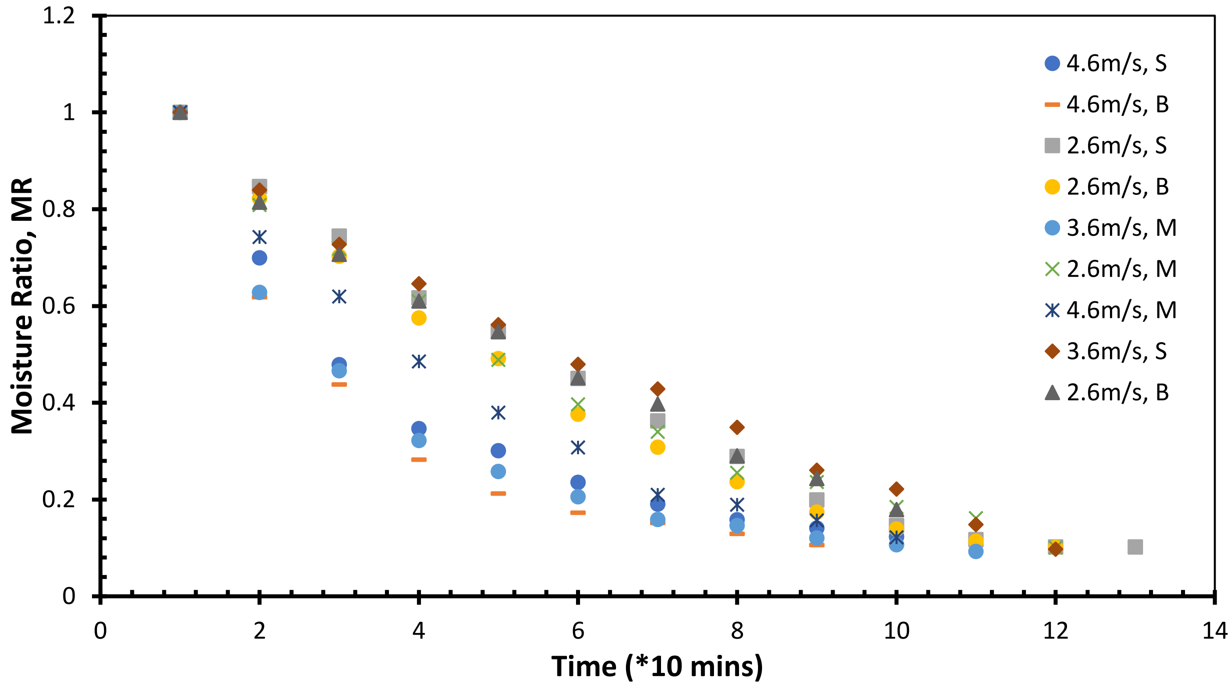

Fig. 2 Moisture ratio variation versus drying duration at various air velocities (2.6, 3.6, and 4.6m/s) and leaf sizes (S ($0.0028m^2$), M ($0.0044m^2$), and B ($0.0063m^2$)) of bitter leaf.

3.2 Drying Rate (D_R)

The drying rate of bitter leaf samples was analysed using 3D surface and contour plots (Fig. 2), revealing the influence of air temperature and airflow on the drying process. The 3D graphic reveals that both temperature and airflow boost the drying rate, albeit temperature exerts a greater impact. Additionally, insights from Ndukwu (2009) support this conclusion, indicating that notably, at higher temperatures (up to 60 °C), the drying rate reached its maximum at roughly 5 g/h, particularly with the highest airflow (4.6 m/s). The contour map validates this result, revealing that drying efficiency rises dramatically with rising temperature relative to airflow. These graphical studies reveal that while both parameters boost the drying rate, temperature is the most significant input factor. The ANOVA table (Table 4) validates this finding, suggesting that temperature (T) is the most influential variable, with an F-value of 418.11 and a p-value < 0.0001. This is also consistent with the findings of Putra & Ajiwiguna (2017), who conducted an experimental investigation into the effects of air temperature and velocity on the drying process. Airflow (V) also has a large impact, evidenced by an F-value of 65.96

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and a p-value < 0.0001, whereas leaf area (A) has a lower but still notable effect (F-value = 25.28, p-value = 0.0015). However, the interaction effects, such as temperature-airflow (TV, p = 0.8350) and airflow-leaf area (AV, p = 0.0927), are not statistically significant. The quadratic term for temperature (T^2) is significant (F-value = 24.35, p = 0.0017), demonstrating a nonlinear correlation between temperature and drying rate. With a high model F-value of 58.78 and an R^2 of 0.9869, the model indicates a robust fit, suggesting that temperature is the dominant factor driving the drying rate in this study. Consequently, the relationship defined and articulated in coded terms in Eq. (7) delivers a precise prediction of the drying rate of the bitter leaf. With an R^2 value of 0.9869, Eq. (7) shows a significant correlation between the predicted and observed data, explaining 98.76% of the variation in the response variable. The model's high R^2 indicates that it can accurately and consistently predict drying behaviour under a range of circumstances. The limited unexplained variance (1.24%) suggests that the drying process is mostly unaffected by factors that are outside the purview of the model. All things considered, the strong R^2 value highlights how well the model captures the drying kinetics and streamlines the procedure.

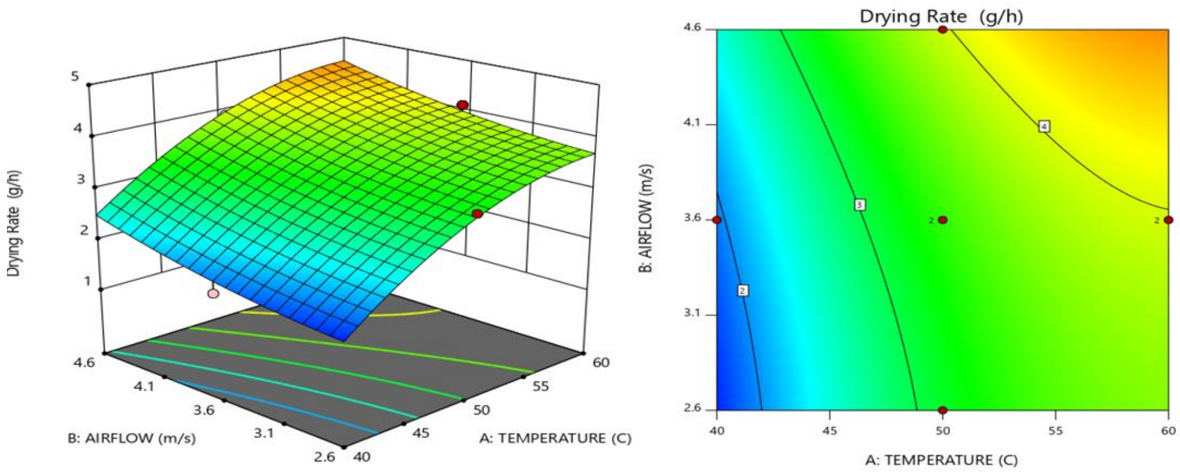

Fig. 2 Impact of process conditions (airflow and temperature) on the drying rate of bitter leaf (a) Three-dimensional plot (b) Contour plot.

Table-4 Analysis of variance for bitter leaf drying rate.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	14.15	9	1.57	58.78	< 0.0001	significant
T-TEMPERATURE	11.18	1	11.18	418.11	< 0.0001	"
V-AIRFLOW	1.76	1	1.76	65.96	< 0.0001	"
A-LEAF AREA	0.6760	1	0.6760	25.28	0.0015	"
TV	0.0013	1	0.0013	0.0467	0.8350	n.s
AT	0.0113	1	0.0113	0.4207	0.5373	"
AV	0.1013	1	0.1013	3.79	0.0927	"
T^2	0.6512	1	0.6512	24.35	0.0017	significant
V^2	0.0479	1	0.0479	1.79	0.2226	n.s
A^2	0.0025	1	0.0025	0.0941	0.7680	n.s
Residual	0.1872	7	0.0267			
Lack of Fit	0.1872	5	0.0374			
Pure Error	0.0000	2	0.0000			
Cor Total	14.34	16				

n.s = not significant at a p-value of 0.05.

$$D_R = 3.41 + 1.02T + 0.42V + 0.26A - 0.0125TV + 0.0375AT + 0.1125AV - 0.4588T^2 + 0.1297V^2 + 0.0297A^2 \quad [R^2 = 0.9869] \quad (7)$$

3.3 Shrinkage (ψ)

The response surface and contour plots (Fig. 3) indicate the effects of temperature (T) and airflow (V) on shrinkage parameters. The 3D surface figure reveals that shrinkage increases as temperature rises, notably at greater airflow rates, with a noticeable curvature indicating a quadratic connection with temperature. The contour plot further shows this pattern, with shrinkage being more responsive to temperature than airflow, as seen by the narrower gradient along the temperature axis. These visual trends correlate with the ANOVA results, where temperature indicates a highly significant effect on shrinkage ($p < 0.0001$), and airflow also contributes significantly ($p < 0.0001$), but to a lesser degree.
The ANOVA analysis also suggests that temperature (T) is the dominant factor impacting shrinkage, both linearly ($F = 272.86$, $p < 0.0001$) and quadratically ($F = 55.75$, $p = 0.0001$), with airflow (V) also having a substantial impact ($F = 142.09$, $p < 0.0001$). In contrast, leaf area (A) and the interaction terms (TV, AT, and AV) reveal non-significant statistical effects ($p > 0.05$), showing little influence on shrinkage. With a high model F-value of 56.61 and an R^2 of 0.9864, the model demonstrates a good fit, as evidenced by the low residual sum of squares (17.46). This result coincides with findings by Sturm *et al.*(2014), who indicated that shrinkage is largely governed by temperature, humidity, and airflow levels during drying operations. Their examination of the impacts of process management measures on drying kinetics, colour, and shrinkage of air-dried apples similarly underscored the crucial importance of temperature in influencing shrinkage outcomes. As a result, the relationship specified and expressed in coded terms yields an accurate prediction of the bitter leaf percentage shrinkage. Eq. (8) indicates that a 2nd-order quadratic model is fully appropriate for predicting the percentage shrinkage from experimental data, and this is also consistent with the results of (Uzoma *et al.*, 2020).

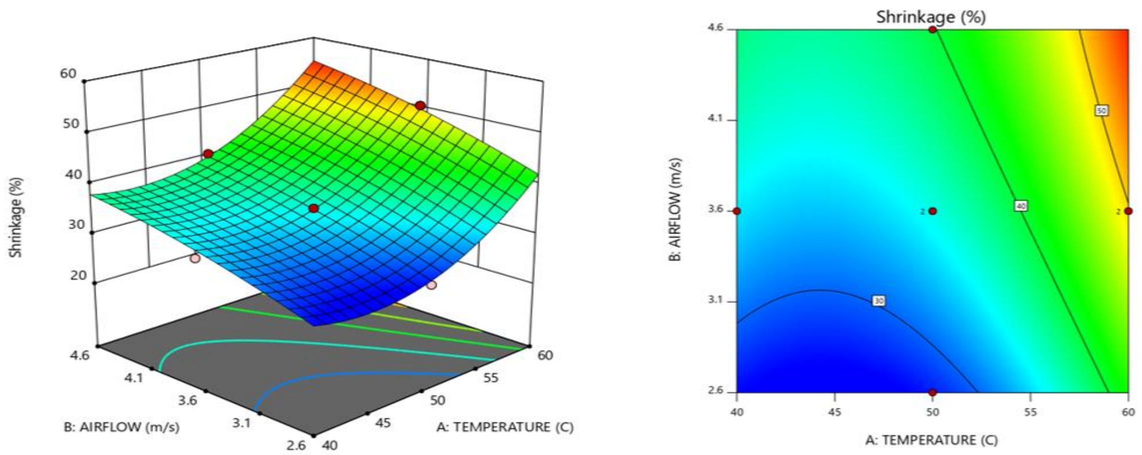

Fig. 3 Impact of process conditions (airflow and temperature) on the percentage shrinkage of bitter leaf (a) Three-dimensional plot (b) Contour plot.

Table-5 Analysis of variance for bitter leaf shrinkage.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1271.03	9	141.23	56.61	< 0.0001	significant
T-TEMPERATURE	680.77	1	680.77	272.86	< 0.0001	"
V-AIRFLOW	354.50	1	354.50	142.09	< 0.0001	"
A-LEAF AREA	5.34	1	5.34	2.14	0.1867	n.s
TV	2.69	1	2.69	1.08	0.3335	"
AT	0.0882	1	0.0882	0.0354	0.8562	"

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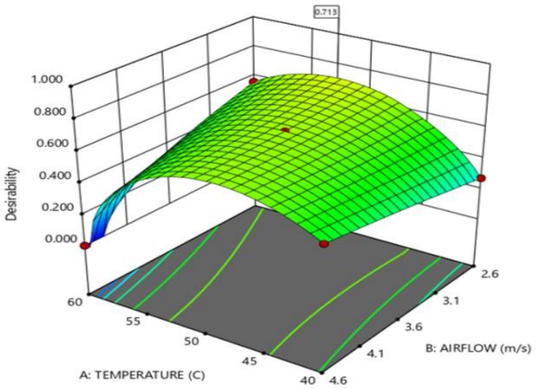
AV	3.35	1	3.35	1.34	0.2843	"
T^2	139.08	1	139.08	55.75	0.0001	significant
V^2	3.89	1	3.89	1.56	0.2517	n.s
A^2	0.6702	1	0.6702	0.2686	0.6202	"
Residual	17.46	7	2.49			
Lack of Fit	17.46	5	3.49			
Pure Error	0.0000	2	0.0000			
Cor Total	1288.49	16				

n.s = not significant at a p value of 0.05

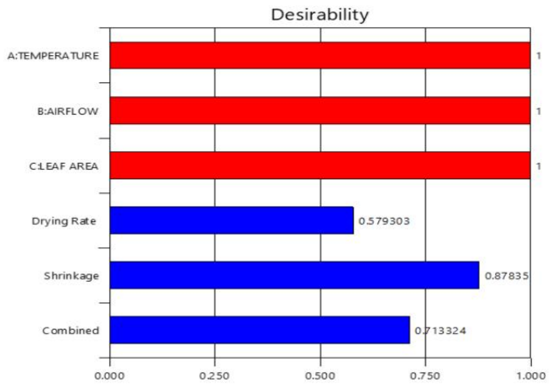
$$\psi = 35.04 + 7.98T + 5.95V + 0.731A + 0.58TV + .105AT + 0.6475AV + 6.7A^2 - 1.17B^2 + 0.4853C^2 \quad (R^2 = 0.9864) \quad (8)$$

3.4 Optimization of the Leaf Drying Process

The 3D surface plot and desirability bar chart (Fig. 4a and 4b) depicts the optimization of temperature (T), airflow (V), and leaf area (A) with regard to two critical responses: drying rate (DR) and shrinkage (ψ), leading to a combined desirability score (D^n). The 3D plot demonstrates that the ideal combination of T = 52.36°C and V = 2.6 m/s maximizes the desirability index at 0.71, establishing a balance between a high drying rate and low shrinkage. The related bar chart demonstrates that the individual desirabilities for input variables; temperature, airflow, and leaf area, are maximized (1.0); nonetheless, the desirabilities for drying rate (0.579) and per cent shrinkage (0.878) suggest a trade-off between the two outcomes. The overall combined desirability of 0.713 was obtained. The simulated results closely matched the experimental findings for the drying rate and shrinkage, with slight deviations of 1.40% for the drying rate and 3.38% for shrinkage, indicating the robustness of the model (Table-6). According to (Aneke *et al*., 2018; Uzoma *et al*., 2020; Nwakuba *et al*., 2021), who reported less than a 5 per cent error between simulated and test values in comparable convective drying setups, the optimization strategy was successful overall, as indicated by the combined desirability of 0.713. These minor errors further validate the model's reliability and the optimization technique adopted.



a.



b.

Fig. 4a. Joint desirability RSM plot (b) Optimized desirability values of input, response, and collective parameters for bitter leaf

Table-6 Desirability limit for optimal dryer operation of bitter leaf

Source	Input parameters			Desirability index		
	T (°C)	V (m/s)	A (m^2)	D_R (g/h)	ψ (%)	(D_n)
Simulated	52.36	2.6	Small (28)	3.53	30.62	0.71
Experimental				3.58	31.69	
Error				1.40	3.38	

CONTRIBUTION TO KNOWLEDGE

This research contributes to existing knowledge by developing statistically robust predictive models for the drying kinetics and shrinkage characteristics of Vernonia amygdalina under convective drying. Using a multi-response desirability strategy, the study optimises key process variables (air temperature, air velocity, and leaf size) by applying Box-Behnken Design and response surface methodology. In addition to offering precise forecasts, the generated models aid in determining the optimal drying parameters that strike an acceptable balance between efficiency and product quality. This integrated modeling and optimization framework addresses a notable gap in literature related to the energy-efficient drying of high-moisture leafy vegetables.

CONCLUSION

In summary, the examination of drying rate and shrinkage proportion in bitter leaf samples indicates the important role of temperature and airflow in optimizing both drying rate and shrinkage. Temperature was the key factor impacting both the drying process and shrinkage, with substantial linear and quadratic impacts. Airflow had a considerable, though secondary, impact, while leaf area and interaction effects had limited significance. The high F-values and R^2 values, coupled with low residual errors, show the reliability of the predictive models, with minor disparities between simulated and experimental outcomes. The desirability analysis found a trade-off between maximising the drying rate and minimising the shrinkage of bitter leaf samples. The best conditions (T = 52.36°C and V = 2.6 m/s) achieved a combined desirability score of 0.713, ensuring effective drying while retaining product quality. The close alignment between experimental and simulated findings further confirms the viability of the optimization strategy, similar to earlier studies in convective drying processes for vegetable products. In addition to examining the micromechanics of these vegetables during the drying process, further experimental testing could investigate Finite Element (FE) modelling of heat and mass transfer during the convective drying of several native leafy vegetables with varying leaf areas. The microstructural behaviour of various species under different pre-treatments and drying conditions should also be investigated in future research using image analysis techniques. To extract useful data, techniques like noise reduction, segmentation, feature extraction, and object detection should be used.

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CONFLICT OF INTEREST

The authors have no conflict of interest.

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