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Assessing the Interaction of Blanching and Drying Parameters in Yam Drying through Response Surface Methodology

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ABSTRACT

Blanching facilitates thermal energy utilization in yam drying by softening the tissue structure, so that heat penetrate more efficiently to minimize drying time. Higher drying temperatures further improve thermal energy utilization by accelerating moisture removal, though excessively high temperatures may reduce energy efficiency and product quality. The aforementioned conditions, including blanching time, has not been collectively run in any Response Surface Methodology (RSM) tool prior to this study, to test their effect on yam drying. In this study, Central Composite Design (CCD) in Design Expert 7.0 software was employed to assess the moisture content as response variable. Yam slices of 7–8 mm thickness were blanched at varying temperatures (70–90°C) and durations (15–35 min) and subsequently dried in a hot air tray dryer at temperatures between 50–70°C for 4–10 h. The quadratic model showed an excellent fit with an R^2 value of 0.9750 and 95% confidence intervals. Among the tested interactions, the combination of blanching temperature and blanching duration exhibited a strong synergistic effect on moisture removal efficiency. The optimal conditions – blanching at 90°C for 23.9 min and drying at 70°C for 10 h, resulted in a minimum moisture content of 3.99% with a desirability of 0.812. It further signifies a high thermal efficiency and minimal energy loss. Hence, the findings demonstrate the process's potential for yam flour production, due to its effective dehydration, nutrient preservation, and energy-efficient drying performance. Attention must be given to differences in yam types, which currently includes, white yam, yellow yam, bitter yam, water yam and three-leaved yam, when opting for drying RSM, kinetics and thermodynamic studies.

1. INTRODUCTION

Nigeria is the world's leading producer of yam, yielding over 45.004 million metric tonnes annually. Factors affecting yam production and post-harvest handling in Nigeria are limited finance, inputs, and storage constrain productivity [1]. An improved access to information, technologies, and government support through subsidies and affordable loans can enhance sustainable yam production and value addition [2]. Yam farming in southern Nigeria is deeply influenced by indigenous socio-cultural beliefs and practices, as elderly farmers rely on traditional methods, informal networks, and community cooperation [3]. Peeling remains largely unmechanized compared to other processes, based on the features, performance, and limitations of existing designs highlighted by Oladipo et al. [4]. Yam flour production involves cleaning, peeling, slicing, drying, and milling yam tubers into fine powder for use in various food preparations. It provides a convenient and storable form of yam, which reduces post-harvest losses and extend shelf life. The process also supports rural industries by creating employment and adding value to locally produced yams. Previous experiment by Adeleye et al. [5] found that 12% moisture, 576 rpm shaft speed, and 5200 mm^2 feed opening are the ideal conditions for optimized dry yam milling using response surface methodology (RSM). Social relations in yam flour distribution in Lagos and Oyo States of Nigeria, is driven by associations-guided interactions among actors, and Olawore [6] says that

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market failures and self-interest weaken cooperation, to enhance collaboration and productivity. Different drying methods affect the physicochemical, functional, and rheological properties of yam flour [7]. Li et al. [8] reveals how microwave-assisted drying alters the composition, viscosity and the texture of yam. The high bacterial, fungal, and heavy metal contamination in samples of yam flakes, chips and flour discovered in Nigeria by Omohimi et al. [9] is attributed to drying, storage and handling. Because, moisture plays a key role in promoting microbial growth and contamination during the processing and storage of yam chips, flakes, and flour. Thermal energy is utilized in drying to supply the heat required to evaporate moisture from yam products, reducing their water content to safe storage levels. The drying time determines how efficiently this moisture is removed. Short drying time may leave excess moisture that encourages spoilage, and longer drying periods degrade nutrients and texture. In this case, sufficient drying ensures product stability, extended shelf life, and improved quality of the final yam product [10].

Thermal energy utilization in yam drying refers to the efficient use of heat to remove moisture from yam slices while preserving their nutritional and physical qualities. The effectiveness of this process depends on drying parameters which influence the rate of heat and mass transfer. According to Nwosu-Obieogu et al. [11], the energy and exergy analysis of three-leaved yam starch drying showed that optimizing temperature, time, air velocity, and sample thickness improves drying efficiency, minimizes exergy loss, and enhances sustainability. Under optimal conditions, the process achieved high energy efficiency of 75.09% and exergy efficiency of 99.22%. In convective hot air drying of water yam, increasing air temperature and optimizing slice thickness raises the drying rate, energy and exergy efficiencies and the overall sustainability, with Midilli's model providing the best fit for predicting moisture behavior [12]. Optimizing thermal energy utilization not just reduces energy consumption and processing time but also enhances product quality and sustainability in yam drying operations. Ojediran et al. [13] indicates that the activation energy for yam drying increased with rising air velocity but showed fluctuations across different temperatures and slice thicknesses, ranging between 10.59 and 54.93 kJ/mol. Response Surface Methodology (RSM) methodology application in drying of yam is not new [14]. Normally, the drying technique, selection of influential parameters and design method are often divergent in RSM studies on yam drying [15]. This research focuses on yam flour production from yam samples, optimizing drying conditions and the determination of the nutritional quality of the dried yam produced at the optimal condition of blanching and drying times and temperature. Because, the nutritional quality of yam during drying can be improved by optimizing drying time and conditions to maximize vitamin C retention and minimize nutrient loss [16]. Using a hot air dryer reduced the drying time of yam chunks to 6 h, compared to 5–7 days for sun drying and 2 days for other conventional drying methods, according to Aasa et al. [17]. One major contribution of this research is the study of blanching conditions. Blanching in yam processing is a pre-treatment method that involves briefly boiling the yam slices in hot water to inactivate enzymes, enhance texture and color, and improve drying or frying quality [18].

2. METHODOLOGY

2.1 Materials

White yam was purchased from local market in Yola, Nigeria. Equipment employed are tray dryer, mercury thermometer, measuring cylinder, stainless steel knife, water heater, plastic sieves, Vernier caliper and meter rule.

2.2 Yam Chip Formation and Drying Operation

Yam tubers were selected (as shown in Figure 1a), peeled and washed, as reported by Olagunju-Yusuf et al. [19]. It was then cut into smaller particles using a stainless-steel knife to 5-6 cm in size lengths, as conducted by Sobukola et al. [20]. A meter rule was used to determine the lengths mentioned. As for the thickness, Vernier caliper was used to ensure a thickness of 7-8 mm, close to 6 mm employed in Zhang et al. [21] or 10 mm in Abud-Archila et al. [22]. A total of 10 chips per yam sample was produced before blanching. During blanching, 1500 cm^3 of clean water was measured and heated to 70°C. The yam chips were introduced into the hot water for 15, 25 and 35 min (in separate runs). Blanching was repeated for water heated to 80 and 90°C, in line with the procedure reported in Nwadike et al. [23]. After blanching, the yam chips were then drained using a sieve. Following this step, the chips were spread on trays and loaded into the dryer for further processing (Figure 1b).

Before drying, the dryer was pre-heated to 50°C. A temperature regulator ensures the drying chamber's stability before introducing the yam chips. The samples were dried for 4, 7 and 10 h in accordance with the number of runs specified by a Design Expert 7.0 software by weighing at every 1-hour interval. Figure 1c shows the dried yam chips obtained. Via a top loading balance, the weights were recorded. The process was repeated for different samples at 60 and 70°C based on the 21 runs given by Design Expert 7.0 employed previously by Adejumo et al. [24]. Actually, the reported air drying temperature of 50, 60 and 70°C in Ojediran et al. [13], was adopted. The air flow velocity was kept constant at 2 m/s throughout the drying process, as outlined in Figure 1d and in Amedor et al. [25]. In a nutshell, the 3 time and temperature conditions for both blanching and drying of yam chips was set as range of values.

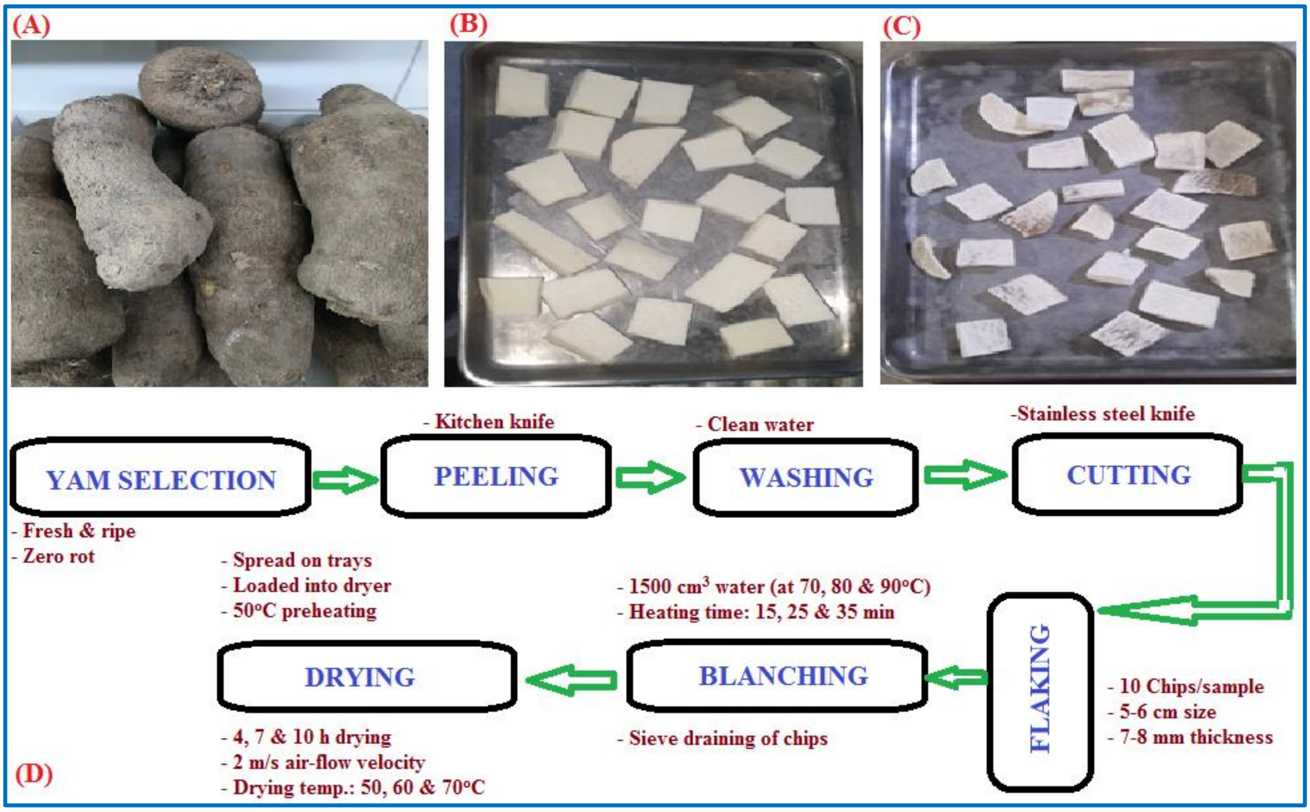

Fig. 1. Yam Samples and Drying Conditions Employed

2.3 Optimization of Drying Condition

Within the software, Central Composite Design (CCD) under RSM was selected. So that, the range of the 4 factors or independent variables, including blanching temperature (70-90℃), blanching duration (15-35 min), drying temperature (50-70℃) and drying time (4-10 h) can be specified. The drying temperature between 50-70℃ was also run by Wang et al. [26]. Small CCD, which are minimal point design that are very sensitive to outliers was employed. Small CCD was selected to minimize experimental runs. The aforementioned variables or conditions were related to moisture content (or response variable) which determine the rate at which the sample get dried. At this juncture, the software is expected to give the number of parameter combinations for a 21-run experiment. It is 21 runs because the center points, replicates of factorial points and replicates of axial (star) points specified were 5, 1 and 1 respectively, for a rotatable ($k < 6$) = 1.68179 designs. After running the experiment for the random combinations, the moisture content was later inputted to analyze the data statistically. The effect of the process variables on optimized yam drying was determined by analyzing the analysis of variance (ANOVA), contour diagram, 3D surface plot, regression model suggested, desirability, optimal combination and the fit quality.

3. RESULT AND DISCUSSION

3.1 Factorial DOE Runs and Fit Summary

Both blanching and drying parameters interact strongly to influence yam moisture reduction, with temperature and time being the most critical factors for achieving efficient drying. Table 1 presents a 4-factor Design of Experiment (DOE) used to optimize the drying process of yam by evaluating the combined effects of blanching temperature, blanching duration, drying temperature, and drying time on the final moisture content. Respectively, they are tagged 'A', 'B', 'C' and 'D'. The blanching temperature varied between 63.2 and 96.8℃, while blanching duration ranged from 8.2-41.8 min, in order to capture both mild and intense pretreatment conditions. Sobukola et al. [20] reported how drying pretreatment influences oil and moisture contents, breaking force, and color characteristics of yam chips. Similarly, drying temperature spanned from 43.2-76.8℃, and drying time from 2-12 h, for a comprehensive analysis of drying kinetics. In a study by Chinedu [7], for 100 g of sample and between 50-60℃ drying temperature, the MC ranged from 75-83.6%. Table 1 indicate that the lowest moisture content (0%) occurred at a drying time of 12 h, showing that prolonged drying facilitates moisture removal. Moisture content reported as 0% is interpreted as below the detection limit of the weighing method, since complete removal of bound water is thermodynamically unattainable in hot air drying systems. Conversely, the highest moisture content (19.21 %) was observed at lower drying temperatures (50℃) and shorter drying durations (4 h), which points to the inefficiency of mild drying conditions. Runs with moderate blanching (around 80℃ for 25 min) and drying at 60–70℃ for 7–10 h produced optimal results with moisture contents around 9%.

Table 1. Four-Factor DOE for Yam Drying Optimization

		Factor A	Factor B	Factor C	Factor D	Response 1
Std	**Run**	**Blanching Temperature (℃)**	**Blanching Duration (min)**	**Drying Temperature (℃)**	**Drying Time (h)**	**Moisture Content (%)**
7	1	70	35	70	10	1.6
9	2	63.2	25	60	7	9.72
10	3	96.8	25	60	7	8.91
19	4	80	25	60	7	9.26
1	5	90	35	70	4	16.92
13	6	80	25	43.2	7	11.02
15	7	80	25	60	2	9.27
18	8	80	25	60	7	9.27
12	9	80	41.8	60	7	9.8
6	10	70	15	70	4	17.3
16	11	80	25	60	12	0
2	12	90	35	50	4	18.95
5	13	90	15	50	10	3.8
17	14	80	25	60	7	9.26
14	15	80	25	76.8	7	7.05
21	16	80	25	60	7	9.26
8	17	70	15	50	4	19.21
11	18	80	8.2	60	7	9.04
3	19	90	15	70	10	0.52
4	20	70	35	50	10	2.61
20	21	80	25	60	7	9.26

Design expert additionally summarizes the sequential model sum of squares (SS) used to evaluate the adequacy and complexity of statistical models for yam drying optimization. The comparison begins with the mean model, which accounts for the largest portion of variation (SS = 1755.98), followed by the linear model that significantly improves the fit with an F-value of 13.83 and a very low p-value (< 0.0001), indicating strong statistical significance. The two-factor interaction (2FI) model further enhances the prediction with a p-value of 0.0552, which suggest it may be relevant though marginally vital at the 95% confidence level [27]. In Table 2, quadratic model adds a modest improvement (F = 3.21, p = 0.0982), which indicates limited additional contribution beyond the 2FI model. However, the cubic model shows an abnormally high F-value (386482.21) and a p-value < 0.0001, indicating it is aliased—meaning it likely overfits the data or duplicates lower-order terms. The residual SS is extremely small (8×10^{-5}), implying a good overall model fit. Therefore, the linear and 2FI models are statistically suggested by Design Expert as the most appropriate for describing the drying process behavior without overfitting.

Table 2. Sequential Model Sum of Squares (MSS)

Comparison	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**Prob > F (p-value)**	
Mean vs Total	1755.977186	1	1755.977186			
Linear vs Mean	480.4571461	4	120.1142865	13.82825694	< 0.0001	Suggested
2FI vs Linear	90.41132254	6	15.06855376	3.102629273	0.0552	Suggested
Quadratic vs 2FI	33.10767741	4	8.276919352	3.212389752	0.0982	
Cubic vs Quadratic	15.45928824	2	7.729644122	386482.206	< 0.0001	Aliased
Residual	8E-05	4	2E-05			
Total	2375.4127	21	113.1148905			

Lack of Fit tests is used to evaluate how well different models describe the yam drying experimental data. The linear model shows a very high F-value of 579,076.20 with a p-value < 0.0001, indicating that it provides a statistically good fit to the data and is therefore suggested. Similarly, the 2FI model also demonstrates a strong fit, with an F-value of 404,724.71 and a p-value below 0.0001, to confirm its suitability for explaining variations in the response. The quadratic model continues this trend with an F-value of 386,482.21 and p-value (< 0.0001), although the improvement over the 2FI model is relatively small. As for the cubic model, it is aliased because it includes redundant terms and cannot be properly evaluated due to model over-parameterization. In Table 3, the pure error term has a very low SS (8×10^{-5}), which signifies a minimal unexplained variation in the data.

Table 3. Lack of Fit Tests

Model	Sum of Squares	df	Mean Square	F Value	Prob > F (p-value)	
Linear	138.9782882	12	11.58152402	579076.2008	< 0.0001	Suggested
2FI	48.56696565	6	8.094494275	404724.7138	< 0.0001	Suggested
Quadratic	15.45928824	2	7.729644122	386482.2061	< 0.0001	
Cubic	0	0				Aliased
Pure Error	8E-05	4	2E-05			

Lack of fit tests in Table 3 confirms that the linear and 2FI models provide adequate and statistically weighty descriptions of the system without unnecessary complexity. Therefore, it is recommended for accurate prediction and optimization of the yam drying process. Table 4 divulge the model summary statistics used to assess the performance and predictive capability of different models for yam drying optimization. Quadratic model shows the highest coefficient of determination (R^2 = 0.9750), indicating an excellent fit between the predicted and experimental data compared to the linear (R^2 = 0.7756) and 2FI (R^2 = 0.9216) models. Although its adjusted R^2 (0.9168) is slightly lower, it still demonstrates strong model reliability, and suggest that most variations in moisture content are well explained by the quadratic relationship. Despite the negative predicted R^2 (-1.9192), which suggests limited predictive performance outside the experimental range, the low standard deviation (1.6052) indicates consistent model accuracy within the tested domain.

Table 4. Model Summary Statistics

Model	Std. Dev.	R^2	Adjusted R^2	Predicted R^2	PRESS	
Linear	2.947227173	0.775637068	0.719546335	0.560794023	272.0597804	Suggested
2FI	2.203793222	0.92159467	0.843189341	-0.054255481	653.043286	Suggested
Quadratic	1.605167086	0.975042813	0.916809375	-1.919214184	1808.264939	
Cubic	0.004472136	0.999999871	0.999999354		+	Aliased

The cubic model, although showing an almost perfect R^2 value (0.9999), is aliased and thus not suitable for interpretation due to overfitting. Considering both the high R^2 and reasonable model stability, the quadratic model is preferred for capturing the non-linear effects among blanching and drying parameters in yam drying optimization. For that reason, the ANOVA results for the quadratic response surface model were reported.

3.2 ANOVA, Response Model and Statistical Metric

ANOVA gives an F-value of 16.74 and a p-value of 0.0012. By confirmation the quadratic model effectively explains variations in moisture content. Among the individual factors, drying temperature (C) and drying time (D) have serious effects on the response, with p-values of 0.0457 and 0.0065, respectively, indicating that they are the most influential parameters. The interaction between blanching temperature (A) and blanching duration (B) is also highly significant (p = 0.0011), and suggest a strong combined effect of these pretreatment conditions on drying performance. The quadratic term of drying time (D^2) is significant (p = 0.0419), in line with a nonlinear relationship between D and final moisture content. Other factors and interaction terms show higher p-values (> 0.05) in Table 5, simply because they have minimal or no observable influence on the response [21]. ANOVA confirms that the quadratic model fits well, with drying temperature, drying time, and their interaction effects being the dominant contributors to yam drying efficiency.

Table 5. ANOVA for Response Surface Quadratic Model

	Sum of Squares	df	Mean Square	F Value	Prob > F (p-value)	
	603.976146	14	43.14115329	16.74369325	0.0012	significant
A	0.32805	1	0.32805	0.127320856	0.7334	
B	0.2888	1	0.2888	0.112087375	0.7492	

C	16.26979363	1	16.26979363	6.314537584	0.0457	
D	42.96645	1	42.96645	16.67588843	0.0065	
AB	88.6642625	1	88.6642625	34.41185737	0.0011	
AC	0.7140125	1	0.7140125	0.277118375	0.6175	
AD	0.338773745	1	0.338773745	0.131482894	0.7293	
BC	0.5778125	1	0.5778125	0.224257224	0.6526	
BD	0.101148792	1	0.101148792	0.03925728	0.8495	
CD	0.0153125	1	0.0153125	0.005942998	0.9411	
A^2	5.085546528	1	5.085546528	1.973772711	0.2096	
B^2	5.753950834	1	5.753950834	2.233189899	0.1857	
C^2	3.504829025	1	3.504829025	1.360273836	0.2877	
D^2	17.11228628	1	17.11228628	6.641520923	0.0419	
Residual	15.45936824	6	2.576561374			
Lack of Fit	15.45928824	2	7.729644122	386482.2061	< 0.0001	significant
Pure Error	8E-05	4	2E-05			
Cor Total	619.4355143	20				

Despite significant lack of fit ($p < 0.0001$), the quadratic model was retained due to its ability to capture curvature effects. Cubic model was aliased and therefore unsuitable for reliable interpretation. Box–Wilson RSM framework accepts quadratic models when cubic models are aliased or impractical. The standard deviation of 1.605 indicates that the experimental data points are closely distributed around the model's predicted values, for good accuracy, in consonance with 3.45 and 1.15 obtained by Nwosu-Obieogu et al. [11] for energy and exergy studies, respectively. Model summary statistics (Table 4) are presented separately from fit diagnostics (Table 6) to distinguish between model selection criteria and performance evaluation of the chosen quadratic model. The mean moisture content of 9.144 shows the average response level in Table 6, automatically serving as a reference point for assessing variation in drying performance. The coefficient of variation (C.V.) of 17.55% reflects moderate variability, which is acceptable for biological and drying experiments, implying the model results are reasonably consistent. A C.V. of 17.55% reflects moderate experimental variability even with reduced precision in predictive accuracy. As for the Predicted Residual Error Sum of Squares (PRESS) value of 1808.265, it is relatively high closer to findings of Nwadike et al. [23], which suggest that the model may not predict unseen data as effectively as it fits the current dataset. The negative predicted R^2 indicates weak extrapolative capability, therefore model application is restricted strictly to the experimental design space. However, the adequate precision value of 13.87, which is well above the threshold of 4, indicates a strong signal-to-noise ratio and confirms the model's suitability for navigating the design space [28]. As such, the predictive ability of the model outside the tested conditions may require further improvement or validation.

Table 6. Fit Statistics

Metric	Value
Std. Dev.	1.605167
Mean	9.144286
C.V. %	17.55377
PRESS	1808.265
R^2	0.975043
Adj. R^2	0.916809
Pred R^2	-1.91921
Adeq. Precision	13.87014

The final equation in terms of coded (i.e., Equation 1) or actual factors (Equation 2) is presented. Equation 1 simplifies interpretation by normalizing the variables within a fixed range (typically –1 to +1). It portrays an easier comparison of each factor's influence on the response. The coefficients show that drying temperature (C) and drying time (D) have the most significant negative effects. This means higher values of the aforementioned parameters strongly reduce moisture content. Previously, a hot air dryer improved nutrient levels and hygiene of yam chunk by preventing mucus growth, based on the 6 h drying by Aasa et al. [17]. The positive coefficient for the AB interaction (+5.20) indicates that blanching temperature and duration jointly enhance moisture removal efficiency. Among interaction terms, only blanching temperature–duration interaction showed statistical significance, indicating limited interaction dominance across the full parameter space. But the negative interaction terms such as BD (–0.17) and CD (–0.044) suggest slight antagonistic effects. Moreso, the quadratic terms (A^2, B^2, C^2 & D^2) reflect the curvature of the response surface, with the negative D^2 coefficient (–1.09) confirming a nonlinear relationship between drying time and residual moisture.

Equation 2 goes ahead to express the same model in actual experimental units (°C, minutes, and hours). It is suitable for predicting real-world moisture content under specific processing conditions. Table 7 presents the Confidence Intervals (CI) and Variance Inflation Factors (VIF) for the coefficients in the quadratic model developed to predict yam moisture content. The intercept value of 8.75 represents the average moisture content when all coded factors are at their central levels, i.e., the model's baseline prediction. Factors C (drying temperature) and D (drying time) have negative coefficients (–1.09 and –2.78, respectively) with 95% CI that do not include zero. That is to say, both reduce moisture content during drying. The positive coefficient for the interaction term AB (5.20) and its narrow CI (3.03 to 7.37) show a strong synergistic effect between blanching temperature and blanching duration, as shown in Table 7.

Table 7. CI and VIF of Model Coefficients

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	8.746337301	1	0.686127843	7.06744301	10.42523159	
A	-0.241071429	1	0.67560984	-1.894229094	1.412086237	2.417234
B	0.226190476	1	0.67560984	-1.42696719	1.879348142	2.417234
C	-1.091961773	1	0.434546903	-2.155259701	-0.028663845	1
D	-2.781	1	0.681014719	-4.447382927	-1.114617073	2.44
AB	5.20025	1	0.886482498	3.031105547	7.369394453	2.44
AC	-0.29875	1	0.567512266	-1.687402439	1.089902439	1
AD	0.319940476	1	0.88233714	-1.83906065	2.478941603	2.417234
BC	0.26875	1	0.567512266	-1.119902439	1.657402439	1
BD	-0.174821429	1	0.88233714	-2.333822555	1.984179698	2.417234
CD	-0.04375	1	0.567512266	-1.432402439	1.344902439	1
A^2	0.584134916	1	0.415780959	-0.433244403	1.601514234	1.010859
B^2	0.621337297	1	0.415780959	-0.396042022	1.638716615	1.010859
C^2	0.484928567	1	0.415780959	-0.532450752	1.502307885	1.010859
D^2	-1.08503586	1	0.42102736	-2.11525266	-0.054819059	1.010099

Most other terms, such as A, B, AC, AD and BD, have confidence intervals that include zero, implying they are not statistically significant at the 95% confidence level. The quadratic term for drying time (D^2) is also significant with a negative coefficient (–1.09), suggesting a nonlinear relationship between drying time and moisture reduction. All VIF values are below 2.5, indicating the absence of multicollinearity and confirming that the predictors are independent and reliable. The standard errors are generally small, which enhances the precision of the estimated coefficients and strengthens the model's reliability. The positive quadratic terms (A^2, B^2 & C^2) indicate slight curvature effects but are less influential than the linear and interaction terms. Table 7 confirms that drying temperature, drying time, and their interactions are the most influential parameters controlling yam moisture content. The quadratic model remains statistically stable and free from collinearity issues. Figure 2 gives the relationship between the experimental MC and the model predicted correspondence.

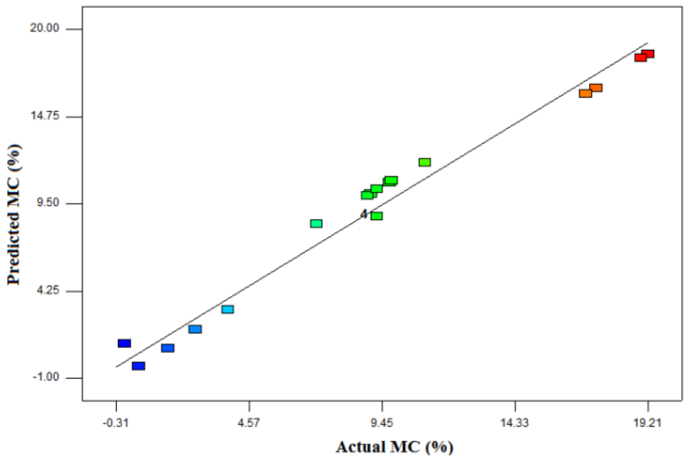

Fig. 2. Correlating Predicted and Actual MC of Yam

3.3 Dual Effect of Drying Conditions

3.3.1 Effect of Blanching Temperature and Blanching Duration on MC

The contour plot shows a curved pattern (Figure 3a), where both parameters interact very well. MC decreases as both blanching temperature and duration increase. It tallied with a minimum at higher temperature (around 90°C) and moderate duration (about 25 min). But Amedor et al. [25] maintained that blanching affects yam drying by enhancing its texture, color, and drying efficiency, with a 4-min blanching time producing the best quality yam chips at optimal energy consumption. The 3D surface plot in Figure 3b complements this trend by displaying a steep decline in MC at these optimal ranges. At very low blanching temperatures and short durations, the yam retains more moisture, which is an indication of insufficient gelatinization of cell walls. However, excessively long blanching can lead to texture degradation without substantial moisture improvement.

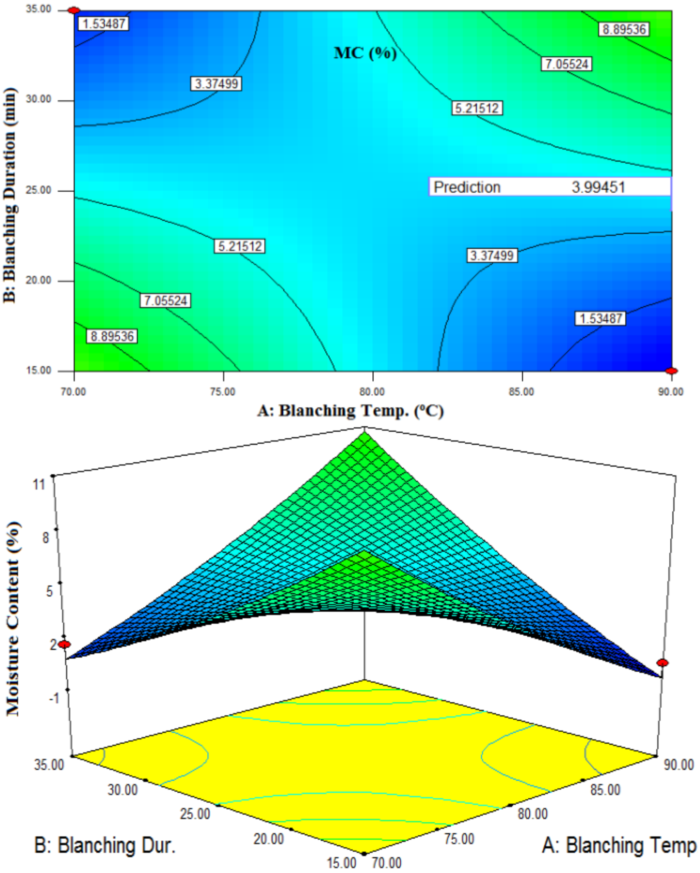

Fig. 3. AB (a) Contour and (b) 3D Surface Plots

In this case, moderate-to-high blanching temperatures and durations yield the most efficient pretreatment for moisture reduction in yam drying. This behavior reflects improved thermal efficiency, as higher blanching temperature of 90°C accelerate heat penetration and enhance internal moisture migration. Variation in blanching temperature and time in Sobukola et al. [18] affected the moisture, oil content, texture, and color of yam chips, with optimal quality achieved at 70–75°C blanching temperature for 4–5 min. In contrast to the current study, longer time of ≈ 24 min at a higher temperature is obtained as maximum. The optimized blanching condition in this study ensure that thermal energy is effectively utilized for structural softening rather than wasted through prolonged heating. Consequently, the process achieves maximum moisture reduction with minimal energy loss. It is an excellent balance between heat input and drying performance.

3.3.2 Effect of Blanching and Drying Temperatures on MC

The contour map in Figure 4a reveals that moisture content declines sharply as drying temperature increases, regardless of blanching temperature. Indirectly, it emphasizes drying temperature's dominant role. The 3D surface plot on the other hand (Figure 4b), illustrates a strong gradient toward lower MC values at high drying temperatures (65–70°C), signifying faster water removal rates. Blanching temperature exhibits a milder effect, though higher blanching levels slightly enhance drying efficiency by weakening cell structures. At low drying temperatures, moisture remains high even with intense blanching. Thus, heat transfer during drying is the key driver of water loss. Li et al [29] said that the dielectric properties of yam slices decrease as moisture is being lost during drying.

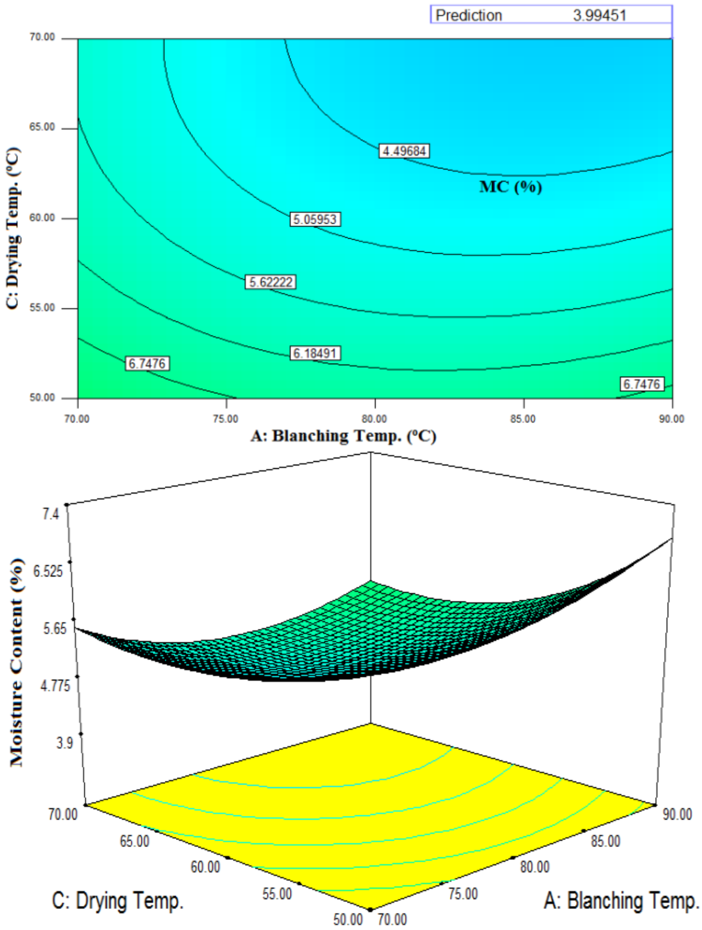

Fig. 4. AC (a) Contour and (b) 3D Surface Plots

The interactive behavior between A and C implies that preheating the yam via blanching complements higher drying temperatures. Together, the two plots validate the synergistic impact of pretreatment and drying heat on optimizing yam dehydration. It is later observed that the interaction demonstrates high thermal efficiency, as the applied drying heat is effectively converted into latent energy for moisture evaporation and not lost to the surroundings. The combination of optimal blanching and elevated drying temperature of 70°C promotes uniform heat distribution, which accelerates internal moisture diffusion. Ononogbo et al. [30] found that the moisture diffusivity of yam tubers ranged from 7.27 × 10^{-10} m^2/s at 55°C to 5.60 × 10^{-9} m^2/s at 75°C. That is, it increases with higher drying temperature and air velocity. As a result, the process achieves rapid drying with reduced energy consumption.

3.3.3 Effect of Blanching Temperature and Drying Time on MC

Figure 5 depict the relationship between blanching temperature (A) and drying time (D) on yam moisture content using a contour plot in Figure 5a and a 3D plot of Figure 5b. In Figure 5a, prolonged drying will reduce moisture content across all blanching temperatures. In this case, time is a major contributor to dehydration efficiency. The 3D surface view demonstrates how longer drying durations (8–10 h), the effect of blanching temperature becomes less pronounced, as moisture is nearly eliminated. Conversely, at shorter drying times, higher blanching temperatures slightly enhance drying by pre-softening the yam tissues. The surface curvature suggests a nonlinear response, aligning with the significance of D^2 in the ANOVA results.

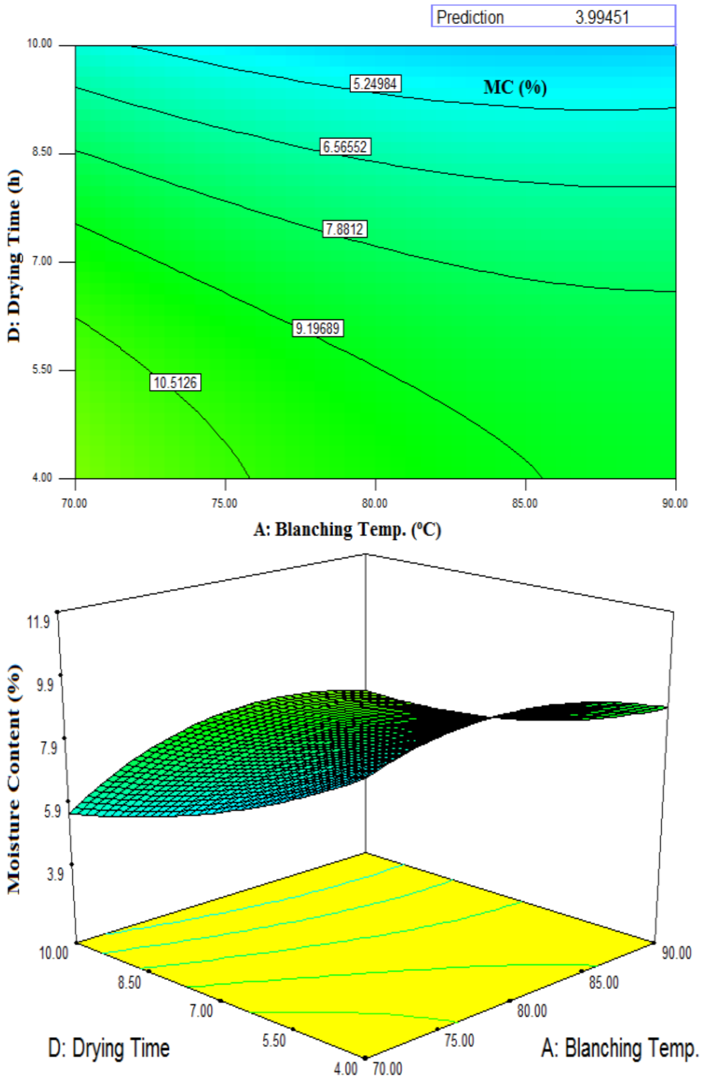

Fig. 5. AD (a) Contour and (b) 3D Surface Plots

Extremely low blanching temperatures combined with short drying times result in high MC values, due to incomplete drying. Blanching thus, assists the process, but drying time is the most influential factor in achieving optimal moisture reduction in yam drying. This trend also highlights strong thermal efficiency, as prolonged drying time allows sufficient heat transfer and moisture diffusion throughout the yam matrix. Increasing microwave power in pulse-spouted microwave freeze drying in Li et al. [31] will accelerate the evaporation of bound water, reduced drying time and energy consumption. They confirm that about 600 W provided the best balance between energy efficiency and nutritional quality retention in their study. The effective utilization of drying heat ensures that the energy supplied is directed toward evaporating bound water.

3.3.4 *Effect of Blanching Duration and Drying Temperature on MC*

Contour plot reveals a pronounced decline in MC as drying temperature increases, as shown in Figure 6a. So, temperature has a strong role in accelerating moisture removal. At lower drying temperatures, even extended blanching durations fail to achieve effective drying, due to the fact that heat intensity remains the dominant variable. The 3D surface plot (Figure 6b) depicts a steep downward slope toward higher drying temperatures (65–70°C), signifying faster moisture loss. Moderate blanching durations (around 25 min) yield optimal results, as excessively long blanching may cause cell wall rupture that hinders moisture escape.

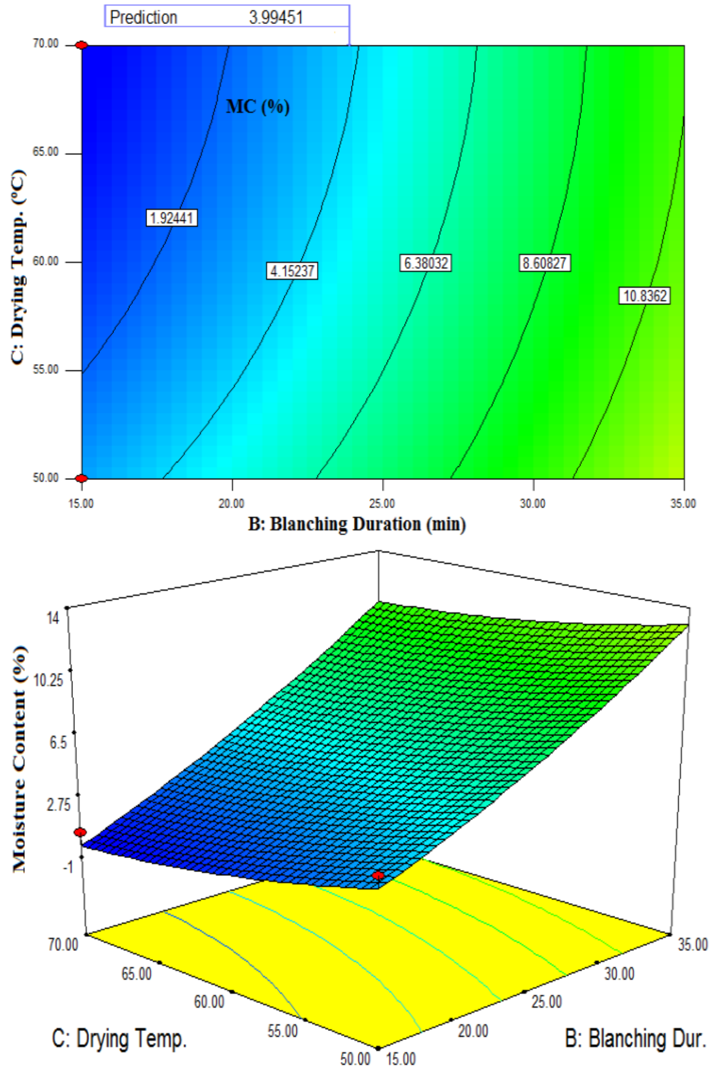

Fig. 6. BC (a) Contour and (b) 3D Surface Plots

The interaction between B and C is therefore synergistic. Adequate blanching enhances the efficiency of thermal drying. Combining moderate blanching duration with high drying temperature positively reduce yam moisture content.

3.3.5 *Effect of Blanching Duration and Drying Time on MC*

In Figure 7a, contour plot shows a consistent reduction in MC with longer drying time. Therefore, the duration in the dryer is crucial for complete moisture removal. As for Figure 7b, the 3D surface plot demonstrates that beyond 8 h of drying, moisture reduction levels off, suggesting that equilibrium moisture content is reached. Blanching duration has a lesser but noticeable effect. Moderate blanching (around 25 min) improves drying efficiency by loosening the yam's cell matrix. Excessive blanching (over 35 min) slightly increases moisture retention, possibly due to structural collapse and restricted airflow.

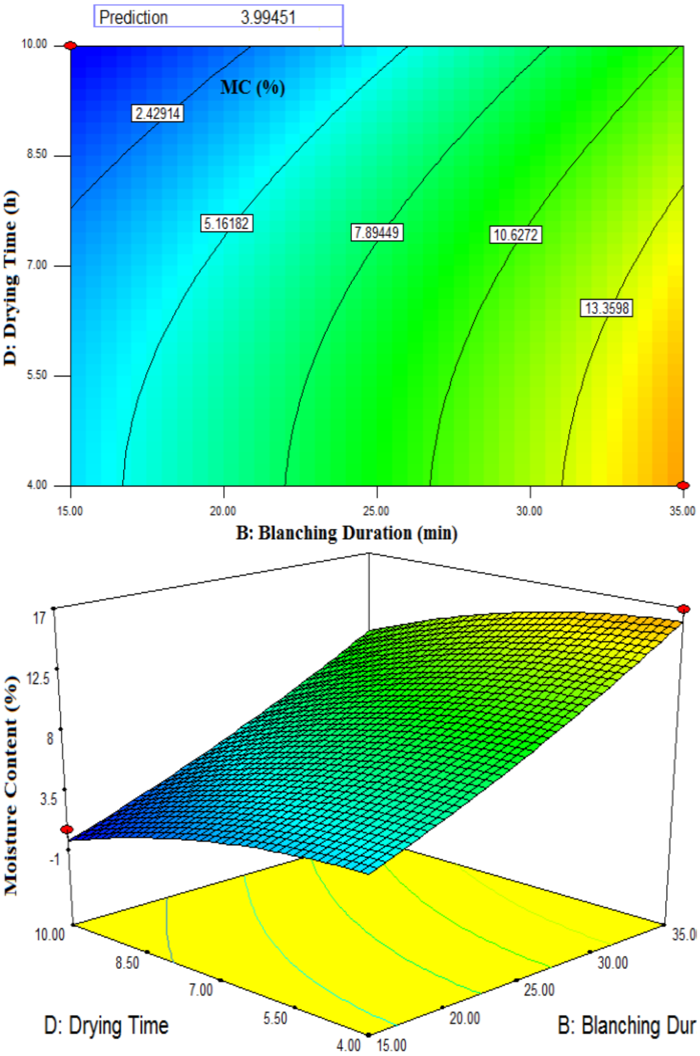

Fig. 7. BD (a) Contour and (b) 3D Surface Plots

The surface curvature suggests a diminishing return effect for prolonged drying, aligning with the significant quadratic term (D^2) in the regression model. Similar representation in 3D bar chart plot was given by Abano & Amoah [32]. Thus, drying time plays a more dominant role than blanching duration in minimizing yam moisture content.

3.3.6 Effect of Drying Temperature and Drying Time on MC

Figure 8 show the combined effect of drying temperature (C) and drying time (D) on yam moisture content, as exemplified in Aneke et al. [28], whose optimal were 70-74.9°C and 116.1-165 min. The contour plot displays steep gradients, where it is observed that both temperature and time strongly influence drying efficiency. The 3D surface plot reveals that high drying temperature (around 70°C) and extended drying time (10–12 h) produce the lowest MC values, approaching near-zero moisture levels. Also, the study by Okunola et al. [12] indicates that a drying temperature of 70°C yields the best results, due to higher drying rate, energy and exergy efficiencies, and overall process performance. At lower drying temperatures, even long drying times are insufficient to achieve complete dehydration, highlighting the importance of adequate heat supply. The plot's curvature also confirms a nonlinear response, consistent with the significant D^2 term in the ANOVA results.

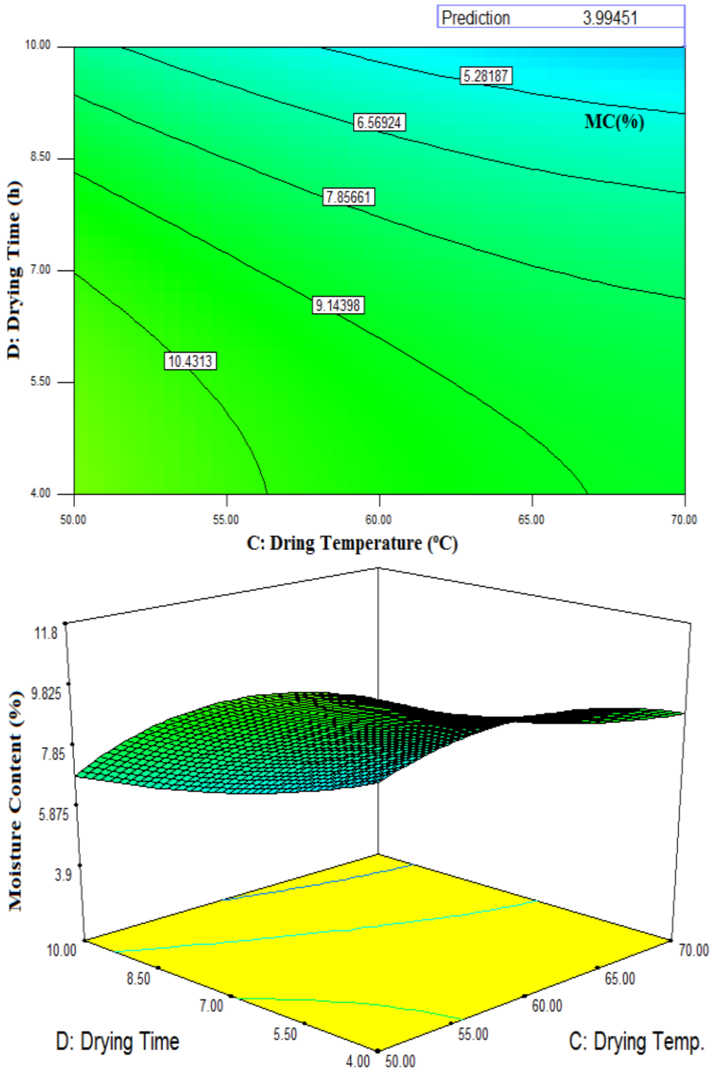

Fig. 8. CD (a) Contour and (b) 3D Surface Plots

Obvious interaction between C and D is strongly synergistic. Temperature accelerates moisture vaporization while time ensures complete diffusion and release. Collectively, Figure 8a and 8b confirm how optimizing both drying temperature and time lets us achieve an efficient and uniform yam drying. Table 8 presents the optimal combination of process variables for achieving the minimum MC in yam drying, as determined through RSM. The results show that a blanching temperature of 90°C and a blanching duration of 23.9 min yield the best pretreatment condition for efficient drying. The longer blanching duration obtained in this study reflects process optimization for drying efficiency rather than product quality, which differs from literature focused on sensory attributes. These conditions ensure partial gelatinization and softening of yam tissues, enhancing internal water diffusion and reducing resistance to heat transfer during drying. A drying temperature of 70°C was found to be optimal for thermal energy utilization, as it provides sufficient heat for rapid evaporation without causing product scorching or nutrient degradation. The lowest energy consumption during yam drying was achieved by Chibuike et al. [33] at an optimal temperature of 75℃, air velocity of 1 m/s, and slice thickness of 1 cm (equal to minimum electric power consumption of 44.63 W-h). Similarly, a drying time of 10 h ensures complete removal of bound moisture while maintaining product quality and uniformity. In Lin et al. [27], an optimal drying time of < 8 h was enough. The resulting minimum moisture content of 3.99% indicates that the system achieves high thermal efficiency and effective mass transfer under these combined conditions. A confirmatory experiment at the predicted optimum conditions should be conducted to validate the model prediction of 3.99% moisture content.

Table 8. Optimal Combination for Minimum Moisture Level

Variable Tag	Name	Optimum
A	Blanching Temperature	90℃
B	Blanching Duration	23.9 min
C	Drying Temperature	70℃
D	Drying Time	10 h
Response	MC	3.99451%
Desirability	Desirability	0.812

The desirability value of 0.812 reflects an excellent optimization outcome, signifying that the chosen parameters simultaneously satisfy the model's response objectives. In Abano & Amoah [32], blanching time of 1 min at 80℃ produced the most desirable results, which contributed to an overall desirability value of 0.63. From a thermal perspective, the optimized conditions balance energy input and moisture diffusion rate, thereby minimizing heat loss and maximizing drying performance. This implies that the drying process operates within an energy-efficient range, achieving substantial water removal with reduced thermal wastage. For yam drying, moisture diffusivity increases with temperature, despite the fact that the activation energy for moisture diffusion does not show a clear or consistent relationship with the moisture content [30]. Table 9 presents a comparative overview of previous studies that applied RSM and other optimization models to various yam drying systems.

Table 9. Previous RSM Studies on Yam Drying

Heat Source	Experimental Design	Model	Optimal Condition	Response	Study
Solar drying	CCD	Second order polynomial regression model	Yam mass (71 & 70g), slice thickness (3.2 & 3 mm) and airspeed of dryer (1.5 & 1.5 m/s) for blanched and unblanched sample	MC = 12.3 & 18%	Nwadike et al. [23]
MWHA	Single factorial design	Quadratic	Slice thickness = 8.5 mm, hot-air velocity = 2.5 m/s, hot-air temperature = 61.7℃ & microwave power density = 5.9 W/g	TSC = 5.72 g/100g & RR = 1.83 g/g	Wang et al. [26]
Infrared combined hot-air drying	BP NN GWO	Quadratic	Temp. = 63.57℃, slice thickness = 4.27 mm & radiation distance = 91.39 mm	Drying time = 133.71 min, color difference = 133.71 min, unit energy consumption = 8.54 kJ h kg^{-1}, polysaccharide content = 20.73 mg/g, rehydration ratio = 2.84 kg/kg & allantoin content = 3.69 µg/g	Zhang et al. [21]
Hot air drying	CCD	Quadratic	Air temp. = 70 & 74.9℃, slice thickness = 6 & 6.6 mm and drying time = 165 & 116.1 min for treated and untreated water yam	0.000345 & 0.000358 kg/m^2s	Aneke et al. [28]
FIR freeze drying	BBD	Second order polynomial	Distance from FIR plate = 50 mm, drying temp. =	Drying time = 6.79-7.9 h &	Lin et al. [27]

		regression model	34–37°C & slice thickness = 7–8 mm	rehydration ratio = 5.17-5.27	
Cabinet dryer	Face centered composite design	Quadratic model	Feed composition = 20%, feed moisture = 13.28% & barrel temp. = 108.83°C	LE = 144.65%, density = 0.222g/cm^3, WAI = 6.002 g/g, WSI = 7.217% & maltose content = 305.15 μg/g	Yadav et al. [34]
Explosion puffing drying	Rotation combination design combined with fuzzy evaluation	Three-factor quadratic regression	Puffing temp. = 87°C, vacuum drying temp. = 74°C & vacuum drying time = 138 min	Rehydration rate = 1.82, colour = 91.32, shrinkage rate = 36.12% & CS = 8.71	Ming et al. [35]
Hot air drying	ANFIS	Fuzzy modeling	Air drying temp. = 70°C, air velocity = 1.5 m/s & slice thickness = 3 mm	High rehydration ratio & diffusivity = 6.382×10-9 to 1.641×10-7 m^2/s	Ojediran et al. [13]
Osmotic drying	Orthogonal experimental design	Polynomial	Slide thickness = 5 mm, sucrose content = 60º Brix, temp. = 60°C & immersion time = 6 h	Water loss – 93%, solid gain = 90% & MCR = 89%	Abud-Archila et al. [22]
Microwave vacuum drying	Rotation orthogonal experiment	Quadratic regression model	Slice thickness = 3 mm, pressure = 0.08 MPa & drying temp. = 55°C	Polysaccharide content = 4.12%, whiteness = 78.04% & rehydration rate = 223.29%	Lei et al. [15]
Hot air drying	3- Level Factorial Design	Kinetic model & polynomial	Pretreatment time = 5 min, blanching time = 1 min & drying temp. = 70°C	Moisture diffusivity = 8.81 × 10^{-9} m^2 s^{-1}	Abano & Amoah [32]
Tray dryer (hot air dryer)	CCD	Quadratic model	Blanching temp. = 90°C, blanching time = 23.9 min, drying temp. = 70°C & drying time = 10 h	Moisture content = 3.99%	This study

TSC – Total Sugar Content; *MWHA – Microwave Coupled with Hot Air*; *RR – Rehydration Ratio*; *NN GWO – Neural Network Gray Wolf Algorithm*; *BBD – Box Behnken Design*; *LE – Lateral Expansion*; *WAI – Water Absorption Index*; *WSI – Water Solubility Index*; *CS – Comprehensive Score*; *ANFIS – Artificial Neural Network Fuzzy Inference System*; *MCR – Moisture Content Reduction*

Across the reviewed works, optimal drying temperatures typically ranged from 55 to 75°C, and slice thicknesses from 3-8 mm, which align closely with this study's conditions of 7–8 mm thickness and 70°C drying temperature. Blanching conditions as observed in Table 9, are not usually considered during drying assessment. The most interesting parameters are drying time, drying temperature and slice thickness. Only few research is reported on CCD and BBD specification, but hot air drying is almost the most employed drying approach for yam. Almost all studies in Table 9 did not take moisture content as the response variable. Nevertheless, the moisture content of 3.99% predicted by the model happened to be the best contribution of this study. This is however, not backed by a laboratory validation.

3.4 Nutritional Composition of Yam

It is worthy of note that the nutritional constituent of yam are differently reported [16]. A final moisture content of 7.20% indicates effective drying performance. Because the optimized thermal conditions successfully removed excess water without over drying or nutrient loss. This moderate residual moisture ensures product stability, and prevents microbial spoilage despite preserving the yam's physical integrity. The ash content of 1.32% reflects the retention of essential minerals, as the applied heat did not cause relevant volatilization or mineral degradation. A protein value of 6.5% shows that the drying process maintained the yam's nutritive quality, as excessively high drying temperatures could have caused protein denaturation. The fat (5.3%) and fiber (3.5%) contents in Table 10 indicate that thermal treatment preserved key macromolecules important for energy and digestion. Soaking conditions and drying temperature did not significantly influence the moisture or protein content of the yam dried by Adejumo et al. [24].

Table 10. Proximate and Nutritional Compounds in Yam

Nutritional Content	Percentage
Moisture	7.20
Ash	1.32
Protein	6.5
Fat	5.3
Fiber	3.5
Carbohydrate	83.305

Calories/kJ.(100g)$^{-1}$	192.5

Yadav et al. [34] realized a moisture level of 9.2% which is 27.78% greater than 7.2% obtained herein, as well as 6.06% protein content, which is 6.77% less than 6.5 obtained in this study. High carbohydrate level (83.31%) demonstrates that most of the yam's caloric energy was retained, highlighting the efficiency of heat transfer and controlled dehydration. Thus, the recorded caloric value of 192.5 kJ per 100 g emphasizes that the optimized drying parameters yielded an energy-dense product suitable for consumption and storage. Efficient thermal utilization during drying not just minimized moisture but also maximized nutrient retention. The observed balance between drying intensity and nutritional preservation confirms that the optimized process conditions achieved both high thermal efficiency and high product quality in yam flour production. Otherwise, sublimation drying could avail any disruption in nutrient presence. Sublimation drying of yam slices implies a process where frozen water within the yam is directly converted to vapor without passing through the liquid phase (up to 16 h), to preserve nutrients, structure and quality [36].

4. Conclusion

Without any drying condition specification, a drying temperature of 7.2% was realized compared to 3.99% at optimized conditions. The optimized conditions given by CCD-RSM tool are blanching temperature = 90°C, blanching time = 23.9 min, drying temperature = 70°C and drying time = 10 h, based on hot air-drying method. Based on the 3D analysis, drying temperature and drying time were identified as the most influential factors affecting moisture reduction and overall drying efficiency of yam. Simply due to the fact that the R^2 = 0.9750, points to a strong fit between experimental and predicted data. The interaction between blanching temperature and blanching duration also showed a momentous synergistic effect (p = 0.0011) in improving moisture removal efficiency. The two parameters work best together to optimize heat transfer and mass diffusion, for rapid and uniform dehydration. Current findings show that efficient control of temperature and time minimizes thermal energy loss by maximizing the conversion of supplied heat into latent heat of vaporization. The nutritional content of the yam analyzed happed to be in consonance with previously documented properties. Future study should consider the reduction in the size and thickness of the yam chips so as to reduce the required drying time and the cost of energy consumption. Although slice thickness was not varied experimentally, literature indicates its strong influence on drying kinetics. An automatic cutting machine should be introduced to reduce manual errors and cutting stress. In this era of automation, automatic controllers should be introduced to ensure adequate control of the process variables.

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