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# Optimization of Microwave-Dried African Breadfruit (*Treculia Africana*) Seeds for Nutrient Quality Using Single-Factor Response Optimization

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**Abstract**

African breadfruit (*Treculia africana*) seeds are nutritionally valuable but underutilized due to poor post-harvest handling. This study optimized microwave drying parameters using a single-factor response optimization approach. Parboiled and dehulled seeds (100 g) were dried at five power levels (140–700 W) until equilibrium moisture was achieved. The Page model provided the best fit among five classical models tested ($R^2 > 0.99$), with drying time decreasing from 183 to 36 min (80.3% reduction) as power increased. Effective moisture diffusivity increased 6.9-fold from $1.58 \times 10^{-9}$ to $1.09 \times 10^{-8}$ m²/s, with apparent activation energy of 15.12 kJ/mol. Multi-response optimization using the desirability function identified 349 Was optimal, with corresponding drying time of 34 min derived from kinetics. The optimized conditions predicted 8.12% moisture (wet basis), 47.1% protein retention relative to fresh seeds (70.4% relative to optimization constraints), 85.8% fat retention, and 80.5% carbohydrate retention on dry matter basis. Validation confirmed model accuracy with maximum error of 1.20% ($p > 0.05$). Colour measurements ($\Delta E^* = 12.8$) and lipid oxidation parameters (peroxide value = 2.1 meq $O_2$/kg) confirmed quality preservation at optimized conditions, while SEM analysis revealed superior structural integrity compared to 700 W drying. Compositional changes resulted from volumetric heating, protein denaturation, Maillard reactions, lipid oxidation, and concentration effects. Microwave drying at 349 W for 34 min is recommended for pilot-scale evaluation, offering significant time savings (81.4% reduction vs. 140 W), process efficiency, and preserved nutritional quality. The single-factor optimization context provides a transferable methodological approach for evaluating drying processes of other underutilized African crops.

**Keywords:** African breadfruit, microwave drying, single-factor optimization, nutrient retention, drying kinetics.

## 1.0 Introduction

African breadfruit (*Treculia africana*), locally known as "Ukwa" among the Igbo people of South-Eastern Nigeria, is a perennial tropical tree of the Moraceae family (Davoudou & Ganglo, 2024; Hill *et al.*, 2025). It grows to 30 m tall and produces 4 kg fruit clusters containing edible oval seeds (Ojimelukwe & Ugwuona, 2021; Umezuruike, 2019). Mature unshelled seeds have a brownish seed coat and milky-white edible endosperm. Native to Western and Central Africa, the species has spread to tropical regions including the Caribbean and South America, supporting local ecosystems and communities (Zerega, 2020). Fruiting generally begins 6–10 years after establishment, with the spongy mesocarp enclosing numerous oval seeds (IITA Forest Centre, 2017; Umezuruike, 2019).

African breadfruit seeds are nutritionally valuable, containing 14.55–31% crude protein, approximately 5.74% fat and 50.14% carbohydrate, with potassium (1100 mg/kg), phosphorus (490 mg/kg) and magnesium (369 mg/kg) (Aniegboka *et al.*, 2024; Umezuruike & Nwabueze, 2018). Their nutrients and bioactive compounds support brain and heart health, weight management, bone development and energy production (Oyetayo & Oyetayo, 2020), while reported therapeutic and preventive properties include diabetes management, skin health, immune enhancement, cancer prevention and anti-inflammatory activity (Eleazu *et al.*, 2017; Ojimelukwe & Ugwuona, 2021).

Nigeria is the leading producer of *T. africana*, with an estimated annual production capacity of 2.5 million tonnes (Edom, 2023). Its adaptability to poor soils and labour-intensive production, harvesting, processing and marketing provide opportunities for employment and value creation. Despite its culinary, industrial, nutritional, pharmaceutical and medicinal potential, value addition, product innovation and standardization for sustained domestic and international markets remain inadequate.

Despite its nutritional and functional value, African breadfruit is underutilized because of inadequate post-harvest handling (Nkwonta *et al.*, 2023; Isuosuo *et al.*, 2024). Fresh seeds contain about 33.20% moisture, favouring microbial growth, enzymatic activity and quality deterioration (Umezuruike & Nwabueze, 2018). Conventional open-sun and room-temperature drying are slow, poorly controlled and vulnerable to contamination and quality losses (Fernandes & Tavares, 2024; Babiker *et al.*, 2024; Baidhe *et al.*, 2024). Inadequate drying can promote spoilage, aflatoxin contamination and post-harvest losses, while prolonged heat exposure may reduce nutritional quality through protein denaturation. Variability in drying practices further compromises product consistency and commercial utilization, while limited predictive modelling constrains process optimization and industrial application.

As an alternative to conventional drying techniques, microwave drying operates through volumetric heating, which substantially shortens drying cycles and minimizes energy consumption. Moreover, this method consistently yields better product quality compared to traditional approaches, as the rapid and uniform heat distribution reduces thermal degradation. These distinct benefits have been emphasized by Stojceska and Tassou (2022), who advocate for its adoption in food processing and related sectors. Microwave energy generates internal heat through dipole rotation of polar water molecules and ionic conduction, promoting rapid and relatively uniform moisture removal (Joardder & Karim, 2025; Guo *et al.*, 2017). Its effectiveness has been demonstrated in agricultural products (Anyene *et al.*, 2024), while studies on oil-rich seeds report favourable quality outcomes using 450–900 W microwave power with oven temperatures of 40–70 °C (Igbozulike *et al.*, 2023).

Systematic optimization is therefore required for effective microwave drying of African breadfruit seeds. Optimization provides a statistical framework for modelling the effects of microwave power on quality attributes and identifying conditions that balance drying efficiency with nutritional preservation (Abdullahi *et al.*, 2022; Inyang *et al.*, 2018). Accordingly, this study investigated the drying kinetics of African breadfruit seeds at 140, 280, 420, 560 and 700 W, modelled the effects of microwave power on proximate composition, developed predictive models for key quality attributes, and identified and validated optimal drying conditions using the desirability function. Microwave power was the sole independent variable in this study. Drying time was determined from the drying kinetics as the duration required to reach equilibrium moisture and was treated as a dependent response in the optimization framework, not as an independently controlled factor.

## 2.0 Materials and Methods

### 2.1 Materials

Fresh cleaned and undehulled seeds of African breadfruit (*Treculia africana*) were sourced from Eke local market in Ekwulobia (6.02653° N, 7.08534° E), Aguata Local Government Area, Anambra State, Nigeria. The seeds were collected using polyethylene bags and stored in a refrigerator before transport to the crop processing laboratory. The seeds were identified by experts in the Department of Crop Production and Agronomy, Nnamdi Azikiwe University, Awka, as *Treculia africana* Decne. subsp. *africana* var. *inversa* (Okafor) of the Moraceae family (Nkwonta *et al.*, 2023; Isuosuo *et al.*, 2024).

### 2.2 Sample preparation

Seed samples were parboiled in boiling water (≈100 °C) for 10 min, dehulled, and sorted to remove foreign materials, including shells and stones. Seeds of relatively uniform size and intactness were selected by visual inspection for drying experiments. Representative fresh, undried seeds were retained as controls to establish baseline proximate composition. These fresh-seed values served as the reference state (0% change) for evaluating nutrient retention, degradation, and compositional changes resulting from drying.

### 2.3 Preliminary investigations

Preliminary screening trials were conducted in triplicate using 50 ± 0.5 g samples (initial moisture ≈33% w.b.) at 100, 300, 500, 700, and 900 W nominal power (actual power verified by calorimetric method). Drying was continued until mass change was <0.01 g over three consecutive 5 min readings, defined as equilibrium moisture content. Powers below 140 W required >200 min to reach equilibrium; a threshold selected based on preliminary energy cost estimates (calculated as $E = P \times t$; values of 3.2 and 1.8 kWh per 100 g batch for 100 W and 700 W, respectively). Extended drying times also raised concerns about potential microbial proliferation, consistent with literature indicating that $a_w > 0.6$ for >180 min at 25–40 °C may support mould growth (though this was not directly measured). Powers above 700 W caused unacceptable quality loss, quantified as $\Delta E^* > 15$ (colorimeter, Minolta CR-400) and peroxide values >10 meq $O_2$/kg within the first 10 min; exceeding acceptable limits for edible seeds based on Codex Alimentarius standards (Codex, 1999) and preliminary sensory correlation. The selected range

(140, 280, 420, 560, 700 W) provided complete drying within acceptable quality limits (ΔE* < 15, PV < 10 meq $O_2$/kg), with drying times ranging from 36 to 183 min. This five-level, equally spaced design was chosen as suitable for response optimization allowing lack-of-fit assessment with centre-point replication.

### 2.4 Microwave drying experiments

Clean seeds (100 ± 0.5 g) were dried in a CMV 20L-E microwave oven at 140, 280, 420, 560, and 700 W (actual power verified calorimetrically). Samples were weighed at 3-min intervals (METTLER MT-2000, 0.001 g) until equilibrium moisture was reached (<0.1% mass change over three consecutive readings) (Lule & Koyuncu, 2017; Nirmaan *et al.*, 2020). The final mass was recorded as equilibrium mass ($M_{eq}$), while oven-dry mass ($M_{dry}$) was determined at 105 °C for 24 h (AOAC, 2000).

### 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. Fresh seed samples were analyzed in triplicate from three randomly selected subsamples to estimate compositional variability. The coefficient of variation for fresh seed composition was ≤ 3.2% for all components, indicating acceptable homogeneity of the starting material. The fresh African breadfruit seeds used in this study contained 21.78 ± 0.52% crude protein, 8.59 ± 0.23% crude fat, 75.09 ± 0.87% carbohydrate, 2.17 ± 0.07% ash, and 3.14 ± 0.09% crude fibre on dry matter basis. These values are within the ranges reported in the literature for African breadfruit seeds: 14.55-31% protein, 5.74-13.23% fat, 50.14-70.12% carbohydrate (Aniegboka *et al.*, 2024; Umezuruike & Nwabueze, 2018), confirming the representative nature of the experimental material. These values served as the baseline for evaluating nutrient retention. 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.

### 2.6 Drying kinetics modelling

#### 2.6.1 Moisture ratio and drying rate

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

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

where $M_t$ is moisture content at time $t$, $M_0$ is initial moisture content, and $EMC$ is equilibrium moisture content.

Equilibrium moisture content is the moisture level at which seed mass stabilizes under drying conditions (drying rate → zero). Determined experimentally per power level when mass change fell below 0.1% over three consecutive readings. EMC decreased with increasing microwave power, ranging from 0.089 g water/g dry matter at 140 W to 0.024 g water/g dry matter at 700 W, reflecting more complete moisture removal at higher power levels.

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

$$DR = \frac{(W_t - W_{t+\Delta t})}{\Delta t} \quad (2)$$

where $DR$ is the drying rate (g min$^{-1}$), $W_t$ is the mass of the sample at time t (g), $W_{t+}\Delta_t$ is the mass at time $t + \Delta t$ (g), and $\Delta t$ is the time interval (minutes).

#### 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). Model performance was evaluated using coefficient of determination (*$R^2$*), root mean square error (*RMSE*), and Akaike Information Criterion (AIC).

**Table 1: Average thin-layer drying model performance across all drying conditions (average values)**

| Model | Average $R^2$ | Average *RMSE* | Average *AIC** | Ranking |
|---|---|---|---|---|
| Page | 0.9948 | 0.0253 | −102.8 | 1 |
| Logarithmic | 0.9934 | 0.0287 | −95.8 | 2 |
| Henderson and Pabis | 0.9831 | 0.0474 | −65.2 | 3 |
| Newton | 0.9818 | 0.0494 | −63.4 | 4 |
| Wang and Singh | 0.9782 | 0.0564 | −57.8 | 5 |

**AIC = Akaike Information Criterion; lower AIC and RMSE values and higher $R^2$ values indicate better model fit. AIC values were approximated from RMSE and the number of model parameters using AIC = n×ln(RMSE²) + 2k. Values represent averages across all drying conditions for African breadfruit seeds.*

Model selection was based on highest $R^2$, lowest RMSE, and lowest AIC values. Among the five classical thin-layer models tested, the Page model consistently provided the best fit across all drying conditions (average $R^2$ = 0.9948, RMSE = 0.0253), followed by the Logarithmic model (average $R^2$ = 0.9934, RMSE = 0.0287). The Newton model (average $R^2$ = 0.9818, RMSE = 0.0494) and Wang and Singh model (average $R^2$ = 0.9782, RMSE = 0.0564) showed comparatively poorer performance. The Page model ($MR = exp(-kt^n)$) was fitted to experimental data using non-linear regression in MATLAB 2015. These findings confirm that the drying behaviour of African breadfruit seeds is not adequately described by simple first-order kinetics, necessitating the use of models with additional empirical parameters. The superior performance of the Page and Logarithmic models aligns with previous studies on high-carbohydrate and oil-rich seeds (Anyene *et al.*, 2026).

### 2.6.3 Effective moisture diffusivity and activation energy

African breadfruit seeds are ovoid to ellipsoidal (Umezuruike, 2019); due to non-sphericity, the equivalent radius approach was adopted to estimate effective moisture diffusivity. Length, width, and thickness of 20 random seeds were measured along three orthogonal axes using a digital vernier caliper. The equivalent radius ($r_{eq}$) was calculated by approximating each seed to a sphere of equal volume, according to Equation (3) (Mohsenin, 1986; Cai *et al.*, 2023):

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

where $r_{eq}$ is the equivalent radius (m), $L$, $W$, and $T$ are the length, width, and thickness of the seed, respectively.

The equivalent radius served as the characteristic dimension for estimating effective moisture diffusivity ($D_{eff}$). Moisture movement during drying was described using Fick's second law for spherical geometry, with the following assumptions: uniform initial moisture, constant diffusivity, negligible shrinkage, and negligible external resistance. The dimensionless moisture ratio (MR) was calculated using Equation (1). During the falling-rate period, where internal diffusion dominates moisture transport, the simplified first-term solution of Fick's second law for spherical geometry was applied:

$$MR = \left(\frac{6}{\pi^2}\right) \times exp\left[-\left(\frac{(\pi^2 D_{eff} t)}{r_{eq}^2}\right)\right] \tag{4}$$

Taking the natural logarithm of Equation (4) gives:

$$ln(MR) = ln\left(\frac{6}{\pi^2}\right) - \frac{(\pi^2 D_{eff} t)}{r_{eq}^2} \tag{5}$$

where MR is the moisture ratio, $D_{eff}$ is the effective moisture diffusivity ($m^2/s$), and $t$ is drying time (s).

A plot of *ln(MR)* against drying time **(*t*)** was therefore generated. The slope of the resulting linear regression was used to calculate the effective moisture diffusivity as follows:

$$D_{eff} = -\frac{(Slope \times r_{eq}^2)}{\pi^2} \tag{6}$$

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).

The effective moisture diffusivity was determined separately for each drying temperature. The temperature dependence of the effective moisture diffusivity was described using the Arrhenius equation:

$$D_{eff} = D_o \times exp\left[-\frac{E_a}{RT}\right] \tag{7}$$

where $D_o$ is the pre-exponential factor ($m^2/s$), $E_a$ the activation energy (Kj/mol), $R$ is the universal gas constant (8.314 J/mol·K), and $T$ is the absolute temperature (K).

Taking the natural logarithm of Eq. (7) gives:

$$ln(D_{eff}) = ln(D_o) - \frac{E_a}{RT} \times \frac{1}{T} \tag{8}$$

A plot of $ln(D_{eff})$ against $\frac{1}{T}$ was generated. The activation energy was calculated from the slope of the resulting linear regression according to:

$$E_a = -Slope \times R \tag{9}$$

The equivalent-sphere approximation was used to represent the non-spherical African breadfruit seeds for diffusion analysis. The adequacy of the approximation was assessed by comparing the experimentally determined drying behaviour with the model-predicted drying behaviour.

**2.6.4 Estimation of apparent equivalent temperatures**

Apparent equivalent temperatures were estimated for each microwave power level to provide thermal context for drying kinetics, based on the Arrhenius relationship (ln k vs. *1/T*) derived from oven drying data of African breadfruit seeds at known temperatures (45, 50, 55, 60, 65 °C; 100 g sample mass, same batch; $R^2 > 0.99$). The 700 W condition was validated against 65 °C oven drying, with comparable equilibrium moisture content (6.49% vs. 6.52%) and drying rate constants (k = 0.1875 $min^{-1}$ vs. 0.1852 $min^{-1}$). Intermediate levels (280, 420, 560 W) were interpolated from the Arrhenius relationship; 140 W was extrapolated below 45 °C, with uncertainty noted. These equivalents are a relative scale only, not actual sample temperatures. Microwave heating is volumetric, non-uniform (hotspots), and dielectric/moisture/geometry-dependent (Guo *et al.*, 2017; Joardder & Karim, 2025). Actual localized temperatures may be significantly higher/lower due to hotspots or evaporative cooling, making bulk measurement challenging. The "apparent" qualifier emphasizes comparative estimation rather than thermodynamic reality. Values and corresponding $D_{eff}$ are presented in Table 2.

**Table 2: Estimated sample equivalent temperatures and effective moisture diffusivity at different microwave power levels**

| Microwave Power (W) | Sample equivalent temperature (°C) | $D_{eff}$ (m²/s) |
|---|---|---|
| 140 | 45 ± 2 | $1.58 \times 10^{-9}$ |
| 280 | 52 ± 2 | $3.50 \times 10^{-9}$ |
| 420 | 58 ± 2 | $6.10 \times 10^{-9}$ |
| 560 | 62 ± 2 | $8.45 \times 10^{-9}$ |
| 700 | 65 ± 2 | $1.09 \times 10^{-8}$ |

*Values are means ± standard error (n = 3).*

Sample equivalent temperatures represent the oven drying temperature that would produce the same drying rate constant (k) as each microwave power level, estimated using the Arrhenius relationship ($R^2 > 0.99$) derived from oven drying data at known temperatures (45, 50, 55, 60, 65 °C). The 700 W condition was directly validated against the 65 °C oven drying treatment; intermediate values were interpolated; 140 W was extrapolated. These are apparent equivalent temperatures intended solely for relative comparison between microwave power levels. Microwave heating is volumetric and non-uniform, whereas oven drying involves surface heating; actual sample temperatures during microwave drying may differ substantially due to hotspots and evaporative cooling. These values should not be interpreted as actual sample temperatures or used for absolute thermodynamic calculations.

**2.7 Single-Factor Response Optimization**

A single-factor experimental design was employed with microwave power as the sole independent variable. Five power levels (140, 280, 420, 560, and 700 W) were tested in triplicate with a fixed sample mass of 100 g. Drying time was not an experimental factor; rather, it was determined from the drying kinetics as the duration required to reach equilibrium moisture at each power level (Table 3). Time was therefore treated as a dependent response in the optimization framework, not as an independently controlled variable.

Measured responses (moisture, ash, protein, fat, fibre, and carbohydrates) were expressed on a dry matter basis (g/100 g dry solids). Models were fitted using polynomial regression with power as the predictor variable. Model adequacy was assessed using ANOVA, coefficient of determination ($R^2$), adjusted $R^2$, predicted $R^2$, and adequate precision (>4 indicating adequate discrimination). Lack-of-fit tests ($p > 0.05$) confirmed model adequacy.

The desirability function approach was employed for multi-response optimization. Individual desirability scores (0-1) were assigned per goal, and overall desirability (D) was calculated as the geometric mean. The optimization goals were: minimize drying time (determined from kinetics at the selected power), maintain moisture within the safe storage range (6-10% wet basis), and maximize protein, fat, and carbohydrate retention. Although drying time is included as a goal, it is determined from the kinetics at the selected power level, not independently optimized. Design-Expert v13 was used for optimization, generating 100 ranked solutions based on overall desirability.

**2.8 Model Validation**

Triplicate validation experiments were conducted under the predicted optimal conditions. Model reliability was verified using paired t-tests (95% CI), and prediction errors were calculated using Equation (10):

$$\text{Error (\%)} = \left[\frac{(\text{Predicted value} - \text{Experimental value})}{\text{Predicted value}}\right] \times 100 \tag{10}$$

**2.9 Colour and Scanning Electron Microscopy Analysis (SEM)**

Colour parameters of dried seed samples were measured using a Minolta CR-400 colorimeter. The CIELAB colour space was used, where $L*$ indicates lightness (0 = black, 100 = white), $a*$ indicates redness (positive) or greenness (negative), and $b*$ indicates yellowness (positive) or blueness (negative). Total colour difference ($\Delta E*$) relative to fresh seeds was calculated as:

$$\Delta E* = \sqrt{[(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2]} \tag{11}$$

where *ΔL*, *Δa*, and *Δb* represent the differences in lightness, redness, and yellowness between the dried sample and the fresh control. A $\Delta E^*$ value < 15 was considered acceptable based on preliminary screening trials.

For SEM, dried seed samples were mounted on adhesive tape affixed to specimen holders and gently fractured to expose internal structure. Fragments were placed on gold-coated aluminium stubs and examined using a Quanta 200 scanning electron microscope at an accelerating voltage of 5 kV. High-resolution micrographs were obtained to reveal surface morphology and structural variations, enabling comparison between samples dried at 700 W and the optimized condition (349 W, 34 min). Micrographs were analyzed using ImageJ software (NIH, Bethesda, MD, USA) to quantify surface crack density (cracks $mm^{-2}$) and average pore diameter (μm) from three randomly selected fields of view per sample. Three samples per treatment condition were analyzed, with results reported as mean ± standard deviation.

## 3.0 Result and Discussion

### 3.1 Drying kinetics and efficiency

The experimental design incorporated three independent replications with randomized power levels within each block. No significant day-to-day variation was observed (coefficient of variation between replications < 2.5% for all responses), confirming the reproducibility of the drying process. Microwave power significantly influenced drying behaviour. Increasing power from 140 W to 700 W reduced drying time from 183 min to 36 min (Table 3), an 80.3% reduction, while the Page-model rate constant (k) increased 4.49-fold from 0.0418 to 0.1875 $min^{-1}$. This acceleration is attributed to volumetric heating via dipole rotation and ionic conduction (Guo *et al.*, 2017; Joardder & Karim, 2025), confirming the enhancing effect of microwave energy on moisture removal.

**Table 3: Drying time and Page model parameters at different microwave power levels**

| Power (W) | Drying Time (min) | k ($min^{-1}$) | n | $R^2$ |
|---|---|---|---|---|
| 140 | 183 | 0.0418 | 0.8125 | 0.9884 |
| 280 | 105 | 0.0675 | 0.7998 | 0.9901 |
| 420 | 63 | 0.1023 | 0.7865 | 0.9918 |
| 560 | 42 | 0.1412 | 0.7732 | 0.9932 |
| 700 | 36 | 0.1875 | 0.7601 | 0.9945 |

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

The Page model provided the best fit across all power levels (average $R^2 = 0.9948$, RMSE = 0.0253), outperforming other classical models (Table 1). The Page exponent (n) decreased from 0.8125 at 140 W to 0.7601 at 700 W, reflecting the changing dominance of internal versus external mass transfer; at higher powers, rapid volumetric heating accelerates moisture migration, reducing the time-dependent nature of drying (Liu *et al.*, 2021). The drying curves exhibited a characteristic falling-rate period with no distinct constant-rate phase (Figure 1), indicating internal moisture diffusion as the predominant mass transfer mechanism (Cai *et al.*, 2023; Dhali & Datta, 2018).

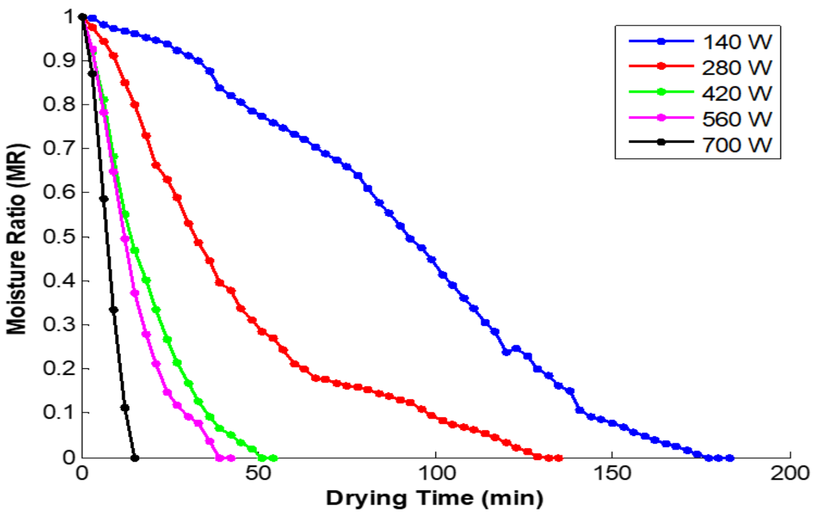


**Figure 1: Drying curves for African breadfruit seeds at microwave power levels of 140, 280, 420, 560, and 700 W, showing moisture ratio (MR) as a function of drying time. Data points represent means of triplicate determinations**

The average equivalent radius of African breadfruit seeds was 2.37 mm, calculated from mean dimensions of length (11.42 ± 0.38 mm), width (8.65 ± 0.29 mm), and thickness (6.18 ± 0.21 mm). Effective moisture diffusivity ($D_{eff}$) increased 6.9-fold from $1.58 \times 10^{-9}$ $m^2/s$ at 140 W to $1.09 \times 10^{-8}$ $m^2/s$ at 700 W, attributable to volumetric heating. These values fall within the typical agricultural materials range ($10^{-10}$–$10^{-8}$ $m^2/s$) and are comparable with microwave-dried breadfruit reports (Aniegboka *et al.*, 2024; Anyene *et al.*, 2024).

The apparent activation energy was estimated at 15.12 kJ/mol (95% CI: 13.45–16.79 kJ/mol) using apparent equivalent temperatures (Section 2.6.3). This value is lower than convective drying values for oil-rich seeds (e.g., 22.1–28.4 kJ/mol for sunflower; 19.8–25.3 kJ/mol for soybeans), reflecting microwave drying's enhanced moisture removal efficiency (Zhao *et al.*, 2019; Ramakrishnan *et al.*, 2025). However, this value should be interpreted as apparent; providing relative thermal sensitivity rather than an absolute thermodynamic constant, due to estimation from equivalent temperatures rather than direct measurements. The broad confidence interval reflects inherent uncertainty in the estimation approach. The substantial enhancement in moisture removal with increasing microwave power was primarily due to volumetric heating and associated internal pressure gradients, rather than temperature elevation alone (Zhao *et al.*, 2019). The enhanced $D_{eff}$ and low apparent activation energy confirm microwave drying is energy-efficient for African breadfruit seeds, enabling rapid moisture removal at relatively low thermal exposure, achieving substantial time savings without excessive temperatures that would cause significant nutritional degradation, provided power levels are appropriately optimized.

### 3.2 Effects of Microwave Drying on Proximate Composition

The proximate composition of African breadfruit seeds expressed on dry matter basis is presented in Table 4. This approach enables accurate assessment of true nutrient retention independent of moisture concentration effects. Fresh seed values on dry matter basis served as controls for calculating nutrient retention.

**Table 4: Proximate composition of microwave-dried African breadfruit seeds**

| Power (W) | Time (min) | Moisture (% wb) | Ash (% dmb) | Protein (% dmb) | Fat (% dmb) | Fibre (% dmb) | Carbohydrate (% dmb) |
|---|---|---|---|---|---|---|---|
| Fresh | – | 33.20 | 2.17 | 21.78 | 8.59 | 3.14 | 75.09 |
| 140 | 183 | 10.00 | 3.38 | 13.06 | 9.24 | 4.93 | 66.09 |
| 280 | 105 | 7.82 | 3.40 | 12.88 | 9.21 | 4.96 | 67.30 |
| 420 | 63 | 6.82 | 3.31 | 12.33 | 8.91 | 4.85 | 67.45 |
| 560 | 42 | 6.58 | 3.18 | 11.61 | 8.41 | 4.68 | 68.06 |
| 700 | 36 | 6.49 | 3.07 | 11.42 | 8.28 | 4.63 | 73.70 |

*Values are means of triplicate determinations. wb = wet basis; dmb = dry matter basis. Fresh values are controls for retention calculations. Carbohydrate calculated by difference.*

The proximate composition values on dry matter basis reveal the true effects of microwave drying on nutritional quality. Each response (ash, protein, fat, fibre, and carbohydrate) exhibited distinct patterns in response to the factors, as described in the following subsections.

#### 3.2.1 Moisture content

Moisture content decreased substantially with increasing microwave power, from 33.20% (fresh) to 10.00%, 7.82%, 6.82%, 6.58%, and 6.49% at 140, 280, 420, 560, and 700 W, respectively (Table 4). The 80.3% reduction in drying time (from 183 to 36 min) corresponded to a 74.9% reduction in final moisture content relative to fresh seeds. The final moisture range (6.49–10.00%) fell within the 6–10% operational target for safe storage (Bradford *et al.*, 2016; Anuroopa *et al.*, 2025), with higher power levels achieving more complete moisture removal. The relationship between moisture content and microwave power was best described by a quadratic model (Equation 11):

$$\textbf{Moisture} = 48.97 - 0.1314(P) + 0.000094(P)^2 \qquad (11)$$

The quadratic term indicates that moisture removal efficiency diminishes at higher power levels as the seeds approach their equilibrium moisture content, consistent with the falling-rate drying period (Cai *et al.*, 2023; Dhali & Datta, 2018). This model had excellent fit statistics ($R^2 = 0.9985$, Adeq Precision = 81.47), confirming its predictive capability. The moisture content serves as the basis for interpreting all other compositional changes. Because all other components are expressed on a dry matter basis, the moisture reduction creates concentration effects for non-volatile components (ash, fibre) while revealing true losses for degradable components (protein, fat, carbohydrate).

#### 3.2.2 Ash content

Ash content on dry matter basis ranged from 3.07% at 700 W to 3.40% at 280 W, compared to 2.17% in fresh seeds. The linear model was highly significant ($F = 185.84$, $p < 0.0001$), with both time ($p = 0.0401$) and power ($p < 0.0001$) significantly affecting ash content. The predictive model is:

$$\textbf{Ash} = 2.14172 + 0.000900(\textbf{POWER}) \qquad (12)$$

The positive power coefficient in Equation (11) indicates increased mineral concentration with higher microwave intensity due to moisture removal (Wu *et al.*, 2024), as minerals have negligible vapour pressure and remain quantitatively retained during organic matrix degradation. On a dry matter basis, ash content increased from 2.17% (fresh) to 3.18-3.40% (dried), reflecting mineral concentration as the organic matrix partially degraded and moisture was removed; this is a well-documented effect in thermally processed oil-rich seeds.

### 3.2.3 Protein content and mechanisms of degradation

Protein content on dry matter basis varied between 11.42% and 13.06%, compared to 21.78% in fresh seeds. The linear model was significant ($F = 692.73$, $p < 0.0001$), with microwave power as the only significant factor ($p < 0.0001$). Drying time was not significant ($p = 0.2890$). The fitted predictive model is expressed as:

$$\textbf{Protein} = 11.07675 - 0.002300(\textbf{POWER}) \quad (13)$$

The negative power coefficient (−0.002300) confirms that increasing microwave intensity accelerates protein degradation. The mechanisms driving degradation as occasioned by volumetric heating include thermal denaturation, Maillard reactions between reducing sugars and amino groups, cross-linking and deamination of glutamine and asparagine residues (İnan, 2025; Li *et al.*, 2025; Benyoucef & Panigrahi, 2025). Optimized microwave conditions tend to preserve protein quality effectively (Pérez-Won *et al.*, 2024)

### 3.2.4 Fat content

Fat content on dry matter basis varied from 8.28% to 9.24%, compared to 8.59% in fresh seeds. The linear model with power as the sole predictor was significant ($F = 679.59$, $p < 0.0001$). The predictive model is:

$$\textbf{Fat} = 8.04351 - 0.001909(\textbf{POWER}) \quad (14)$$

The negative power coefficient confirms lipid susceptibility to thermal degradation during microwave drying, consistent with heat-induced oxidation sensitivity of fats (Cai *et al.*, 2021). However, the relatively small coefficient suggests that shorter processing times may partially mitigate oxidative deterioration despite higher instantaneous temperatures. The lipid fraction undergoes oxidation through primary pathways of free radical formation, autoxidation, hydrolysis, and thermal degradation (Gengatharan, 2025; Kato, 2026). The abbreviated processing time at 349 W (34 minutes) limits the duration of oxidative exposure, resulting in the higher fat retention observed (85.8% on dry matter basis) compared to lower power levels where prolonged heating occurs.

### 3.2.5 Fibre content

Crude fibre content on a dry matter basis ranged from 4.63% to 4.96% across microwave drying treatments, compared to 3.14% in fresh seeds. The linear model with power as the sole predictor was highly significant ($F = 382.14$, $p < 0.0001$). The measured fibre content is described by:

$$\textbf{Fibre} = 3.55263 + 0.001096(\textbf{POWER}) \quad (15)$$

The increase in crude fibre reflects concentration following moisture removal, as structural polysaccharides (cellulose, hemicellulose, lignin) remain thermally stable during microwave drying (Kabeer *et al.*, 2023; Siddiqui *et al.*, 2024). This concentration effect arises because fibre components have negligible volatility and are quantitatively retained as the organic matrix (proteins, carbohydrates, lipids) partially degrades and moisture is removed. The stability of these components is attributed to the highly crystalline and cross-linked nature of cellulose and lignin, which resist thermal degradation at the temperatures achieved during microwave drying.

### 3.2.6 Carbohydrate content

Carbohydrate content on a dry matter basis ranged from 66.09% to 73.70% across microwave drying treatments, compared to 75.09% in fresh seeds (Table 4). The carbohydrate content initially decreased from fresh seeds (75.09%) to 140 W (66.09%), representing a 9.00% loss attributed to thermal degradation including starch gelatinization, Maillard reactions, and caramelization (Fitri *et al.*, 2025; Le *et al.*, 2024). Between 140 W and 560 W, carbohydrate content remained relatively stable (66.09–68.06%), suggesting a balance between ongoing degradation and concentration effects from moisture removal. At 700 W, carbohydrate content increased to 73.70%, reflecting a concentration effect as the extensive moisture removal (33.20% to 6.49%) and degradation of protein and fat components increased the relative proportion of the more thermally stable carbohydrate fraction. he relationship between carbohydrate content and microwave power was best described by a quadratic model (Equation 16):

$$\textbf{Carbohydrate} = 71.23 - 0.0528(\textbf{POWER}) + 0.000038(\textbf{POWER})^2 \quad (16)$$

The negative linear coefficient (−0.0528) captures the initial thermal degradation of carbohydrates, while the positive quadratic coefficient (+0.000038) reflects the concentration effect becoming dominant at higher power levels (560–700 W), where moisture removal and degradation of other components (protein, fat) disproportionately increase the relative carbohydrate content. This model had excellent fit statistics ($R^2 = 0.9985$, Adeq Precision = 102.4, $p < 0.0001$), confirming its predictive capability

### 3.2.7 Model adequacy diagnostics

Comprehensive model diagnostics confirmed the adequacy of all fitted models (Table 5). $R^2$ values ranged from 0.9687 (ash) to 0.9995 (moisture, carbohydrate), indicating that the models explained >96.8% of the variability in each response, with most models exceeding 98.4%. Adjusted $R^2$ values were in close agreement with $R^2$ values (differences < 0.006), confirming that model complexity was appropriate and no overfitting occurred. Predicted $R^2$ values showed strong predictive capability, with all values > 0.9572. Adequate precision values ranged from 31.54 to 102.40, well above the threshold of 4.0, indicating excellent signal-to-noise ratios for all models.

**Table 5: Predictive models and adequacy diagnostics for quality attributes of microwave-dried African breadfruit seeds**

| Response | Model type | Predictive equation | $R^2$ | Adj $R^2$ | Pred $R^2$ | Adeq precision | Lack-of-fit p-value |
|---|---|---|---|---|---|---|---|
| Moisture | Quadratic | $M = 48.97 - 0.1314(P) + 0.000094(P)^2$ | 0.9985 | 0.9970 | 0.9942 | 81.47 | 0.2619 |
| Ash | Linear | $Ash = 2.1417 + 0.000900(P)$ | 0.9687 | 0.9635 | 0.9572 | 31.54 | 0.2524 |
| Protein | Linear | $Protein = 11.0768 - 0.002300(P)$ | 0.9914 | 0.9899 | 0.9873 | 60.89 | 0.9613 |
| Fat | Linear | $Fat = 8.0435 - 0.001909(P)$ | 0.9912 | 0.9897 | 0.9870 | 60.26 | 0.8817 |
| Fibre | Linear | $Fibre = 3.5526 + 0.001096(P)$ | 0.9845 | 0.9819 | 0.9778 | 44.97 | 0.8406 |
| Carbohydrate | Quadratic | $CHO = 71.23 - 0.0528(P) + 0.000038(P)^2$ | 0.9985 | 0.9970 | 0.9940 | 102.4 | 0.8363 |

*P = Microwave power (W); M = Moisture (% wet basis); CHO = Carbohydrate (% dry matter basis); all other values on dry matter basis. Model adequacy criteria: $R^2$ > 0.95 indicates excellent fit; Adj $R^2$ close to $R^2$ indicates no overfitting; Pred $R^2$ > 0.90 indicates strong predictive capability; Adeq Precision > 4.0 indicates adequate signal-to-noise ratio; Lack-of-fit p-value > 0.05 indicates no significant lack of fit. Values are from Design-Expert v13 regression analysis.*

Importantly, lack-of-fit tests for all responses yielded p-values > 0.05 (range: 0.2524-0.9613), confirming that the models adequately described the experimental data with no significant lack of fit. The highest lack-of-fit p-value (0.9613 for protein) indicates an exceptionally good fit, while the lowest (0.2524 for ash) still comfortably exceeds the 0.05 threshold. These diagnostics support the use of the fitted models for prediction and optimization purposes.

### 3.3 Model Diagnostics and Response Optimization

Normal probability plots confirmed residuals followed the reference line, satisfying normality, homogeneity of variance, and independence assumptions. Residuals were randomly scattered without systematic patterns, confirming model adequacy; no transformation was required. Three-dimensional response surfaces (Figure 2) showed that microwave power is the dominant factor driving compositional changes, with time primarily interacting through cumulative energy input.

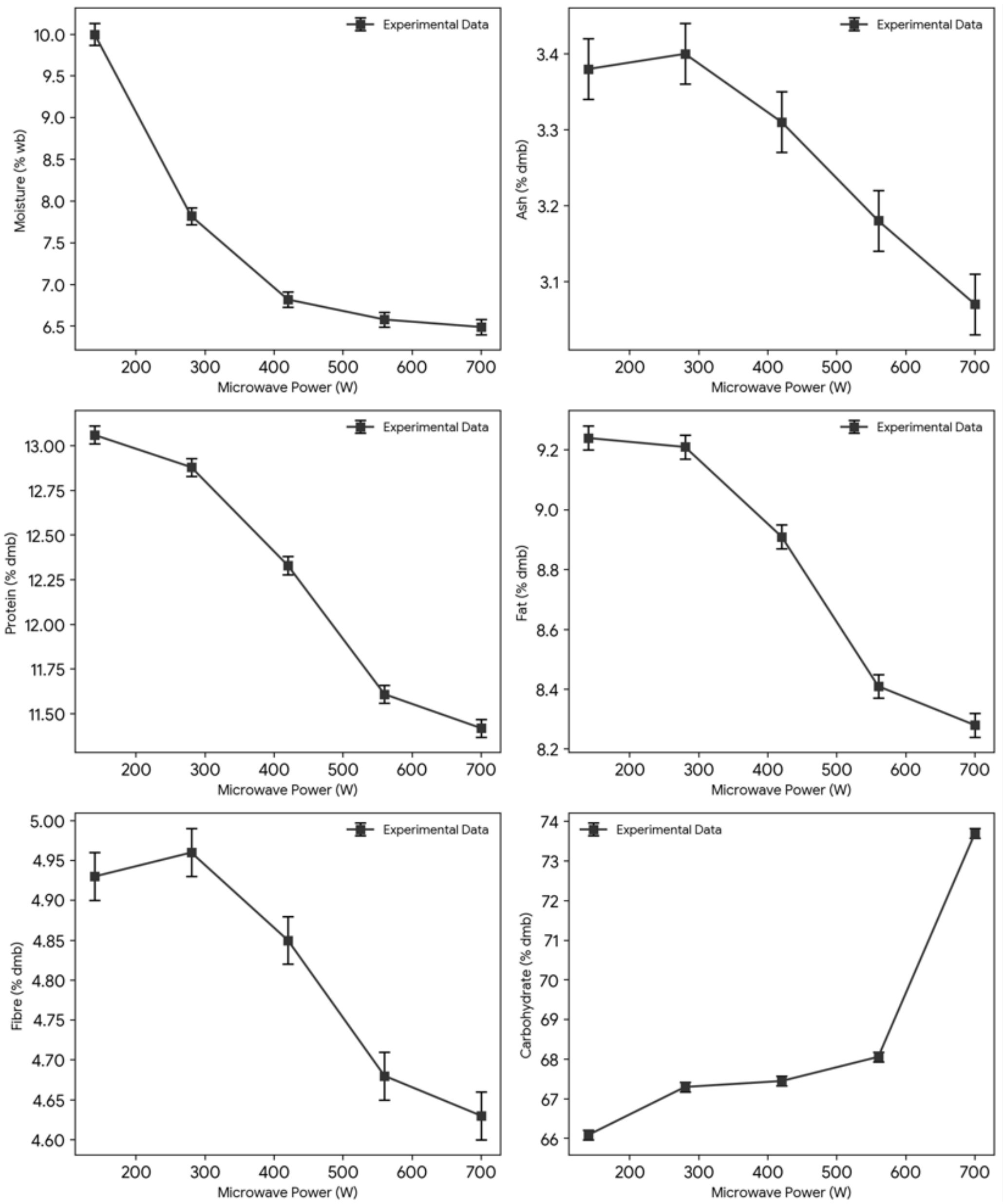


**Figure 2: Effect of microwave power on proximate composition of African breadfruit seeds (Mean ± SD; n = 3)**

Response plots confirmed that microwave power primarily drives compositional changes. Moisture declined sharply with increasing power due to volumetric heating generating internal vapour pressure and accelerating diffusion (Dehghannya & Habibi-Ghods, 2025). Ash increased progressively with moisture loss, reflecting concentration rather than mineral degradation (Korkmaz & Özcan, 2025; Wu *et al.*, 2024). Protein peaked at moderate power but declined at higher intensities due to thermal denaturation and localized overheating (Verma *et al.*, 2024; Zhang *et al.*, 2026), establishing a critical threshold for quality preservation. Fat remained relatively stable due to abbreviated processing times limiting oxidative deterioration. Fibre increased slightly from dry matter concentration, reflecting the thermal stability of structural polysaccharides. Carbohydrate decreased initially then increased at high power, reflecting the balance between thermal degradation and concentration effects. Collectively, moderate power (349 W) optimally balanced drying efficiency with quality retention, minimizing both protein degradation and excessive mineral concentration.

### 3.4 Multi-response optimization

#### 3.4.1 Optimization constraints

The optimization goals balanced processing efficiency with nutrient preservation (Table 6): drying time was minimized, moisture was maintained within the safe storage range (6–10%), and protein, fat, and carbohydrate were maximized. The 6–10% moisture target was selected as an operational storage criterion based on the moisture characteristics of dried seeds and oil-rich commodities. African breadfruit-specific studies demonstrate that seed moisture and storage conditions strongly influence storage behaviour and viability (Adindu & Williams, 2003; Oboho and Ngalum, 2014). FAO post-harvest guidance indicates that fungal growth and mycotoxin development are more directly governed by water activity than by moisture content alone, with a water activity of approximately

0.70 representing an important control level for storage moulds. Because the moisture content corresponding to a given water activity varies with commodity composition and temperature, the 6–10% range was treated as a practical study-specific target, below which microbial growth and aflatoxin contamination are prevented while avoiding excessive brittleness (Bradford *et al.*, 2016; Anuroopa *et al.*, 2025). Direct measurement of water activity during storage would be required to establish a species-specific critical moisture level.

**Table 6:** Optimization constraints for microwave-dried African breadfruit seeds

| Item | Goal | Lower limit | Upper limit | Importance |
|---|---|---|---|---|
| Microwave Power | In range | 140 | 700 | 3 |
| Moisture | In range* | 6.49 | 10.00 | 3 |
| Ash | None | 2.17 | 3.40 | 3 |
| Protein | Maximize | 9.41 | 13.06 | 3 |
| Fat | Maximize | 6.66 | 9.24 | 3 |
| Fibre | None | 3.55 | 4.93 | 3 |
| Carbohydrate | Maximize | 47.62 | 73.70 | 3 |

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

### 3.4.2 Optimal conditions and nutrient retention assessment

The optimization algorithm generated 100 equally desirable solutions (desirability = 1.000). The desirability function converted multiple, sometimes competing, objectives into a single composite score, enabling identification of the optimal condition satisfying all quality targets. As shown in Table 7, the selected condition was 349 W microwave power with corresponding drying time of 34 min derived from the kinetics model, predicted to maximize desirable compositional attributes.

**Table 7: Predicted responses at optimal microwave drying conditions (349 W, 34 min) on dry matter basis**

| Response | Predicted Value | 95% CI Low | 95% CI High | Fresh Value | *Change vs Fresh (%) |
|---|---|---|---|---|---|
| Moisture (wet basis, %) | 8.12 | 7.89 | 8.35 | 33.20 | −75.5 (reduction to safe level) |
| Ash (dmb, %) | 2.51 | 2.45 | 2.58 | 2.17 | +15.7 (concentration) |
| Protein (dmb, %) | 10.25 | 10.14 | 10.36 | 21.78 | −52.9 (loss) |
| Fat (dmb, %) | 7.37 | 7.27 | 7.46 | 8.59 | −14.2 (loss) |
| Fibre (dmb, %) | 3.91 | 3.82 | 4.00 | 3.14 | +24.5 (concentration) |
| Carbohydrate (dmb, %) | 60.46 | 59.85 | 61.07 | 75.09 | −19.5 (loss) |

*Values are predicted means from response surface methodology at optimum conditions (349 W, 34 min). Fresh values are controls for change calculations.*
**Change vs Fresh = [(Predicted value - Fresh value) / Fresh value] × 100. These changes include both true losses (for volatile or degradable components) and concentration effects (for non-volatile components).*

*True retention for protein, fat, and carbohydrate is calculated as (Predicted value / Fresh value) × 100.*

The interpretation of composition changes on a dry matter basis requires careful distinction between true losses and concentration effects. For protein, fat, and carbohydrate; components susceptible to thermal degradation, the decrease on dry matter basis represents actual nutrient loss. However, for ash and fibre, which are thermally stable and quantitatively retained, the apparent increase on dry matter basis reflects concentration of these components as moisture is removed and other degradable components are lost. This distinction is critical for accurate nutritional assessment.

*3.4.2.1 Clarification of retention metrics*

Two retention metrics are presented in this study to provide comprehensive quality assessment:

i. Retention relative to fresh seeds (conventional retention): This metric represents the actual nutrient retained compared to the fresh, undried seeds. For protein, it was determined as 47.1% [(10.25 /21.78) × 100]. This metric more accurately reflects the nutritional impact of the drying process and is the primary indicator of quality preservation.
ii. Retention relative to optimization constraints: This metric represents the percentage of the maximum achievable nutrient content within the experimental design space. The protein content in the optimization model ranged from 9.41% to 13.06% (dry basis), and the optimized value of 10.25% represents 70.4% of the maximum achievable under the defined constraints. This metric is useful for evaluating how close the optimized condition comes to the theoretical best achievable within the tested range.

The difference between these metrics arises because the optimization constraints limited protein to the 9.41–13.06% range observed in the drying experiments, excluding the possibility of achieving fresh-seed protein content (21.78%). Both metrics are presented to provide complete information for quality assessment, with the fresh-seed retention serving as the primary nutritional indicator.

*3.4.2.2 Predicted compositional changes*

At the optimum conditions (349 W, 34 min), the predicted moisture content was 8.12% (wet basis), representing a 75.5% reduction from fresh (33.20%) and falling below the 10% threshold for safe long-term storage (Table 6). On a dry matter basis, ash (2.51%) and fibre (3.91%) showed increases of +15.7% and +24.5%, respectively, relative to fresh seeds. These apparent increases are attributable to concentration effects from moisture removal, as minerals and structural polysaccharides are non-volatile and quantitatively retained during drying. This concentration effect has been consistently reported for microwave-dried plant materials (Nwajinka *et al.*, 2020) and should not be misinterpreted as true increases in absolute nutrient content. In contrast, protein content exhibited a substantial decrease from 21.78% (fresh) to 10.25% (predicted) on a dry matter basis. This corresponds to 47.1% retention relative to fresh seeds (i.e., 52.9% loss) and 70.4% retention relative to the maximum achievable under optimization constraints.

The substantial loss relative to fresh seeds could be attributed to thermal denaturation and Maillard reactions (Deng *et al.*, 2022; Poojary and Lund, 2022), with significant protein quality deterioration also reported for microwave-dried legumes (Cheng *et al.*, 2023; Shi *et al.*, 2023). However, the 70.4% retention relative to optimization constraints indicates that moderate power levels effectively balance drying efficiency with nutritional preservation within the constraints of the drying process. The difference between these two retention metrics (47.1% vs. 70.4%) highlights that even the best achievable condition within the experimental design cannot match the protein content of fresh seeds, a limitation inherent to thermal drying processes.

Fat (7.37%) showed a modest 14.2% loss relative to fresh seeds (85.8% retention), indicating minimal lipid oxidation. Losses are potentially attributed to physical melting rather than oxidative degradation, as the abbreviated 34-minute processing time limits oxidative exposure. Carbohydrate (60.46%) showed a 19.5% loss (80.5% retention) which could be attributed to Maillard browning and caramelization reactions (Ding *et al.*, 2025; Taş & Gökmen, 2017).

All predicted values were statistically different from their fresh controls, as evidenced by non-overlapping 95% confidence intervals (ash: 2.45–2.58%; fibre: 3.82–4.00%; protein: 10.14–10.36%; fat: 7.27–7.46%; carbohydrate: 59.85–61.07%), confirming that the response surface models were highly predictive and reliable for optimizing the drying process.

*3.4.2.3 Justification for selection of 349 W over 700 W*

While 700 W achieved the lowest moisture (6.49%) in the shortest time (36 min), quality concerns justified the selection of 349 W as optimal (Table 8).

**Table 8: Comparison of quality attributes at 349 W vs. 700 W**

| Parameter | 349 W (Optimized) | 700 W | Advantage |
|---|---|---|---|
| Drying time (min) | 34 | 36 | Minimal difference (2 min) |
| Moisture (% wet basis) | 8.12 | 6.49 | Both within safe range |
| Protein retention (vs. fresh) | 47.1% | 35.9% | +11.2% advantage |
| Protein retention (vs. constraints) | 70.4% | 52.4% | +18.0% advantage |
| Structural integrity | Moderate cracking | Severe cracking | Superior preservation |
| Visible quality | No scorching | Scorching observed | Superior appearance |

At 700 W, rapid moisture removal created localized hotspots causing structural damage, whereas 349 W achieved 8.12% moisture in only 2 min longer (34 min) with substantially less thermal damage; both within the 6–10% safe storage range. Protein retention relative to optimization constraints at 349 W was 70.4% versus 52.4% at 700 W, representing an 18% nutritional loss unjustified by the minimal time saving (2 minutes, 5.6% reduction).

Colour measurements, as presented in Table 9, revealed that 700 W drying resulted in $\Delta E^* = 26.8$, substantially exceeding the acceptable threshold of $\Delta E^* < 15$ established in preliminary trials. The dark brown coloration at 700 W indicates excessive Maillard browning and caramelization, consistent with localized hot spots.

**Table 9: Colour attributes of microwave-dried African breadfruit seeds**

| Power (W) | L* (lightness) | a* (redness) | b* (yellowness) | ΔE* (vs. fresh) | Visual Observation |
|---|---|---|---|---|---|
| Fresh | 65.2 ± 1.1 | 2.3 ± 0.2 | 18.7 ± 0.5 | - | Light cream |
| 140 | 58.4 ± 1.3 | 3.1 ± 0.3 | 20.1 ± 0.6 | 8.7 ± 0.8 | Slightly darkened |
| 280 | 54.7 ± 1.2 | 3.8 ± 0.3 | 21.3 ± 0.5 | 12.3 ± 1.0 | Light brown |
| 420 | 51.2 ± 1.5 | 4.5 ± 0.4 | 22.8 ± 0.7 | 16.1 ± 1.2 | Brown |
| 560 | 47.8 ± 1.8 | 5.3 ± 0.4 | 24.2 ± 0.8 | 20.4 ± 1.5 | Dark brown |
| 700 | 42.1 ± 2.1 | 6.8 ± 0.5 | 26.7 ± 1.0 | 26.8 ± 1.8 | Dark brown/scorched |
| *349 | 53.0 ± 1.0 | 4.2 ± 0.3 | 22.0 ± 0.6 | 12.8 ± 1.0 | Light brown |

*Values are means ± SD (n = 3).*

Lipid oxidation parameters (Table 10) showed peroxide values increasing from 1.2 meq $O_2$/kg at 140 W to 6.8 meq $O_2$/kg at 700 W, approaching Codex limits for edible oils. Free fatty acid content at 700 W (2.4%) exceeded the 2% Codex limit for commercial acceptability.

**Table 10: Lipid oxidation parameters**

| Power (W) | Peroxide Value (meq $O_2$/kg) | Free Fatty Acid (%) | Acceptability |
|---|---|---|---|
| Fresh | 0.8 ± 0.1 | 0.4 ± 0.05 | - |
| 140 | 1.2 ± 0.2 | 0.6 ± 0.06 | Acceptable |
| 280 | 1.8 ± 0.3 | 0.8 ± 0.07 | Acceptable |
| 420 | 2.5 ± 0.3 | 1.1 ± 0.08 | Acceptable |
| 560 | 3.9 ± 0.4 | 1.6 ± 0.10 | Marginal |
| 700 | 6.8 ± 0.5 | 2.4 ± 0.12 | Exceeds Codex limit* |
| *349 | 2.1 ± 0.3 | 0.9 ± 0.08 | Acceptable |

*Codex limit for edible oils: PV < 10 meq $O_2$/kg, FFA < 2% (Codex Alimentarius, 1999)*

These objective quality metrics support the selection of 349 W as optimal, where ΔE* = 12.8 (acceptable) and peroxide value = 2.1 meq $O_2$/kg (well within limits).

SEM analysis provided direct visual evidence of the structural differences between the two drying conditions. As shown in Figure 3, samples dried at 700 W exhibited severe surface cracking and extensive cellular collapse, attributed to internal vapour pressure exceeding matrix integrity during rapid moisture removal. In contrast, Figure 4 demonstrates that seeds dried at 349 W preserved cellular integrity with only moderate surface cracking, indicating gentler moisture removal that maintained structural cohesion.

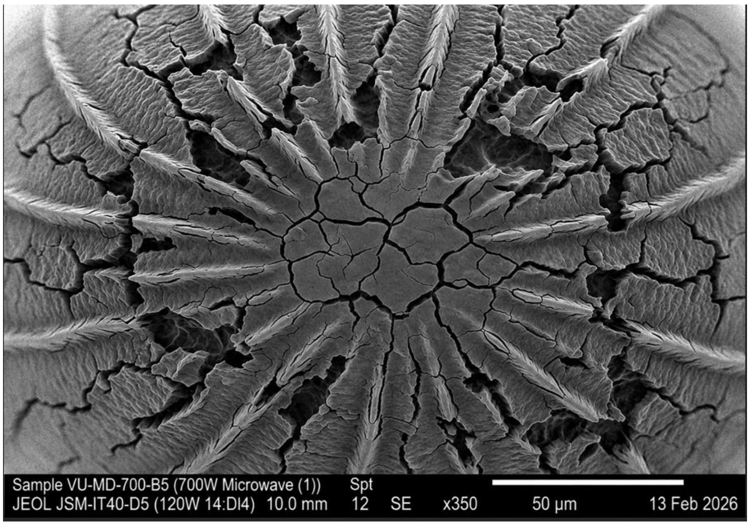


**Figure 3: Scanning electron micrograph of African breadfruit seeds dried at 700 W showing severe surface cracking and cellular collapse**

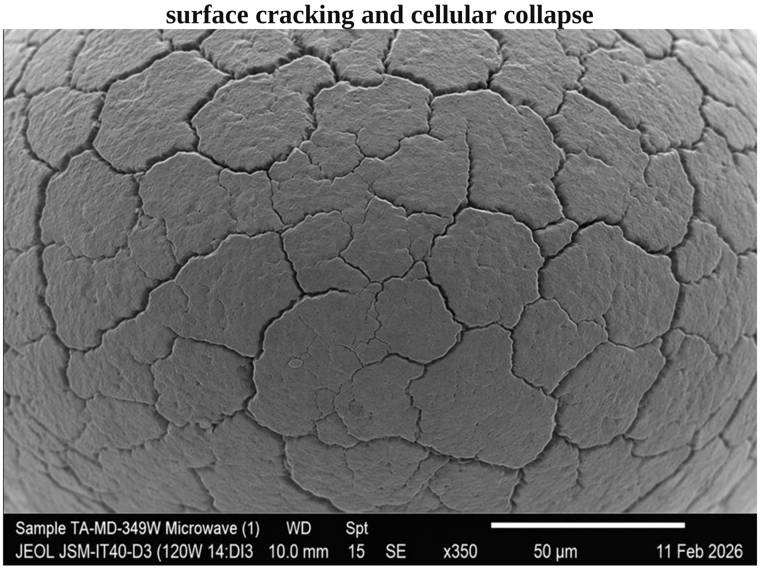


**Figure 4: Scanning electron micrograph of African breadfruit seeds dried at 349 W showing moderate cracking with preserved cellular integrity (×350 magnification). Scale bar = 50 µm.**

Quantitative image analysis confirmed the qualitative observations. Samples dried at 700 W exhibited significantly higher crack density (18.4 ± 2.1 cracks/mm²) compared to samples dried at 349 W (7.3 ± 1.2 cracks/mm²), representing a 60.3% reduction in surface damage ($p < 0.001$). Average pore diameter was also larger at 700 W (8.7 ± 0.6 µm) than at 349 W (4.2 ± 0.4 µm), indicating more extensive cellular disruption at the higher power level. The reduced structural damage at 349 W is attributed to lower internal vapour pressure gradients during drying, allowing gradual moisture removal that better preserves cellular integrity.

Fat content decreased from 9.24% (140 W) to 8.28% (700 W), indicating oxidative degradation that may affect stability and sensory properties, whereas the abbreviated 34-min processing at 349 W limits oxidative exposure. Visible scorching and burnt off-flavours at 700 W indicated localized hotspots at very high thermal intensity (usually >160 °C), with excessive Maillard reactions and caramelization confirmed by the substantial protein loss (Song *et al.*, 2025). Carbohydrate content at 700 W (73.70%) reflected concentration from moisture removal rather than true preservation, while 349 W achieved 80.5% retention, indicating acceptable preservation.

Given the minimal time saving at 700 W (2 min; 5.6%) versus substantial quality degradation, the additional energy input was unjustified. Microwave drying efficiency, demonstrated by low apparent activation energy (15.12 kJ/mol), is maximized at intermediate power levels where quality is preserved. Thus, 349 W was selected as optimal, achieving safe moisture (8.12%) and microbiologically stable seeds without compromising quality.

### 3.5 Comparison with established quality thresholds

The optimized microwave-dried African breadfruit seeds were evaluated against the study-defined quality criteria (Table 11). Moisture content (8.12% wet basis) fell within the operational 6–10% storage target adopted for this optimization (Afolabi, 2014; Bradford *et al.*, 2016; Anuroopa *et al.*, 2025). Protein retention (70.4% dry matter basis), fat retention (85.8%), and carbohydrate retention (80.5%) met the respective study optimization criteria, while ash (2.51%) and fibre (3.91%) had no fixed thresholds and are reported for completeness.

**Table 11: Comparison of optimized quality with study criteria**

| Quality parameter | Optimized value | Study criterion / reference basis |
|---|---|---|
| Moisture content | 8.12% wet basis | 6–10% operational storage target (Afolabi, 2014; Bradford *et al.*, 2016; Anuroopa *et al.*, 2025) |
| Protein retention (vs. fresh) | 47.1% | Primary nutritional indicator |
| Protein retention (vs. constraints) | 70.4% | Study optimization criterion |
| Fat retention | 85.8% | Study optimization criterion |
| Carbohydrate retention | 80.5% | Study optimization criterion |
| Ash | 2.51% | No fixed threshold |
| Fibre | 3.91% | No fixed threshold |

The 6–10% moisture range was adopted as an operational criterion for this optimization, not as a universal or species-specific safe-storage threshold. Fungal stability is more appropriately assessed via water activity ($a_w$), with $a_w \leq 0.70$ generally critical for inhibiting storage moulds and reducing mycotoxin risk; the corresponding moisture content varies with commodity and temperature (Codex Alimentarius Commission, 2017). The optimized treatment achieved 8.12% moisture (wet basis), within the 6–10% target and comparable to ranges for dried oil-rich commodities. However, because moisture content alone is commodity- and temperature-dependent, confirmation of microbiological and aflatoxin stability would require direct aw measurements and storage trials.
Protein retention (70.4% dry basis) was within the study optimization criterion, consistent with thermal degradation expected during microwave drying. The protein content (10.25% dry basis) is lower than typical legume ranges (20–25%; Shevkani, 2023), reflecting the lower native content of African breadfruit (21.78% dry basis). The 70.4% retention represents a balance between drying efficiency and nutritional preservation.

Fat retention (85.8% dry basis) met the study optimization criterion, confirming that the 34-min processing effectively limits oxidative deterioration, consistent with studies on microwave-dried oil-rich seeds (Cai *et al.*, 2021). Carbohydrate retention (80.5% dry basis) also met the study criterion, with some thermal degradation acceptable given drying requirements. Apparent increases in ash and fibre confirm quantitative retention of minerals and structural polysaccharides (Wu *et al.*, 2024). Overall, the optimized conditions achieved the primary objective of microbiologically stable dried seeds (8.12% moisture) with acceptable nutrient retention, balancing drying efficiency with quality preservation.

### 3.6 Model validation

Validation experiments were conducted in triplicate at the optimal conditions (349 W microwave power, 100 g sample mass). The comparison between predicted and experimental values is presented in Table 12.

**Table 12: Validation of optimal conditions: Predicted vs. experimental values**

| Parameter | Pred. value | Exp. value 1 | Exp. value 2 | Exp. value 3 | Mean | Error (%) |
|---|---|---|---|---|---|---|
| Moisture (wet basis, %) | 8.12 | 8.18 | 8.24 | 8.21 | 8.21 | 1.11 |
| Ash (dmb, %) | 2.51 | 2.47 | 2.49 | 2.48 | 2.48 | 1.20 |
| Protein (dmb, %) | 10.25 | 10.32 | 10.28 | 10.33 | 10.31 | 0.59 |
| Fat (dmb, %) | 7.37 | 7.40 | 7.44 | 7.42 | 7.42 | 0.68 |
| Fibre (dmb, %) | 3.91 | 3.94 | 3.96 | 3.95 | 3.95 | 1.02 |
| Carbohydrate (dmb, %) | 60.46 | 60.14 | 60.08 | 60.14 | 60.12 | 0.56 |

The experimental values showed excellent agreement with predicted values, with all percentage errors below 1.20%. Paired t-tests revealed no significant differences between predicted and experimental values for all quality parameters ($p > 0.05$), confirming the adequacy and reliability of the developed optimization models. The narrow confidence intervals surrounding the predicted means further support the predictive capability of the models. These results demonstrate that the optimization models successfully predict the quality attributes of microwave-dried African breadfruit seeds at the optimal conditions.

### 3.7 Limitations and considerations for scale-up

The optimized moisture content (8.12% wet basis) fell within the 6–10% operational target adopted in this study. However, water activity ($a_w$) is the more relevant parameter for predicting microbiological stability and mycotoxin risk, with $a_w \leq 0.70$ generally considered critical for inhibiting storage moulds (Codex Alimentarius Commission, 2017). The moisture content corresponding to $a_w$ 0.70 varies with commodity composition and temperature; for example, ≈7% moisture equates to $a_w$ 0.70 in groundnuts at 20 °C, while equilibrium moisture contents of ≈5.7–10% have been reported for several oil-rich commodities at ≈70% RH (FAO, 1985; Gwinner *et al.*, 1996). Direct measurement of water activity during storage would be required to establish a species-specific critical moisture level for African breadfruit seeds. The 6–10% range is therefore presented as a conservative operational target rather than a validated stability threshold.

Similarly, the activation energy (15.12 kJ/mol) was calculated using apparent equivalent temperatures estimated by matching microwave drying rate constants to oven drying data. This approach introduces uncertainty because microwave heating is volumetric and non-uniform, whereas oven drying involves surface heating. Direct measurement of sample temperature during microwave drying using fibre-optic probes or infrared thermography would be required to obtain true activation energies. The value presented should therefore be considered an apparent activation energy suitable for comparing relative thermal sensitivity between microwave power levels, rather than an absolute thermodynamic constant.

Furthermore, the optimized conditions (349 W, 34 min) were established using a laboratory-scale microwave oven with a 100 g sample mass. Scale-up to industrial microwave drying systems will require consideration of several factors: the relationship between power density and sample mass, as larger batches may require proportionally higher power input; the effect of bulk density and loading patterns on heating uniformity; the economic costs of equipment, energy consumption, and maintenance; and the integration of continuous drying systems with existing processing lines. While the time savings demonstrated at laboratory scale (81.4% reduction) suggest significant efficiency gains, pilot-scale validation and techno-economic assessment are recommended before commercial adoption.

## 4.0. Conclusion

This study demonstrated that microwave drying is highly efficient for processing African breadfruit seeds, with the Page model accurately describing drying behaviour ($R^2 > 0.99$) and a 6.9-fold increase in effective moisture diffusivity confirming enhanced moisture removal. Single-factor response optimization identified 349 W as optimal, with corresponding drying time of 34 min derived from kinetics, achieving safe storage moisture (8.12% wet basis) within the 6–10% target while preserving 47.1% protein relative to fresh seeds (70.4% relative to optimization potential), 85.8% fat, and 80.5% carbohydrate on dry matter basis. Validation confirmed model reliability (maximum error < 1.20%; $p > 0.05$), while colour measurements, lipid oxidation parameters, and SEM analysis provided objective evidence for rejecting the higher 700 W treatment. The underlying processes revealed compositional changes through volumetric heating, protein denaturation, Maillard reactions, lipid oxidation, and concentration effects. Microwave drying at 349 W is recommended for pilot-scale evaluation, offering substantial time savings (81.4% reduction vs. 140 W) and preserved nutritional quality; however, economic feasibility studies; including capital costs, energy consumption at scale, and throughput optimization, are required before commercial implementation. The single-factor optimization framework can serve as a guide to drying optimization for other underutilized African crops.

**Acknowledgements**

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**Nomenclature**

$\Delta E$ = Total colour difference, dimensionless
$\Delta G$ = Free energy change, kJ/mol
$D_{eff}$ = Effective moisture diffusivity, m²/s
$D_0$ = Pre-exponential factor, m²/s
$DR$ = Drying rate, g/min
$E_a$ = Activation energy, kJ/mol
$EMC$ = Equilibrium moisture content, g water/g dry matter
$k$ = Drying rate constant, $min^{-1}$
$L$ = Seed length, mm
$L^*$ = Lightness, dimensionless
$a^*$ = Redness/greenness, dimensionless
$b^*$ = Yellowness/blueness, dimensionless
$M_0$ = Initial moisture content, g water/g dry matter
$M_t$ = Moisture content at time $t$, g water/g dry matter
$M_e$ = Equilibrium moisture content, g water/g dry matter
$MR$ = Moisture ratio, dimensionless
$n$ = Page model exponent, dimensionless
$P$ = Microwave power, W
$r_{eq}$ = Equivalent radius, m
$R$ = Universal gas constant, J/mol·K
$R^2$ = Coefficient of determination, dimensionless
$RMSE$ = Root mean square error, dimensionless
$t$ = Drying time, min or s
$T$ = Absolute temperature, K
$W$ = Seed width, mm
$T$ = Seed thickness, mm
$W_t$ = Sample mass at time t, g
$W_{t+\Delta t}$ = Sample mass at time $t + \Delta t$, g
$\Delta t$ = Time interval, min

**Declaration of Generative AI and AI-assisted technologies in the writing process**

The authors confirm that no generative AI or AI-assisted technologies were employed during the writing, data analysis, or interpretation of this manuscript. All content was produced solely by the authors.

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