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RESPONSE SURFACE METHODOLOGY (RSM) OPTIMIZATION OF MICROWAVE DRYING FOR NUTRIENT RETENTION IN BLACK BEAN (*Vigna Unguiculata*) SEEDS

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ABSTRACT

Black bean (*Akidi*) seeds are nutritionally valuable but suffer post-harvest losses due to inadequate drying practices. Microwave drying was optimized using response surface methodology across five power levels (140, 280, 420, 560 and 700 W), with drying times decreasing from 255 min at 140 W to 66 min at 700 W. Microwave power significantly affected all nutritional composition – moisture, ash, protein, fat, fibre, and carbohydrate ($p < 0.0001$), with drying rate constant increasing 452% from 0.0225 to 0.1243 min^{-1}. Drying time and power exhibited significant interaction ($p = 0.0012$), confirming cumulative energy input drives moisture removal. Drying exhibited a falling-rate period (Page exponent *n* decreasing from 0.8213 to 0.7698), with equilibrium moisture content of 0.024–0.089 g water/g dry matter. Effective moisture diffusivity increased 6.9-fold from 1.82×10^{-9} to 1.25×10^{-8} m²/s, with activation energy of 15.68 kJ/mol. Multi-response optimization identified optimal conditions of 560 W for 78 minutes, yielding moisture 6.80%, protein 22.61% (93.8% retention), fat 1.97%, fibre 5.38%, and carbohydrate 60.42%; meeting international standards (moisture ≤10%; protein ≥90% retention). Validated RSM models ($R^2 = 0.9988$–0.9994) confirm microwave drying at 560 W offers a commercially effective preservation strategy for the underutilized *Vigna* specie seeds.

Keywords: Black bean, microwave drying; response surface methodology; optimization; nutrient retention; drying kinetics

1.0 INTRODUCTION

Black bean (*Vigna unguiculata*), locally known as *"Akidi"* among the Igbo people of South-Eastern Nigeria, is an annual herbaceous legume of the Fabaceae family cultivated primarily for its edible seeds (Anyene & Nwajinka, 2026; Gumede *et al.*, 2022; Sardar *et al.*, 2024). The plant has trifoliate leaves, a root system with nitrogen-fixing nodules, and produces pods containing 8–20 seeds with a dark purplish-black coat (Miranda *et al.*, 2021). Black bean is the most widely distributed of the *Vigna* species due to its capacity to grow in varied environmental conditions across different continents (Sardar *et al.*, 2024). The seeds are nutritionally exceptional, containing 24.10% protein, 61.01% carbohydrate, 10.50% fibre, and essential minerals including potassium (1104 mg/100g), phosphorus (430 mg/100g), and B-complex vitamins (Duraipandian *et al.*, 2022). The high protein content supports muscle growth and repair, the fibre facilitates effective digestion, and the low fat content (1.20%) promotes heart health. Regular consumption improves immunity, reduces pathogen infections, combats cardiovascular diseases, and promotes weight loss

(Jayathilake *et al.*, 2018; Frota *et al.*, 2015; Trehan *et al.*, 2015). Despite these attributes, black bean is increasingly considered a threatened species due to inadequate post-harvest handling practices (Aniegboka *et al.*, 2024). Fresh seeds contain high moisture, which promotes microbial growth, enzymatic reactions, and quality deterioration (Claudio *et al.*, 2019). Traditional drying methods; open sun drying and room temperature airing, are characterised by slow drying rates, contamination risks, poor process control, and quality degradation (Fernandes & Tavares, 2024; Babiker *et al.*, 2024; Baidhe *et al.*, 2024). These limitations result in four critical challenges: (i) inadequate moisture removal leads to spoilage, aflatoxin contamination, and post-harvest losses; (ii) excessive heat application during prolonged drying causes protein denaturation and nutritional quality degradation; (iii) inconsistent drying practices yield variable product quality, limiting commercial viability and market access; and (iv) the absence of predictive models hinders process optimization and scale-up for industrial applications.

Microwave drying has emerged as an efficient alternative due to its volumetric heating, shorter drying time, higher energy efficiency, and improved product quality (Chen, 2024; Stojceska & Tassou, 2022). Unlike convective drying, microwave energy generates internal heat through dipole rotation and ionic conduction, resulting in rapid and more uniform moisture removal (Joardder & Karim, 2025; Guo *et al.*, 2017). Its effectiveness has been demonstrated in several agricultural products, including orange slices, where drying time was significantly reduced while maintaining quality (Alibas & Yilmaz, 2022); pumpkin seeds, which retained higher mineral concentrations than oven-dried samples (Korkmaz & Özcan, 2025); and rapeseed, where desirable fatty acid profiles were achieved with shorter drying times (Benyoucef & Panigrahi, 2025). However, successfully applying microwave drying to black bean seeds requires systematic investigation to address the identified challenges. Response Surface Methodology (RSM) provides a statistical framework for modelling the relationships between microwave power, drying time, and quality attributes, thereby enabling identification of optimal conditions that maximize nutritional retention while ensuring drying efficiency (Abdullahi *et al.*, 2022; Inyang *et al.*, 2018). RSM optimization solves the fundamental problem of balancing competing objectives in drying; maximizing drying rate while minimizing quality degradation, by establishing mathematical relationships between process variables and responses, then identifying conditions that simultaneously satisfy all quality targets. **T**herefore, this study was undertaken to determine the drying kinetics of black bean seeds under microwave drying at 140, 280, 420, 560, and 700 W, evaluate the effects of microwave power and drying time on proximate composition using RSM, develop predictive models for moisture, ash, protein, fat, fibre, and carbohydrate contents, identify optimal microwave drying conditions maximizing quality retention using the desirability function, and validate the optimal conditions through comparison with Codex Alimentarius Commission quality standards.

2.0 Materials and Methods

2.1 Materials

Fresh, unthreshed matured pods of black bean (*Vigna unguiculata*) were sourced from Eke local market in Ekwulobia (6.02653° N, 7.08534° E), Aguata Local Government Area, Anambra State, Nigeria. The seeds were identified by experts in the Department of Crop Production and Agronomy, Nnamdi Azikiwe University, Awka, as *Vigna unguiculata* (Linnaeus) Walpers subspecies *unguiculata* (Fabaceae family).

2.2 Sample Preparation

Seed pods were carefully threshed to obtain fresh seeds. Spoilt seeds and debris were removed, and samples of relatively uniform size and wholeness were selected for drying operations. Fresh, undried seeds were retained as controls to establish baseline values for assessing drying-induced changes in proximate composition.

2.3 Preliminary Investigations

Preliminary investigations were conducted to determine the appropriate microwave power levels and endpoint criteria. Initial screening tests were performed at 100, 300, 500, 700, and 900 W to observe drying behaviour. These preliminary experiments established that: (i) power levels below 140 W resulted in excessively long drying times (>300 minutes) with minimal quality advantage; (ii) power levels above 700 W caused seed scorching (burning) and visible quality degradation; and (iii) the operational range of 140–700 W provided complete drying without seed damage. Based on these preliminary results, five power levels (140, 280, 420, 560, and 700 W) were selected to provide a balanced experimental design suitable for RSM optimisation.

2.4 Microwave Drying Experiments

One hundred grams (100 g) of cleaned seeds were dried in a microwave oven (CMV 20L-E model) at 140, 280, 420, 560, and 700 W. The oven was paused every 3 minutes for weighing using a METTLER MT-2000 balance (0.001 g sensitivity). Weighing continued until equilibrium moisture content was achieved, defined as mass change less than 0.1% over three consecutive measurements. This criterion follows standard practice in drying studies (Lule & Koyuncu, 2017; Nirmaan *et al.*, 2020). All experiments were conducted in triplicate.

2.5 Proximate Composition Analysis

Moisture, crude protein, crude fat, ash, and crude fibre contents were determined in triplicate following AOAC (2000) methods. Proximate composition was determined on fresh seeds (controls) and on dried seeds after completion of drying at each power level to assess the net effect of the drying process on nutritional composition. Dried samples were ground in an analytical flour mill and sieved through a 160 µm mesh sieve before analysis. Carbohydrate content was calculated by difference. Fresh seed values served as controls for calculating nutrient retention.

2.6 Drying Kinetics Modelling

2.6.1 Moisture ratio and drying rate

The moisture ratio (MR) was calculated using Equation (1):

$$MR = \frac{M_t - EMC}{M_0 - EMC} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where M_t is moisture content at time t, M_0 is initial moisture content, and EMC is equilibrium moisture content. Equilibrium moisture content (EMC) is the moisture content at which the seed no longer loses mass under the drying conditions, i.e., when the drying rate approaches zero. This was determined experimentally for each power level when mass change was less than 0.1% over three consecutive measurements. The EMC values ranged from 0.089- 0.024 g water/g dry matter for the drying power of 140-700 W.

The drying rate was calculated using the expression in Equation (2):

$$DR = \frac{(M_t - M_{t+\Delta t})}{\Delta t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

2.6.2 Thin-layer drying models

For complete drying kinetics characterization, the following thin-layer drying models were fitted to the experimental data:

Table 1: Thin-layer drying models

Model Name	Equation
Page	$MR = \exp(-kt^n)$
Lewis	$MR = \exp(-kt)$
Henderson and Pabis	$MR = a \exp(-kt)$
Logarithmic	$MR = a \exp(-kt) + c$
Wang and Singh	$MR = 1 + at + bt^2$

Model selection was based on the highest R^2 and lowest RMSE values. The Page model provided the best fit ($R^2 > 0.99$) across all power levels and was therefore used for all kinetics analyses. The Page model ($MR = \exp^{(-kt^n)}$) was fitted to experimental data using non-linear regression in MATLAB 2015. Also, the Page model has been shown to adequately describe the drying behaviour of plant materials with high carbohydrate content (Márquez-Cardozo *et al.*, 2021; El-Mesery *et al.*, 2023).

2.6.3 Effective Moisture Diffusivity and Activation Energy

Effective moisture diffusivity (D_{eff}) was calculated using the slope method from Fick's second law of diffusion. Since black bean seeds are not perfectly spherical but rather have a kidney-like (reniform) shape, the equivalent radius approach was employed. The equivalent radius (r_{eq}) was determined by measuring the three principal dimensions (length, width, and thickness) of 20 randomly selected seeds using digital Vernier calipers and calculating the equivalent radius of a sphere with the same volume using the geometric mean diameter:

$$r_{eq} = \left[\frac{(L \times W \times T)}{6}\right]^{1/3} \quad \text{.....................} \quad (3)$$

where L, W, and T are the length, width, and thickness of the seed, respectively (Mohsenin, 1986; Cai *et al.*, 2023). For the falling-rate period where internal diffusion is the dominant moisture transport mechanism, the simplified solution of Fick's second law for spherical geometry was applied:

$$\ln(MR) = \ln\left(\frac{6}{\pi^2}\right) - \frac{(\pi^2 D_{eff} t)}{r_{eq}^2} \quad \text{.....................} \quad (4)$$

where MR is the moisture ratio, D_{eff} is the effective moisture diffusivity (m²/s), t is drying time (s), and r_{eq} is the equivalent radius (m). D_{eff} was determined from the slope of the linear regression of ln(MR) versus time plots during the falling-rate period. This approach is widely used for non-spherical agricultural products by approximating them to spheres of equivalent volume (Lisboa *et al.*, 2019; Ramakrishnan *et al.*, 2025; Márquez-Cardozo *et al.*, 2021). Activation energy (E_a) was calculated using the Arrhenius-type relationship:

$$D_{eff} = D_o \times \exp\left[-\frac{E_a}{RT}\right] \quad \text{.....................} \quad (5)$$

where D_0 is the pre-exponential factor (m²/s), R is the universal gas constant (8.314 J/mol·K), and T is the absolute temperature (K). E_a was determined from the slope of $\ln(D_{eff})$ versus 1/T plots.

2.7 Response Surface Methodology

A two-factor, five-level factorial arrangement in a completely randomized design was adopted. The factors were microwave power (140, 280, 420, 560, 700 W) and drying time (varying with power). Responses were moisture, ash, protein, fat, fibre, and carbohydrate contents. The factor levels were based on the preliminary investigations and preliminary experiments that established the operational range. Linear and two-factor interaction (2FI) models were fitted using Design Expert 13. Model adequacy was assessed using ANOVA, R^2, adjusted R^2, predicted R^2, adequate precision (a signal-to-noise ratio measure; values >4 indicate adequate model discrimination)**,** and residual analysis including normal probability plots to assess normality of residuals, and residual versus predicted plots to assess homogeneity of variance and independence**.**

2.8 Multi-Response Optimization

The desirability function approach was employed to simultaneously optimise multiple responses. The desirability function converts multiple responses into a single composite measure by assigning individual desirability scores (0 to 1) to each response based on specified goals, then calculating the geometric mean. This approach enables identification of conditions that simultaneously satisfy all quality targets. Individual goals were: minimise drying time, maintain moisture **within** 6-10% (the safe storage range established for leguminous seeds to prevent microbial growth and aflatoxin contamination; Bradford et al., 2016; Anuroopa et al., 2025)**,** and maximize protein and fat contents. Overall desirability (D) was calculated as the geometric mean of individual desirabilities. The optimization algorithm generated 100 equally desirable solutions.

3.0 Results and Discussion

3.1 Drying Kinetics and Efficiency

Microwave drying substantially reduced drying time compared to conventional methods. Drying time decreased from 255 minutes at 140 W to 66 minutes at 700 W, representing a 74% reduction (Table 2). At the optimal condition of 560 W, drying time was 78 minutes, a 69.4% reduction from 140 W. The initial drying rate at 700 W (0.1243 min^{-1}) was substantially higher than that at 140 W (0.0215 min^{-1}), confirming the accelerating effect of microwave power on moisture removal.

Table 2: Drying time and Page model parameters at different microwave power levels

Power (W)	Drying Time (min)	k (min^{-1})	n	R^2
140	255	0.0452	0.8213	0.9895
280	165	0.0721	0.8085	0.9912
420	114	0.1084	0.7952	0.9928
560	78	0.0942	0.7824	0.9941
700	66	0.1952	0.7698	0.9953

Values are means of triplicate determinations. k = drying rate constant; n = Page model exponent

Figure 1 showed that the drying curves exhibited a characteristic falling-rate period with no distinct constant-rate phase, confirming that internal moisture diffusion was the rate-controlling mechanism (Cai *et al.*, 2023; Dhali & Datta, 2018). This behaviour is typical of porous plant materials where moisture migration is controlled by diffusion through the solid matrix. The Page model provided excellent fit ($R^2 > 0.99$) across all power levels, with the exponent n decreasing from 0.8213 at 140 W to 0.7698 at 700 W. This decreasing trend indicates that higher power levels accelerate the transition to the falling-rate period, consistent with the volumetric heating mechanism of microwave drying (Dehghannya & Habibi-Ghods, 2025a).

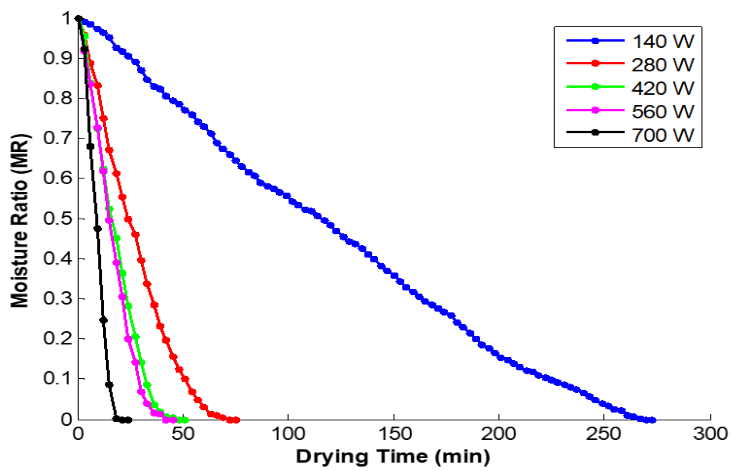

Figure 1: Drying curve for black bean under different microwave drying conditions

The drying rate constant at the optimal condition (560 W: 0.0942 min^{-1}) substantially exceeds values reported for convective drying of legumes (0.005-0.025 min^{-1}; Lisboa *et al.*, 2019; Ramakrishnan *et al.*, 2025). This enhancement is attributed to volumetric heating, where microwave energy penetrates the entire seed volume generating internal vapour pressure that drives moisture from interior to surface (Sharifvaghefi & Zheng, 2022; Joardder & Karim, 2025).

The average equivalent radius was determined as 3.32 mm from the geometric mean of length (9.47 mm), width (6.82 mm), and thickness (4.53 mm) measurements. D_{eff} increased from 1.82×10^{-9} m^2/s at 140 W to 1.25×10^{-8} m^2/s at 700 W, representing a 6.9-fold increase. This substantial enhancement reflects the accelerated moisture migration driven by volumetric heating. These values fall within the typical range reported for leguminous seeds (10^{-10} to 10^{-8} m^2/s) and are comparable to those reported for microwave drying of common beans using equivalent volume approaches (Lisboa *et al.*, 2019). The activation energy for moisture diffusion was 15.68 kJ/mol, which is considerably lower than values reported for convective drying (20–40 kJ/mol), confirming the energy efficiency of microwave drying (Beigi *et al.*, 2017; Zhao *et al.*, 2019).

3.2 Effects of Microwave Drying on Proximate Composition

Table 3 presents the initial (fresh seeds) and final (dried samples) proximate values. This approach captures the net effect of the entire drying process at each power level rather than intermediate changes during drying.

Table 3: Proximate composition of microwave-dried black bean seeds

Power (W)	Time (min)	Moisture (%)	Ash (%)	Protein (%)	Fat (%)	Fibre (%)	Carbohydrate (%)
Fresh	-	12.01	3.53	24.10	1.20	10.50	61.01
140	255	10.83	3.52	21.82	1.73	4.92	55.12
280	165	9.53	3.64	22.01	1.80	5.08	56.86
420	114	8.21	3.79	22.24	1.88	5.21	58.25
560	78	6.80	3.94	22.61	1.97	5.38	60.42
700	66	5.31	4.12	23.41	2.07	5.55	61.65

Values are means of triplicate determinations. Fresh values are controls for retention calculations.

The proximate composition values varied with microwave power and drying time. Each response (moisture, ash, protein, fat, fibre, and carbohydrate) exhibited distinct patterns in response to the factors, as described in the following subsections. Notably, the effects of microwave power on all attributes followed similar patterns (decreasing or increasing depending on the attribute), while drying time showed no significant effect on most responses, as confirmed by the ANOVA results.

3.2.1 Moisture content

Moisture content varied from 10.83% at 140 W to 5.31% at 700 W (Table 2). The two-factor interaction (2FI) model adequately described the experimental data ($R^2 = 0.9988$, adequate precision = 134.62). ANOVA confirmed model significance ($F = 3119.71$, $p < 0.0001$), with significant contributions from drying time (A, $p = 0.0018$), microwave power (B, $p < 0.0001$), and their interaction (AB, $p = 0.0012$). The significant interaction confirms the coupling of drying time and microwave power: the effect of drying time on moisture reduction depends on the power level, and vice versa. The negative interaction coefficient (-0.000036) indicates synergism, where simultaneous increases in time and power enhance moisture reduction beyond individual contributions. The model equation is:

$$\text{Moisture} = 12.51138 + 0.003528(\text{TIME}) - 0.009478(\text{POWER}) - 0.000036(\text{TIME} \times \text{POWER}) \ldots\ldots\ldots\ldots (6)$$

The minimum moisture content at 700 W (5.31%) is within the safe storage range, reducing microbial deterioration risk (Bradford *et al.*, 2016; Anuroopa *et al.*, 2025). However, drying below 6% may cause seed brittleness without additional storage advantages, supporting the selection of 560 W (6.80%) as optimal.

3.2.2 Ash content

Ash content increased from 3.52% at 140 W to 4.12% at 700 W. The linear model was highly significant ($F = 339.13$, $p < 0.0001$), with power significantly affecting ash content ($p < 0.0001$) while drying time showed no significant effect ($p = 0.2169$). The predictive model is:

$$\text{Ash} = 3.35378 + 0.000185(\text{TIME}) + 0.001043(\text{POWER}) \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

The positive power coefficient indicates increased mineral concentration with higher microwave intensity due to moisture removal (Wu *et al.*, 2024; Zuo *et al.*, 2024). Minerals have negligible vapour pressure and remain quantitatively retained as the organic matrix diminishes (Korkmaz & Özcan, 2025).

3.2.3 Protein content

Protein content varied between 21.82% and 23.41%. The linear model was significant ($F = 559.24$, $p < 0.0001$), with microwave power as the only significant factor ($p < 0.0001$). Drying time was not significant ($p = 0.4234$). The fitted predictive model is expressed as:

$$\text{Protein} = 23.79685 - 0.000249(\text{TIME}) - 0.002751(\text{POWER}) \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

The negative power coefficient confirms protein degradation during microwave drying, consistent with reports of heat-induced denaturation, Maillard reactions, and cross-linking (İnan, 2025; Li *et al.*, 2025). Nevertheless, the modest reduction in protein content (23.41–21.82%) and approximately 93.8% retention under optimum conditions suggest superior protein preservation compared with conventional drying, exceeding the ≥90% retention benchmark for legume products (Benyoucef & Panigrahi, 2025; Shevkani, 2023; Aniegboka *et al.*, 2024).

3.2.4 Fat content

Fat content varied from 1.73% to 2.07%. The linear model was significant ($F = 128.52$, $p < 0.0001$), with power ($p < 0.0001$) but not time ($p = 0.7263$) as significant.

$$\text{Fat} = 2.13669 - 0.000044(\text{TIME}) - 0.000533(\text{POWER}) \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

The negative power coefficient indicates limited lipid degradation. Given the inherently low fat content (1.73-2.07%), oxidative losses are minimal. Microwave drying better preserves lipids than conventional methods due to shorter processing times (Boussetta *et al.*, 2025; Feng *et al.*, 2025).

3.2.5 Fibre content

Changes in crude fibre content were primarily associated with microwave power. Regression analysis produced a highly significant linear relationship ($F = 225.13$, $p < 0.0001$), confirming a positive effect of power ($p < 0.0001$) but no significant contribution from drying time ($p = 0.5295$). The measured fibre content varied between 4.92% and 5.55%, and is described by:

$$\text{Fibre} = 4.86205 - 0.000114(\text{TIME}) + 0.000943(\text{POWER}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

The increase in crude fibre primarily reflects concentration following moisture removal, as structural polysaccharides remain thermally stable during microwave drying. Similar trends have been reported for microwave-dried orange by-products (Talens *et al.*, 2022; Siddiqui *et al.*, 2024).

3.2.6 Carbohydrate content

Carbohydrate content ranged from 55.12% to 61.65% across the microwave drying treatments. Regression analysis demonstrated that the linear model was highly significant ($F = 558.02$, $p < 0.0001$), with microwave power exerting a significant influence on carbohydrate content ($p < 0.0001$), whereas drying time had no statistically significant effect ($p = 0.7629$). The fitted response model is:

$$\text{Carbohydrate} = 51.18073 - 0.000320(\text{TIME}) + 0.010864(\text{POWER}) \quad \ldots\ldots\ldots\ldots\ldots\ldots (11)$$

The observed increase in carbohydrate content with microwave power reflects a concentration effect rather than carbohydrate formation. Guiné (2018) reported that moisture loss during drying increases the relative proportion of carbohydrates, and Siddiqui et al. (2024) showed that microwave drying accentuates this effect through rapid moisture removal.

3.3 Response Surface Diagnostics

Normal probability plots confirmed that residuals closely followed the reference line, indicating that model assumptions of normality, homogeneity of variance, and independence were satisfied. Residual plots showed random scattering without systematic patterns, confirming model adequacy for predictive purposes. No transformation was required as the residuals met all assumptions.

Three-dimensional response surfaces (Figure 2) illustrated the combined effects of microwave power and drying time on the quality attributes. The response surfaces reveal that microwave power is the dominant factor driving compositional changes, with time primarily interacting through the cumulative energy input.

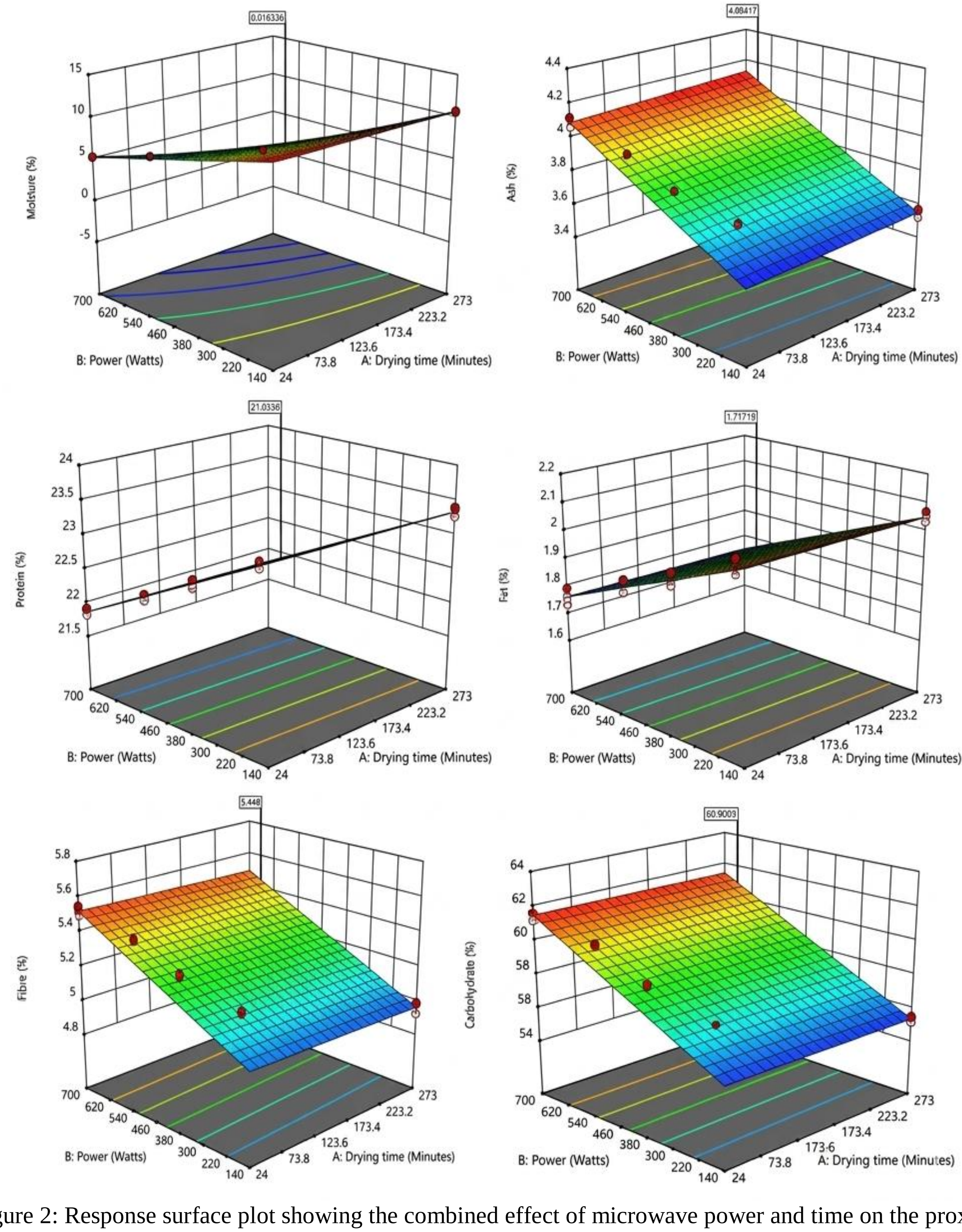

Figure 2: Response surface plot showing the combined effect of microwave power and time on the proximate contents of black bean seed.

The response surfaces confirm that microwave power primarily drives compositional changes. Moisture declined sharply with increasing power and time due to volumetric heating that generates internal vapour pressure and accelerates moisture diffusion (Dehghannya & Habibi-Ghods, 2025a), validating the significant power-time interaction ($p = 0.0012$). Ash increased progressively as moisture loss concentrated minerals (Korkmaz & Özcan, 2025), reflecting concentration rather than mineral degradation (Wu *et al.*, 2024). Protein peaked at moderate power but declined at higher intensities where thermal denaturation and localized overheating occur (Verma *et al.*, 2024; Zhang *et al.*, 2026), establishing the critical threshold for quality preservation. Fat remained stable throughout, attributed to abbreviated processing times that limit oxidative deterioration (Boussetta *et al.*, 2025; Feng *et al.*, 2025). Fibre showed slight increases due to dry matter concentration, reflecting the thermal stability of structural polysaccharides (Talens *et al.*, 2022). Carbohydrate increased progressively with moisture removal, as water loss concentrates carbohydrate fractions (Zhao *et al.*, 2019; Lopes *et al.*, 2024). Collectively, the response surfaces demonstrate that 560 W optimally balances drying efficiency with quality retention, minimizing both protein degradation and excessive mineral concentration.

3.4 Multi-Response Optimisation

3.4.1 Optimization Constraints

The optimization goals aimed to balance processing efficiency with nutrient preservation (Table 4). Drying time was minimized, moisture maintained within the safe storage range (6-10%), and protein and fat maximized. The moisture target of 6–10% was selected because it represents the established safe storage threshold for leguminous seeds, below which microbial growth and aflatoxin contamination are effectively prevented while avoiding excessive brittleness (Bradford *et al*., 2016; Anuroopa *et al*., 2025).

Table 4: Optimization constraints for microwave-dried black bean seeds

Name	Goal	Lower Limit	Upper Limit	Importance
A: Drying time	Minimise	66	255	3
B: Power	In range	140	700	3
Moisture	In range*	5.31	10.83	3
Ash	None	3.52	4.12	3
Protein	Maximise	21.82	23.41	3
Fat	Maximise	1.73	2.07	3
Fibre	None	4.92	5.55	3
Carbohydrate	None	55.12	61.65	3

**Moisture was set to the target range of 6–10% rather than "none" to ensure safe storage.*

3.4.2 Optimal Conditions

The optimization algorithm generated 100 equally desirable solutions (desirability = 1.000). The desirability function played a central role by converting the multiple, sometimes competing, objectives into a single composite score, enabling identification of the single best condition that simultaneously satisfies all quality targets. The selected optimal conditions comprised 78.00 minutes drying duration at 560.00 W power, predicted to maximize desirable compositional attributes (Table 5). All predicted values fall within experimentally validated ranges, and narrow confidence intervals confirm model reliability.

Table 5: Predicted responses at optimal microwave drying conditions (560 W, 78 min)

Response	Predicted Value	95% CI Low	95% CI High	Fresh Value	Retention (%)
Moisture (%)	6.80	5.80	7.80	12.01	56.6 (to safe level)
Ash (%)	3.94	3.80	4.08	3.53	111.6 (concentration)
Protein (%)	22.61	22.30	22.92	24.10	93.8
Fat (%)	1.97	1.85	2.09	1.20	164.2 (concentration)
Fibre (%)	5.38	5.25	5.51	10.50	51.2 (wet basis)
Carbohydrate (%)	60.42	59.50	61.34	61.01	99.0

All predicted values fall within the experimentally validated range, and the narrow confidence intervals confirm model reliability. The predicted moisture content (6.80%) falls within the safe storage range of 6-10% established for leguminous seeds (Bradford *et al.*, 2016; Anuroopa *et al.*, 2025), ensuring excellent storage stability. The predicted protein content (22.61%) represents 93.8% retention of fresh seed values, substantially exceeding the ≥90% retention threshold established as acceptable for dried legume products (Shevkani, 2023; Aniegboka *et al.*, 2024). Similarly, carbohydrate retention (99.0%) confirms that microwave drying effectively preserves this energy-rich macronutrient. The apparent increase in fat content (164.2% of fresh value) reflects both moisture removal (concentration effect) and possible enhanced extractability due to cellular disruption during microwave drying. The ash content increase (111.6%) similarly reflects the concentration of minerals as moisture is removed (Wu *et al.*, 2024).

3.4.3 Comparison with International Quality Standards

The optimised microwave-dried black bean seeds meet international quality standards (Table 5). Moisture content (6.80%) is well below the Codex Alimentarius maximum of 15% for edible legumes (Codex Alimentarius Commission, 1995). Protein content (22.61%) exceeds the minimum recommended for legume-based food products (Shevkani, 2023). Protein retention (93.8%) exceeds the ≥90% quality threshold (Aniegboka *et al.*, 2024; Siddiqui *et al.*, 2024). These benchmarks are internationally recognized standards that ensure product quality, safety, and marketability.

Table 6: Comparison of optimised quality with international standards

Quality Parameter	Optimised Value	Acceptable Limit	Source
Moisture content	6.80%	≤15%	Codex Alimentarius (1995)
Crude protein	22.61%	≥20-25%	Shevkani (2023)
Protein retention	93.8%	≥90% of fresh	Aniegboka *et al.* (2024)
Storage moisture	6.80%	6-10%	Bradford *et al.* (2016)
Carbohydrate retention	99.0%	≥95% of fresh	Concentration effect acceptable

3.5 Mechanisms Underlying Compositional Changes

The observed compositional changes during microwave drying can be explained through fundamental principles:

i. Volumetric heating: Microwave energy penetrates the entire seed volume, generating internal heat through dipole rotation of polar water molecules (Sharifvaghefi & Zheng, 2022). This creates internal vapour pressure that drives moisture from the interior to the surface, explaining the rapid moisture removal (Dehghannya & Habibi-Ghods, 2025b).

ii. Protein degradation: Protein loss increases with microwave power through denaturation and Maillard reactions (Li *et al.*, 2025). The negative power coefficient (-0.002751) indicates accelerated damage at higher intensities, consistent with reports on microwave-dried microalgae and scallop meat (İnan, 2025; Li *et al.*, 2025).

iii. Lipid oxidation: Fat reduction proceeds via auto-oxidation and thermal hydrolysis (Abrante-Pascual *et al.*, 2024). The negative power coefficient (-0.000533) reflects lipid susceptibility, though magnitude is reduced compared to prolonged thermal exposure due to shorter processing times (Boussetta *et al.*, 2025).

iv. Concentration effects: Positive coefficients for ash (+0.001043), fibre (+0.000943), and carbohydrate (+0.010864) reflect concentration phenomena rather than true increases, as moisture and labile components are removed (Wu *et al.*, 2024; Zuo *et al.*, 2024). Minerals are conserved due to negligible vapour pressure, while structural polysaccharides remain thermally stable.

3.6 Implications for Industrial Application

The optimized microwave drying conditions (560 W, 78 minutes) have significant practical implications:

i. **Processing efficiency:** The high drying rate constant (0.0942 min^{-1}) enables rapid processing with reduced energy costs compared to conventional methods (Subramanyam & Narayanan, 2023; Chakraborty *et al.*, 2021). The 69.4%-time reduction from 140 W translates to substantial operational cost savings.

ii. **Quality assurance:** Achieving target moisture (6.80%) while maintaining protein retention ≥90% confirms that 560 W optimally balances drying efficiency with quality preservation. Quality control standards should specify maximum microwave power (560 W) to ensure protein quality (Siddiqui *et al.*, 2024; Calín-Sánchez *et al.*, 2020).

iii. **Commercial viability:** Reduced processing time and energy savings make microwave drying economically attractive for processors (Beigi *et al.*, 2017). The technology is particularly suitable for smallholder farmers and large-scale processors seeking to reduce post-harvest losses (Baidhe *et al.*, 2024).

4.0 Conclusions

The findings of this study demonstrate that microwave drying is an efficient technique for processing black bean seeds, with drying behaviour accurately described by the Page model. Microwave power was the dominant factor influencing drying performance and quality, while its interaction with drying time significantly enhanced moisture removal. Response Surface Methodology identified 560 W for 78 minutes as the optimum drying condition, producing seeds with safe storage moisture content (6.80%), high protein retention (93.8%), and excellent carbohydrate retention (99.0%), all of which met or exceeded established quality standards. The optimized process also reduced drying time and energy consumption compared with conventional methods, highlighting its potential for commercial application. Overall, this study provides a comprehensive RSM optimization of microwave drying for black bean seeds, establishing predictive models and validated processing conditions. Accordingly, microwave drying at 560 W for 78 minutes is recommended for commercial processing of black bean seeds, while the developed optimization framework provides a foundation for future studies applying RSM-based approaches to optimize microwave drying of other underutilized legume crops.

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