ISSN: 2754-477X

Journal of Food Technology & Nutrition Sciences

SCIENTIFIC Research and Community

Research Article

Open Access

Optimization of the Drying Parameters for Plantain Chips using a Locally Made Tray Dryer: A Study on Drying Efficiency and Drying Rate Modeling using RSM

Arinzechukwu H Madukasi[1], Ifeanyichukwu U Onyenanu[2*], Peter O Oghenekaro[2], Chikwendu C Nzenwa[3] and Kingsley E Madu[2]

[1]Department of Mechanical Engineering, University of South Wales, United Kingdom

[2]Department of Mechanical Engineering, Chukwuemeka Odumegwu Ojukwu University, Uli, Nigeria

[3]Department of Mechanical Engineering, Nnamdi Azikiwe University, Awka, Nigeria

ABSTRACT

Plantain chips are a popular snack in many tropical countries, but inefficient drying processes often hinder their production. This study aimed to optimize the drying parameters for plantain chips using a locally made tray dryer, with a focus on enhancing drying rate and efficiency. A D-Optimal design was employed to evaluate the effects of four critical parameters: drying temperature (80–100°C), airflow rate (0.25–0.45 m/s), chimney diameter (20–40 mm), and chip thickness (0.5–1 mm). Response Surface Methodology (RSM) was used to model and optimize the drying process. The results showed that the optimal drying conditions were: temperature (91.9775°C), airflow rate (0.279371 m/s), chimney diameter (21.9722 mm), and chip thickness (1 mm). Under these conditions, the drying rate and efficiency were significantly improved, reaching 0.0161177 kg/h and 88.88%, respectively. This study demonstrates the effectiveness of RSM in optimizing the drying process for plantain chips and provides valuable insights for the development of efficient and cost-effective drying systems for food processing industries. The findings of this research can be scaled up for industrial applications, contributing to the improvement of food security and economic development.

***Corresponding author**
Ifeanyichukwu U Onyenanu, Department of Mechanical Engineering, Chukwuemeka Odumegwu Ojukwu University, Uli, Nigeria.

Received: March 18, 2025; **Accepted:** March 24, 2025; **Published:** April 03, 2025

Keywords: Plantain Chips, Tray Dryer, Drying Parameters, Response Surface Methodology, Energy Efficiency, Drying Rate, Optimization

Introduction

Plantain chips, derived from Musa spp., represent a significant value-added product in tropical regions, particularly in Africa, where plantains are a dietary staple and economic resource [1,2]. Their transformation into shelf-stable chips enhances marketability, extends shelf life and meets growing consumer demand for convenient, nutritious snacks [3,4]. According to Olutomilola, plantain production in Nigeria alone exceeds 2.7 million tons annually with a substantial portion processed into chips by small-scale enterprises [5-8]. This processing supports local livelihoods and contributes to food security by reducing post-harvest losses, estimated at 40% in West Africa due to inadequate preservation technologies [9]. However, the economic and nutritional potential of plantain chips is heavily contingent on the efficiency and effectiveness of drying processes, which remain a critical bottleneck in their production. Despite the growing demand for plantain chips, the drying process remains a significant bottleneck, particularly in rural and resource-constrained settings where advanced drying technologies are often inaccessible [10]. However, traditional drying methods, such as open sun drying, are widely used due to their low cost and simplicity [11,12]. However, these methods are fraught with numerous challenges, including prolonged drying times, contamination by dust and insects, and dependence on favourable weather conditions [12,13]. These limitations often result in inconsistent product quality, high post-harvest losses, and reduced marketability [14]. The inherent variability of open sun drying further exacerbates quality inconsistencies, as fluctuations in solar irradiance, ambient humidity, and irregular airflow lead to non-uniform moisture removal [11,15,16]. This often leaves residual moisture pockets that promote lipid oxidation and rancidity, compromising the nutritional and sensory attributes of the final product [14,17]. Research by Bhuyan demonstrated that open sun drying can take up to 5 days to reduce moisture content in tomatoes from 93% to 4%, with a drying rate of 0.0272 kg/h, a timeline that increases the risk of fungal contamination and nutrient degradation [18]. In contrast, forced convective drying systems, such as biomass solar-enhanced dryers, achieved a final reduced moisture of 12-32% in 3.5-27 hours [19].

Energy inefficiency and environmental vulnerability further undermine open sun drying. In humid climates, prolonged exposure to dew or rain frequently interrupts the drying process, necessitating rehydration and restarting cycles that waste labour and energy [16]. Rajkumar noted that open drying relies on ambient conditions, making it slower than vacuum-assisted solar drying [20]. Tomato slices dried for 360-600 minutes in a solar dryer, compared to 450-750 minutes in open sun drying, depending on slice thickness [20]. Thus, these inefficiencies disproportionately in the open drying method affect smallholders, who lack the capital to invest in mechanised alternatives. Moreover, the decentralised nature of sun drying complicates quality control, as producers often prioritise expediency over standardised protocols. For example, Adenitan observed that small-scale processors in Nigeria commonly produce plantain chips using traditional sun-drying methods, which involve spreading slices on surfaces, increasing the risk of heavy metal contamination from vehicular emissions [21]. Emerging solutions, such as biomass-driven convective dryers and solar tunnel systems, aim to mitigate these challenges. The forced convective biomass dryer tested by achieved a drying rate of 0.03833 kg/hr, four times faster than open sun methods, while maintaining product hygiene through enclosed airflow and heat recirculation [18]. However, the adoption of these technologies remains limited by high upfront costs and technical complexity, particularly in resource-constrained settings. Recent studies have explored various drying parameters to optimise plantain chip production. For instance, the effects of sample thickness, drying temperature, and drying time on moisture content were investigated using Response Surface Methodology (RSM) by [22]. Their findings indicated that optimal drying conditions for sweet potato chips were a temperature of 70°C, slice thickness of 0.6 cm, and drying time of 180 minutes. Under these conditions, treated sweet potatoes had a lower moisture content of 0.1809 g water/g solid compared to untreated ones at 0.3522 g water/g solid. This result highlights the importance of precise control over drying conditions to achieve desired product quality. While frying is a distinct process from drying, understanding optimal thermal conditions can inform drying protocols to ensure consistent product quality. Furthermore, there is a paucity of research on the application of advanced optimisation techniques, such as Response Surface Methodology (RSM), to model and optimise the drying process for plantain chips. RSM, a powerful statistical tool, enables the simultaneous evaluation of multiple factors and their interactions, making it particularly suitable for complex processes like drying [23,24]. By leveraging RSM, it is possible to identify optimal drying conditions that maximise energy efficiency, minimise drying time, and retain product quality, thereby addressing a critical need in the field of food processing. Thus, the primary objective of this study is to optimise the drying parameters for plantain chips using a locally made tray dryer, focusing on energy efficiency, quality retention, and drying rate modelling.

Literature Review

The quest for energy-efficient, low-cost tray dryers for plantain chips remains hamstrung by a persistent disconnect between technical innovation and socioeconomic pragmatism. However, forced convective dryers, such as the biomass-driven system tested by Muritala demonstrated that a forced convective biomass dryer reduced plantain moisture content from 60% to 13% (dry basis) at air velocities of 1.5–3.5 m/s, achieving a drying rate of 0.0140 kg/h four times faster than open sun drying (0.0035 kg/h) [25]. While higher fan speeds improved airflow, experimental tests revealed temperature inconsistencies caused by heat loss from inadequate insulation, deviating from numerical simulations [25]. This flaw, rooted in inadequate optimisation of airflow dynamics, exemplifies a broader issue: studies prioritise technical metrics like drying rate or energy consumption while sidelining user accessibility and cost scalability. Similarly, the electric cabinet dryer evaluated by Owolarafe consumed 346.55 kJ of energy for plantain chips, achieving a drying rate of 34.80 g/h [26]. While efficient, its reliance on three 1800 W electric heating elements and grid power makes it impractical for off-grid rural processors, where biomass or solar energy is more viable [27,28]. Such high-capacity systems overlook the socioeconomic constraints of smallholders, who prioritise low-cost, low-maintenance solutions over complex technologies [29]. For instance, studies emphasize that smallholder-friendly dryers must balance affordability with moderate drying rates (~5–34 g/h) and reduce dependency on costly infrastructure to align with local energy access and financial realities [26,27,28]. A critical analysis reveals that many dryer designs fail to address region-specific constraints, such as intermittent power supply or fluctuating biomass availability. Akubor & Adejo found that most Nigerian processors dry plantain chips near roadways, exposing products to airborne contaminants and heavy metals like lead [30]. The absence of context-sensitive alternatives exacerbates post-harvest losses, which exceed 40% in tropical regions like Nigeria due to inadequate handling, storage, and processing [31]. Even solar dryers, touted for their sustainability, face adoption barriers; Okoroigwe found that their initial solar-biomass hybrid dryer design had low efficiency (5.19% for solar, 0.23% for biomass, and 1.64% for combined solar-biomass heating) due to excessive convective heat losses from the front pass solar collector and a poorly designed biomass combustion unit [32]. They believed the drying efficiency could be enhanced by using a back pass solar collector and a biomass heating stove with a gas-to-gas heat exchanger. Yet, such optimizations are rarely incorporated into localized dryer prototypes, reflecting a systemic neglect of incremental, cost-effective improvements.

Response Surface Methodology (RSM) has emerged as a powerful statistical tool for optimizing complex processes like food drying. RSM enables the simultaneous evaluation of multiple factors and their interactions, making it particularly suitable for identifying optimal drying conditions that maximise energy efficiency and product quality [23]. The methodology involves designing a series of experiments based on a predefined model, such as a quadratic or polynomial model, and analyzing the results to identify the most significant factors and their optimal levels [33,34]. In the context of food drying, RSM has been successfully applied to optimize drying parameters for various products, including fruits, vegetables, and grains [35]. For instance, studies have used RSM to optimize the drying of mango slices, achieving significant improvements in drying rate and energy efficiency while preserving product quality [36]. Despite its proven effectiveness, the application of RSM in optimizing drying parameters for plantain chips remains underexplored, particularly in the context of locally made tray dryers. This gap in the literature represents a critical opportunity for this research, as the optimization of drying parameters using RSM could significantly enhance the performance and adoption of tray dryers in small-scale food processing. Additionally, energy efficiency is a critical consideration in food drying, as the process is inherently energy-intensive. Inefficient drying systems not only increase operational costs but also contribute to environmental degradation through excessive energy consumption and greenhouse gas emissions [37]. Recent studies have focused on improving the energy efficiency of drying systems through the optimization of operating parameters and the integration of renewable energy sources. For example, Udomkun demonstrated that solar-assisted tray dryers can reduce energy consumption by up to 40% compared to conventional electric dryers while maintaining comparable product quality [38]. Similarly, biomass-powered dryers have been shown to achieve high energy efficiency and low operating costs, making them a viable option for small-scale processors in rural areas [25]. However, the energy efficiency of drying systems is highly dependent on the optimization of key parameters, such as drying temperature, air velocity, and tray loading density. Inefficient operation can lead to excessive energy consumption and suboptimal product quality, emphasizing the need for systematic optimization studies. Quality retention is another critical factor in food drying, as the process can significantly impact the nutritional, sensory, and functional properties of the final product. The drying process can cause undesirable biochemical changes, such as nutrient degradation, colour loss, and texture alteration, which compromise product quality and marketability [39,40]. Recent studies have focused on optimizing drying parameters to minimize these adverse effects while achieving efficient moisture removal. For example, Vega-Gálvez demonstrated that controlled drying conditions, such as low temperatures and moderate air velocities, can significantly improve the retention of vitamins and antioxidants in dried apple slices [41]. Similarly, studies on plantain chips have shown that optimized drying parameters can enhance product quality in terms of colour, texture, and flavour while reducing drying times and energy consumption [42,43]. However, the lack of standardized protocols for quality assessment and optimization remains a significant challenge, particularly for small-scale processors who may lack the resources and expertise to conduct systematic studies.

Methodology

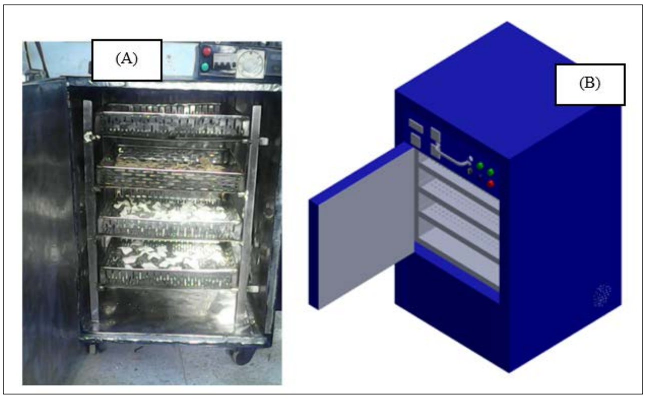
Materials

The primary raw material used in this study was plantain (Musa paradisiaca), specifically the horn plantain variety, which is widely available in Nnewi, Anambra State, Nigeria. The plantains were freshly harvested and procured from the Nkwo Nnewi market [6]. The plantains were manually peeled and sliced into chips of varying thicknesses (0.5 mm, 0.75 mm, and 1 mm) using a stainless-steel knife. A Vernier caliper was employed to ensure accurate chip thickness measurements. The chips were then weighed using a digital balance before loading them into the tray dryer for the drying experiments. The physicochemical properties of the unripe plantain, including moisture content, starch, protein, and ash, were determined to establish baseline characteristics for the drying process.

Figure 1: Pictorial View of Some Sliced Chips Ready for Loading

Locally Made Tray Dryer

The drying experiments were conducted using a locally made tray dryer available at the National Engineering Design Development Institute (NEDDI) in Nnewi, Anambra State - Nigeria. The tray dryer is a double-walled cabinet with a single door, insulated with high-density fiberglass wool to minimize heat loss. The dryer is equipped with stainless steel trays placed on movable trolleys, allowing for uniform drying of the plantain chips. The dryer is also fitted with a control panel board, a digital temperature controller, and a process timer to monitor and regulate the drying conditions. The operational principle of the tray dryer involves the circulation of heated air through the trays, which facilitates the evaporation of moisture from the plantain chips. The dryer's design allows for adjustable recirculation of air, which is particularly useful for optimizing energy consumption during the drying process.



Figures 2A and 2B: Pictorial View of the Developed Tray Dryer and the Rendered 3D Isometric CAD Drawing of the Tray Dryer

Experimental Design

The experimental design for this study was developed using the Optimal D (Custom) Design in Design-Expert software (Version 12.0). This design was chosen for its flexibility in accommodating custom models, categorical factors, and irregular (constrained) regions [44,45]. The design allowed for the optimisation of the drying process by varying four independent variables: drying temperature (80°C to 100°C), airflow velocity (0.25 m/s to 0.45 m/s), chimney diameter (20 mm to 40 mm), and chip thickness (0.5 mm to 1 mm). Each of these variables was tested at three levels to determine their impact on the drying process. The response variables measured in this study included the drying rate (kg/h) and drying efficiency (%). The drying rate was calculated based on the mass of water removed from the plantain chips over time, while the drying efficiency was determined by the ratio of the energy used for moisture evaporation to the total energy supplied to the dryer. These response variables were chosen to evaluate the performance of the dryer and to identify the optimal conditions for drying plantain chips. The experimental runs were conducted according to the design matrix generated by the Design-Expert software, which included 22 runs with varying combinations of independent variables. The results from these runs were analysed using Analysis of Variance (ANOVA) to determine the significance of each factor and their interactions.

Table 1: Experimental Design/Results of the Experiment

	Factor 1	Factor 2	Factor 3	Factor 4	Response 1	Response 2
Run	A: Drying Temperature	B: Air flow rate	C: Chimney Diameter	D: chips thickness	Drying rate	Drying efficiency
	°C	m/sec	mm	mm	Kgh-1	%
1	100	0.25	20	0.5	0.0163	90.1
2	100	0.25	20	0.5	0.0163	90.1
3	85	0.45	20	0.75	0.0165	88.7
4	85	0.3	20	1	0.0165	88.75
5	85	0.25	30	1	0.0164	88.7
6	100	0.45	40	0.75	0.016	89.5
7	80	0.45	20	1	0.0168	88.5
8	100	0.45	40	1	0.016	88.25
9	85	0.45	30	1	0.0164	88.7
10	100	0.25	30	0.75	0.0163	89.75
11	80	0.25	20	0.75	0.0173	89
12	100	0.3	20	1	0.016	88.75
13	80	0.3	40	1	0.0168	88.5
14	80	0.25	40	0.5	0.0169	88.2
15	80	0.3	40	1	0.0168	88.5
16	100	0.25	40	1	0.016	88.75
17	80	0.3	20	0.5	0.018	89.5
18	80	0.45	40	0.5	0.0169	88.9
19	100	0.3	40	0.5	0.0163	89.5
20	80	0.45	30	0.75	0.0169	88.5
21	100	0.45	20	0.5	0.0162	89.7
22	85	0.25	40	0.75	0.0167	89

Results

This study evaluated the effects of four drying parameters drying temperature (A: 80–100°C), airflow rate (B: 0.25–0.45 m/s), chimney diameter (C: 20–40 mm), and chip thickness (D: 0.5–1.0 mm), on the drying rate and efficiency of plantain chips processed in a locally made tray dryer. A full quadratic model, selected for its superior fit to experimental data within a Response Surface Methodology (RSM) framework using Design-Expert software, was employed. The statistical significance of the models was determined via Analysis of Variance (ANOVA), with accuracy further substantiated through regression analysis, coefficients of determination (R^2), and diagnostic plots such as normal probability and residual distributions. The experimental design, based on a D-Optimal custom approach, yielded 22 runs, with the results presented in Table 1. However, Table 1 shows drying rates ranging from 0.0160 to 0.0180 kg/h and efficiencies from 88.25% to 90.1%. The highest drying rate (0.0180 kg/h) was achieved at 80°C, 0.3 m/s, 20 mm chimney diameter, and 0.5 mm thickness, suggesting optimal moisture removal at lower temperatures and thinner chips. Conversely, peak efficiency (90.1%) occurred at 100°C, 0.25 m/s, 20 mm, and 0.5 mm, indicating a potential trade-off between rapid drying and energy conservation

Coefficients in Terms of Coded Factors

Drying Rate

The coded coefficients (Table 2) quantify the influence of each factor on the drying rate, with the intercept (0.0167 kg/h) representing the average response across runs. Drying temperature exerted a significant negative effect (-0.0005, $p < 0.0001$), suggesting that higher temperatures may reduce drying rates, potentially due to surface hardening that impedes moisture diffusion Mujumdar. Airflow rate (-0.0001) and chimney diameter (-0.0001) also negatively affected drying rate, though with lesser magnitude, while chip thickness at 0.5 mm (D[1]: 0.0002) positively influenced it, reflecting reduced internal resistance (Akpinar, 2006). Interaction terms like AC (0.0001) and quadratic effects (A^2: 0.0002, B^2: -0.0004) indicate non-linear dynamics, critical for optimization. Variance Inflation Factors (VIFs < 1.74) confirm minimal multicollinearity, ensuring model reliability [46,47].

Table 2: Coefficients in Terms of Coded Factors for Drying Rate

Term	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	0.0167	1	0.0001	0.0165	0.0169	
A-Drying Temperature	-0.0005	1	0.0000	-0.0005	-0.0004	1.56
B-Air flow rate	-0.0001	1	0.0000	-0.0001	-0.0000	1.20
C-Chinmey Diameter	-0.0001	1	0.0000	-0.0001	-0.0000	1.48
D[1]	0.0002	1	0.0000	0.0002	0.0003	
D[2]	0.0000	1	0.0000	-0.0000	0.0001	
AB	-0.0000	1	0.0000	-0.0001	0.0000	1.41
AC	0.0001	1	0.0000	0.0001	0.0002	1.45
AD[1]	-0.0001	1	0.0000	-0.0002	-0.0000	
AD[2]	0.0000	1	0.0000	-0.0001	0.0001	
BC	4.891E-07	1	0.0000	-0.0000	0.0001	1.26
BD[1]	0.0000	1	0.0000	-0.0000	0.0001	
BD[2]	-0.0001	1	0.0000	-0.0002	-0.0001	
CD[1]	-0.0002	1	0.0000	-0.0002	-0.0001	
CD[2]	0.0001	1	0.0000	8.220E-06	0.0002	
A^2	0.0002	1	0.0001	0.0001	0.0004	1.59
B^2	-0.0004	1	0.0000	-0.0005	-0.0002	1.74
C^2	-0.0001	1	0.0000	-0.0002	0.0000	1.54

Drying Efficiency

For drying efficiency (Table 3), temperature (0.2310, $p = 0.0044$) and chip thickness (D[1]: 0.3547) were positive contributors, aligning with literature that higher temperatures enhance energy utilisation in thin-layer drying [48]. Airflow rate (-0.0988) and chimney diameter (-0.0974) negatively impacted efficiency, likely due to increased heat loss in the locally made dryer's design. Significant interactions (e.g., AB: -0.1402) and quadratic terms (e.g., A^2: -0.1452) suggest an efficiency plateau, with VIFs (< 1.74) indicating robust parameter independence.

Table 3: Coefficients in Terms of Coded Factors for Drying Efficiency

Term	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	89.22	1	0.1959	88.67	89.76	
A-Drying Temperature	0.2310	1	0.0462	0.1028	0.3592	1.56
B-Air flow rate	-0.0988	1	0.0417	-0.2147	0.0171	1.20
C-Chinmey Diameter	-0.0974	1	0.0452	-0.2228	0.0280	1.48
D[1]	0.3547	1	0.0615	0.1840	0.5254	
D[2]	0.1101	1	0.0607	-0.0585	0.2787	
AB	-0.1402	1	0.0496	-0.2780	-0.0024	1.41
AC	0.0929	1	0.0479	-0.0400	0.2259	1.45
AD[1]	0.1030	1	0.0613	-0.0673	0.2733	
AD[2]	0.1822	1	0.0676	-0.0055	0.3699	
BC	0.1301	1	0.0481	-0.0035	0.2637	1.26
BD[1]	0.1695	1	0.0601	0.0028	0.3363	
BD[2]	-0.1151	1	0.0561	-0.2709	0.0407	
CD[1]	-0.2416	1	0.0612	-0.4114	-0.0718	
CD[2]	0.1491	1	0.0701	-0.0455	0.3437	
A^2	-0.1452	1	0.1349	-0.5199	0.2294	1.59
B^2	-0.1183	1	0.1329	-0.4873	0.2506	1.74
C^2	0.0221	1	0.1081	-0.2779	0.3221	1.54

Analysis of Variance (ANOVA)
ANOVA was employed to evaluate model significance and the contribution of individual terms, offering a robust statistical framework for interpreting experimental variability [47].

Drying Rate
The drying rate model is highly significant (F = 82.66, p = 0.0003), with a 0.03% chance of noise interference (Table 4). Significant terms include A (p < 0.0001), B (p = 0.0021), C (p = 0.0023), D (p = 0.0007), interactions AC, AD, BD, CD, and quadratic terms A^2 and B^2 ($p < 0.05$). The R^2 of 0.9989 indicates an excellent fit, explaining 99.89% of the variability. However, the Predicted R^2 (0.1182) diverges markedly from the Adjusted R^2 (0.9972), suggesting overfitting, a recognised challenge in RSM with limited degrees of freedom [49]. The Adequate Precision ratio (37.970) exceeds 4, confirming the model's navigational reliability. Diagnostic plots (Figure. 3) show residuals aligning with a normal distribution, supporting model adequacy, though zero pure error in the lack-of-fit test indicates insufficient replication.

Table 4: Analysis of Variance Results for Drying Rate

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	4.859E-06	17	2.858E-07	82.66	0.0003	significant
A-Drying Temperature	2.943E-06	1	2.943E-06	851.09	< 0.0001	
B-Air flow rate	1.716E-07	1	1.716E-07	49.63	0.0021	
C-Chimney Diameter	1.647E-07	1	1.647E-07	47.64	0.0023	
D-chips thickness	5.186E-07	2	2.593E-07	74.99	0.0007	
AB	1.925E-09	1	1.925E-09	0.5566	0.4971	
AC	1.943E-07	1	1.943E-07	56.18	0.0017	
AD	9.441E-08	2	4.720E-08	13.65	0.0163	
BC	2.570E-12	1	2.570E-12	0.0007	0.9796	
BD	1.007E-07	2	5.037E-08	14.57	0.0146	
CD	2.479E-07	2	1.239E-07	35.84	0.0028	
A^2	7.129E-08	1	7.129E-08	20.62	0.0105	
B^2	1.774E-07	1	1.774E-07	51.30	0.0020	
C^2	1.859E-08	1	1.859E-08	5.38	0.0813	
Residual	1.383E-08	4	3.458E-09			
Lack of Fit	1.383E-08	2	6.916E-09			
Pure Error	0.0000	2	0.0000			
Cor Total	4.873E-06	21				

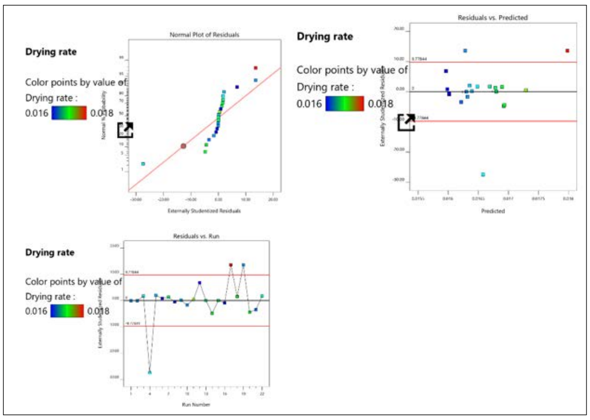


Figure 3: (a) Normal Probability-Residual; (b) Studentized Residuals-Predicted Response; (c) Studentized Residuals-Run

Drying Efficiency
The efficiency model (F = 16.07, p = 0.0078) is significant, with a 0.78% noise probability (Table 5). Key terms, A (p = 0.0044), B (p = 0.0462), C (p = 0.0159), D (p = 0.0030), AB, AD, and CD, account for 98.56% of the variability ($R^2 = 0.9856$). A negative Predicted R^2 implies the mean might outperform the model, potentially due to overfitting or unmodeled higher-order effects [49]. The Adequate Precision ratio (13.227) supports practical utility. Residual plots (Figure. 4) confirm normality and fit, though replication constraints persist.

Table 5: Analysis of Variance Results for Drying Efficiency

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	6.79	17	0.3995	16.07	0.0078	significant
A-Drying Temperature	0.8322	1	0.8322	33.47	0.0044	
B-Air flow rate	0.2025	1	0.2025	8.14	0.0462	
C-chimney Diameter	0.4015	1	0.4015	16.15	0.0159	
D-chips thickness	1.72	2	0.8591	34.55	0.0030	
AB	0.1984	1	0.1984	7.98	0.0476	
AC	0.0937	1	0.0937	3.77	0.1242	
AD	0.5916	2	0.2958	11.90	0.0207	
BC	0.1819	1	0.1819	7.31	0.0538	
BD	0.2140	2	0.1070	4.30	0.1007	
CD	0.3900	2	0.1950	7.84	0.0413	
A^2	0.0288	1	0.0288	1.16	0.3424	
B^2	0.0197	1	0.0197	0.7933	0.4234	
C^2	0.0010	1	0.0010	0.0419	0.8478	
Residual	0.0995	4	0.0249			
Lack of Fit	0.0995	2	0.0497			
Pure Error	0.0000	2	0.0000			
Cor Total	6.89	21				

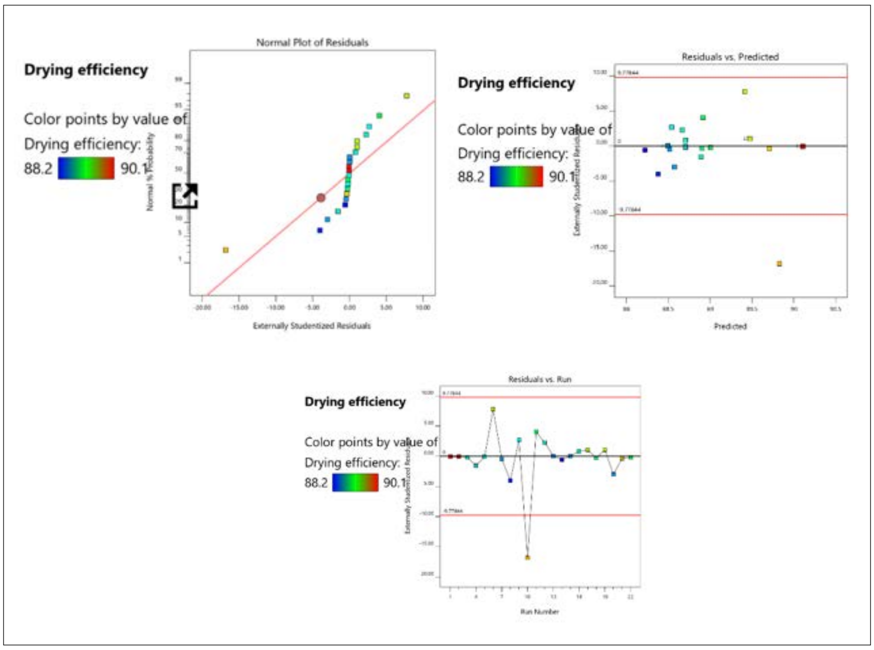


Figure 4: (a) Normal Probability-Residual; (b) Studentized Residuals-Predicted Response; (c) Studentized Residuals-Run

Contour Plots and Parameter Interactions

Contour plots elucidate parameter interactions. For drying rate (Figure. 5a), higher temperatures paired with lower airflow rates enhance rates, consistent with convective drying where excessive airflow may cool surfaces, reducing moisture removal. Meanwhile, for drying efficiency (Figure. 5b), lower airflow and temperature optimise energy use, reflecting the dryer's design efficiency in minimising heat loss.

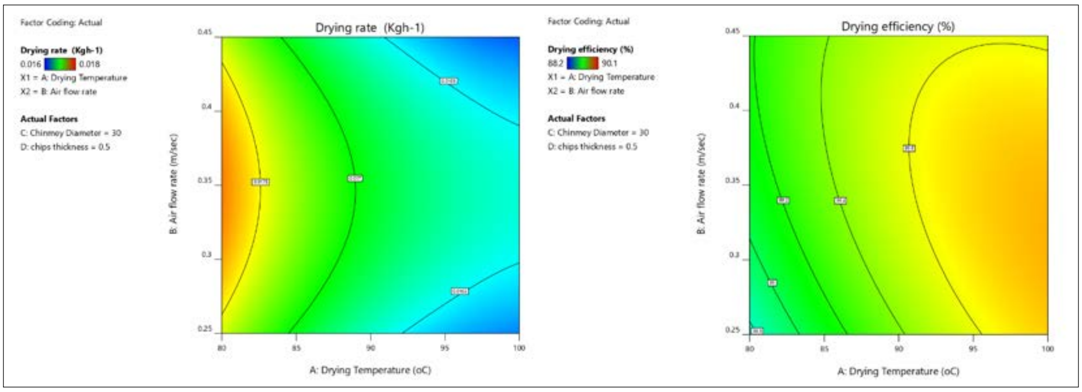


Figure 5: (a) Contour Plots of Drying Rate; (b) Contour Plots of Drying Efficiency

Optimisation

Optimisation via Design-Expert's desirability function maximised the drying rate and efficiency for the locally made tray dryer. Figure 4 displays contour plots of desirability, drying rate, and efficiency against drying temperature (80–100°C) and airflow rate (0.25–0.45 m/s), with chimney diameter and chip thickness fixed (21.9722 mm, 1 mm). Desirability peaked at 1.000 at 91.9775°C and 0.279371 m/s, predicting a drying rate of 0.0161177 kg/h and efficiency of 88.88%. Validation at these conditions (91.9775°C, 0.279371 m/s, 21.9722 mm, 1 mm) confirmed the predicted values with errors below 2.5%, affirming the model's predictive accuracy.

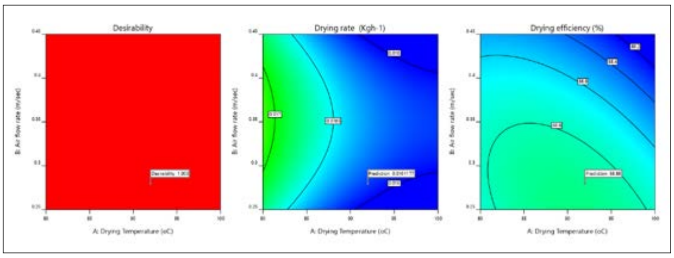


Figure 6: Optimization and Practical Implications

Discussion of Results

The findings of this study demonstrate that optimizing drying parameters using Response Surface Methodology (RSM) significantly enhances the drying efficiency and rate of plantain chips in a locally made tray dryer. The highest drying rate (0.0180 kg/h) was achieved at lower temperatures (80°C) and thinner chip thicknesses (0.5 mm), suggesting that reduced internal resistance facilitates faster moisture removal (Akpinar, 2006). Conversely, the highest drying efficiency (90.1%) was observed at higher temperatures (100°C) and lower airflow rates (0.25 m/s), indicating a trade-off between rapid drying and energy conservation. These results align with previous studies, which emphasize that controlled drying conditions are crucial for maintaining product quality while minimizing energy consumption [41,46]. The negative impact of higher airflow rates on drying efficiency, as observed in this study, can be attributed to increased heat loss in the dryer's design, a common issue in locally made systems [25]. The interaction between drying temperature and airflow rate further highlights the complexity of optimizing drying processes, as excessive airflow can cool the product surface, reducing moisture diffusion (Mujumdar, 2014). These findings underscore the importance of balancing drying parameters to achieve both energy efficiency and product quality, particularly in resource-constrained settings where cost-effective solutions are paramount [27,50].

Conclusion

This study successfully optimized drying parameters for plantain chips using a locally made tray dryer, achieving a maximum drying rate of 0.0180 kg/h at 80°C and 0.5 mm thickness, and peak efficiency of 90.1% at 100°C and 0.25 m/s airflow [25]. RSM effectively identified optimal conditions (91.9775°C, 0.279371 m/s), enhancing energy efficiency and quality retention [41]. These findings offer a scalable, cost-effective solution for small-scale processors, reducing post-harvest losses and improving marketability [27].

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Disclosure

The authors state that there are no conflicts of interest in this study

Author Contributions

All the authors contributed to the development of the work. All authors read and approved the final manuscript.

Declaration of Interests

The authors declare that none of the work described in this study could have been influenced by any known competing financial interests or personal relationships.

References

1. Lescot T, Ganry J (2008) Plantain (Musa spp.) cultivation in Africa: A brief summary of developments over the previous two decades. IV International Symposium on Banana. International Conference on Banana and Plantain in Africa: Harnessing International 879: 445-455.
2. Manzo-Sánchez G, Buenrostro-Nava MT, Guzmán-González S, Orozco-Santos M, Youssef M, et al. (2015) Genetic diversity in bananas and plantains (Musa spp.). Molecular Approaches to Genetic Diversity 93-121.
3. Khanvilkar AM, Kamble AB, Ranveer RC, Ghosh JS, Sahoo AK (2016) Effect of frying media and primary packaging material on shelf life of banana chips. International Food Research Journal 23: 284.
4. Maziya-Dixon B, Alamu EO, Popoola IO, Yomeni M (2017) Nutritional and sensory properties: Snack food made from high-quality cassava flour and legume blend. Food Science & Nutrition 5: 805-811.
5. Olutomilola EO (2021) A review of raw plantain size reduction. Scientific African, 12, e00773.
6. Ezechukwu VC, Oghenekaro PO, Onyenanu IU, Ayadinuno

G, Agwaziam JO (2025) Mathematical Modeling and Optimization of Plantain Chip Drying: A Parametric Study on Air Frying Conditions. IPS Journal of Engineering and Technology 1: 42-52.

7. Onyenanu IU, Ukwu NO, Ezechukwu VC, Onyenanu IM, Nwadiuto CJ (2024) Modelling and Optimization of Banana/Plantain Fiber Extraction Systems through Dimensional Analysis. International Journal of Applied and Natural Sciences 2: 40-52.
8. Akinyemi SOS, Aiyelaagbe IOO, Akyeampong E (2008) Plantain (Musa spp.) cultivation in Nigeria: A review of its production, marketing and research in the last two decades. IV International Symposium on Banana: International Conference on Banana and Plantain in Africa: Harnessing International 879: 211-218.
9. Adi DD (2024) The role of plantain in promoting food security: A review. Food and Nutrition Sciences 15: 313-335.
10. Baidhe E, Clementson CL, Senyah J, Hammed A (2024) Appraisal of Post-Harvest Drying and Storage Operations in Africa: Perspectives on Enhancing Grain Quality. Agri Engineering 6: 3030-3057.
11. Sahdev RK (2014) Open sun and greenhouse drying of agricultural and food products: A review. International Journal of Engineering Research 3.
12. Qu H, Masud MH, Islam M, Khan MIH, Ananno AA, et al. (2022) Sustainable food drying technologies based on renewable energy sources. Critical Reviews in Food Science and Nutrition 62: 6872-6886.
13. Maisnam D, Rasane P, Dey A, Kaur S, Sarma C (2017) Recent advances in conventional drying of foods. Journal of Food Technology and Preservation 1: 25-34.
14. Calín-Sánchez Á, Lipan L, Cano-Lamadrid M, Kharaghani A, Masztalerz K, et al. (2020) Comparison of traditional and novel drying techniques and their effect on the quality of fruits, vegetables and aromatic herbs. Foods 9: 1261.
15. Fuller RJ (2000) Solar drying-a technology for sustainable agriculture and food production. Solar Energy Conversion and Photoenergy Systems 3: 1755-1315.
16. Tiwari A (2016) A review on solar drying of agricultural produce. Journal of Food Processing & Technology 7: 01-12.
17. Guiné R (2018) The drying of foods and its effect on the physical-chemical, sensorial and nutritional properties. International Journal of Food Engineering 2: 93-100.
18. Bhuyan J, Mohanty DK, Jayapuria D (2019) Comparative Study between solar dryer and open sun-dried tomato under north plateau climatic zone. Journal of Krishi Vigyan 8: 28-33.
19. Raitila J, Tsupari E (2020) Feasibility of Solar-Enhanced Drying of Woody Biomass. BioEnergy Research 13: 210-221.
20. Rajkumar P, Kulanthaisami S, Raghavan GSV, Gariépy Y, Orsat V (2007) Drying Kinetics of Tomato Slices in Vacuum Assisted Solar and Open Sun Drying Methods. Drying Technology 25: 1349-1357.
21. Adenitan A, Awoyale W, Akinwande AB, Maziya-Dixon B (2022) Influence of drying methods on heavy metal composition and microbial load of plantain chips. Cogent Food & Agriculture 8: 2113205.
22. Edeani NJ, Anyaene HI (2023) Optimization of Hot Air Drying of Sweet Potato using Response Surface Method. https://doi.org///doi.org/10.29294/IJASE.10.2.2023.3362-3371.
23. Majdi H, Esfahani JA, Mohebbi M (2019) Optimization of convective drying by response surface methodology. Computers and Electronics in Agriculture 156: 574-584.
24. Adie IGE, Inyang UE (2024) Response Surface Methodology for The Optimization of Sweet Potatoes (Ipomoea batatas) Drying Process Conditions. Journal of Modern Technology and Engineering 9: 16-24.
25. Muritala A, Obayopo S, Odediran S (2022) A study of a forced convective biomass dryer for plantain chips. Agricultural Engineering International: CIGR Journal https://cigrjournal.org/index.php/Ejounral/article/view/8243.
26. Owolarafe OK, Bello TK, Ogunsina BS, Falana OB, Adetifa BO, et al. (2021) Performance evaluation of a small-scale dryer for agricultural products. Agricultural Engineering International: CIGR Journal 23.
27. Akowuah JO, Owusu G, Obeng-Akrofi G, Adjei PD (2023) Comparative assessment of three low-capacity drying systems using the analytical hierarchy process. Journal of the Ghana Institution of Engineering 23: 17-25.
28. Kimaro D, Nyangarika A, Kivevele T (2024) Uncovering socioeconomic insights of solar dryers for sustainable agricultural product preservation: A systematic review. Heliyon. https://doi.org/10.1016/j.heliyon.2024.e40726.
29. IFAD (2013) Smallholders, food security, and the environment. https://www.ifad.org/documents/38714170/39135645/smallholders_report.pdf/133e8903-0204-4e7d-a780-bca847933f2e.
30. Akubor PI, Adejo EE (2000) Physicochemical, microbiological and sensory changes in stored plantain chips. Plant Foods for Human Nutrition 55: 139-146.
31. Bolarin FM, Bosa SO (2015) Post-harvest losses: A dilemma in ensuring food security in Nigeria. https://www.cabidigitallibrary.org/doi/full/10.5555/20153202099.
32. Okoroigwe EC, Ndu EC, Okoroigwe FC (2015) Comparative evaluation of the performance of an improved solar-biomass hybrid dryer. Journal of Energy in Southern Africa 26: 38-51.
33. Morshedi A, Akbarian M (2014) Application of response surface methodology: Design of experiments and optimization: a mini review. Indian Journal of Fundamental and Applied Life Sciences 4: 2434-2439.
34. Kodiyalam S, Lin J, Wujek B (1998) Design of Experiments based response surface models for design optimization. 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit. 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit, Long Beach,CA,U.S.A. https://doi.org/10.2514/6.1998-2030.
35. Madamba PS (2002) The response surface methodology: An application to optimize dehydration operations of selected crops. LWT-Food Science and Technology, 35: 584-592.
36. Méndez Calderón EK, Ocampo Castaño JC, Orrego CE (2018) Optimization of convective drying assisted by ultrasound for Mango Tommy (Mangifera indica L) Journal of Food Process Engineering e12634. https://doi.org/10.1111/jfpe.12634.
37. Panigrahi SS, Luthra K, Singh CB, Atungulu G, Corscadden K (2023) On-farm grain drying system sustainability: Current energy and carbon footprint assessment with potential reform measures. Sustainable Energy Technologies and Assessments 60: 103430.
38. Udomkun P, Romuli S, Schock S, Mahayothee B, Sartas M, et al. (2020) Review of solar dryers for agricultural products in Asia and Africa: An innovation landscape approach. Journal of Environmental Management 268: 110730.

39. Devahastin S, Niamnuy C (2010) Invited review: Modelling quality changes of fruits and vegetables during drying: a review. International Journal of Food Science and Technology 45: 1755-1767.
40. Omolola AO, Jideani AIO, Kapila PF (2017) Quality properties of fruits as affected by drying operation. Critical Reviews in Food Science and Nutrition 57: 095-108.
41. Vega Gálvez A, Ah Hen K, Chacana M, Vergara J, Martínez Monzó J, et al. (2012) Effect of temperature and air velocity on drying kinetics, antioxidant capacity, total phenolic content, colour, texture and microstructure of apple (var. Granny Smith) slices. Food Chemistry 132: 51-59.
42. Adeyanju JA, Olajide JO, Adedeji AA (2016) Optimisation of deep-fat frying of plantain chips (ipekere) using response surface methodology. https://www.researchgate.net/publication/312122100_Optimisation_of_Deep-Fat_Frying_of_Plantain_Chips_Ipekere_using_Response_Surface_Methodology.
43. Onyejegbu CA, Olorunda AO (1995) Effects of raw materials, processing conditions and packaging on the quality of plantain chips. Journal of the Science of Food and Agriculture 68: 279-283.
44. Montgomery DC, Loredo EN, Jearkpaporn D, Testik MC (2002) Experimental Designs for Constrained Regions. Quality Engineering 14: 587-601.
45. Willden C, Jensen WA (2020) Optimal designs with axial values. Journal of Quality Technology 52: 235-248.
46. O'brien RM (2007) A Caution Regarding Rules of Thumb for Variance Inflation Factors. Quality & Quantity 41: 673-690.
47. Montgomery DC (2017) Design and analysis of experiments. John wiley & sons. https://books.google.com/s?hl=en&lr=&id=Py7bDgAAQBAJ&oi=fnd&pg=PA1&dq=Montgomery,+D.+C.+(2017).+Design+and+Analysis+of+Experiments+(9th+ed.).+Wiley&ots=X8t-q_JV-3&sig=YuzQkSXVf3SHudOBGTnflLbfV20.
48. Fellows PJ (2022) Food processing technology: Principles and practice. Woodhead publishing. https://www.webpal.org/SAFE/aaarecovery/2_food_storage/Food%20Processing%20Technology.pdf.
49. Myers RH, Montgomery DC, Anderson-Cook CM (2016) Response surface methodology: Process and product optimization using designed experiments. John Wiley & Sons. https://www.wiley.com/en-hk/+Surface+Methodology%3A+Process+and+Product+Optimization+Using+Designed+Experiments%2C+4th+Edition-p-9781118916018.
50. Ukwu NO, Onyenanu IU, Owuama KC (2024) Development of a Low-Cost Banana Fiber Extractor. International Journal of Innovative Science and Research Technology (IJISRT) 1672-1681.