Empirical Study of the Energy Demand and Drying Behaviour of Selected Tuber Crops

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Abstract- This study investigated the persistent challenge of post-harvest losses in selected tuber crops, namely white yam (Dioscorea rotundata), trifoliate yam (Dioscorea dumetorum), and cocoyam (Xanthosoma sagittifolium), which are staple crops of major nutritional and economic significance in Nigeria. This research empirically characterised the drying behaviour and energy demand of white yam, trifoliate yam, and cocoyam under microwave oven drying conditions. Specific objectives included evaluating the effects of key process parameters—temperature (40, 45, 50 °C), air velocity (2, 3, 4 m/s), and slice thickness (3, 4, 5 mm)—on drying kinetics, energy efficiency, product shrinkage, effective moisture diffusivity, and activation energy. The study assessed the performance of ten thin-layer drying models to determine the most appropriate for describing tuber drying behaviour under microwave conditions. Findings revealed that drying occurred predominantly within the falling rate period. Cocoyam exhibited the fastest drying rate and highest effective diffusivity, while trifoliate yam showed the slowest moisture removal. Increased temperature, elevated air velocity, and reduced slice thickness significantly enhanced drying efficiency. Optimal conditions were achieved at 45°C and 3 m/s. Among the tested models, the Midilli et al. model consistently provided the best fit, with R² values exceeding 0.988. The study concludes that microwave drying is highly effective for selected tubers, with performance critically dependent on process parameters, and that microwave oven drying is highly effective for selected tubers, with performance critically dependent on process parameters. The study, therefore recommends 50 °C, 4 m/s, and 3 mm slicing for industrial use, and proposes further research into nutritional retention and the validation of the Specific Thin-Layer Drying Model for Yam Tubers (STLDMYT).

Index Terms-: Tuber Crops, Energy Demand, Microwave Dryers, Drying Behaviour, Drying Efficiency.

I. INTRODUCTION

Preservation of agricultural produce has remained one of the major problems in the world. This is because these food materials are characterized by high moisture content at the point of harvest, which supports the growth of microorganisms that break down the food material producing acids or other waste products during this process. A lot of preservation techniques, among which includes drying, help in lowering the moisture content and increasing their shelf life have been developed for several years to mitigate the loss of agricultural food materials (Nwakuba, Asoegwu, Nwaigwe & Chukwuezie, 2017). Drying is a universal method for conditioning foods by the elimination of the internal water until a level that allows its balance with the ambient air, in such a way that preserves its physical and chemical characteristics (Ruiz & Montero, 2005). Drying has been regarded as probably the most important and oldest food preservation method and it entails a complex thermal process in which simultaneous heat and mass transfer occur (Ojediran & Raji, 2010; Doymaz, 2011). During drying, there is transfer of heat energy to the product and movement of internal moisture to the surface of the product where it is evaporated

Food security has remained a major problem in most developing countries. In sub-Saharan Africa, the root and tubers constitute the most important food crops among which are yam, cocoyam and trifoliate yam which are being used in this study. White yam was chosen as part of a sample material for this study due to its high moisture content (50-80% w.b) together with its susceptibility to deterioration during storage, which is difficult to store (Chen, Li, Mao & Huang, 2017); Falade & Onyeoziri, 2012). This tuber was also chosen, due to its constant usage, large scale farming and economic importance especially in Africa (Abiodun & Akinoso, 2014).

It has been discovered that after the harvest of tubers, they are prone to deterioration by microbial attack.

Loss of viability majorly evolves from poor handling during harvest, insufficient storage and conveyance equipment, deficient technical knowledge of food processing preferences. As cooling is not a feasible technique to prolong the shelf life of these tubers, an alternative to this end is drying. In these modern times, drying of plant-based materials takes preference to energy demand reduction and provision of quality-enriched products with a marginal rise in economic effects, which has become increasingly attractive to drying applications (Darvishi, Asghari, Azadbakht, Najafi & Khdaei, 2013a); Darvishi, Asl, Asghari, Najafi & Gazori, 2013b). As a result of the increased energy demand for crop drying, the development of energy-efficient processes has emerged in most technologically advanced nations. Drying techniques can be generally categorized into solar and mechanical drying. The latter involves microwave drying amongst many other methods. However, this conventional method is faced with some technical hitches which includes: inadequate heat transfer to food matrix in the falling rate interval as a result of the product's low thermal conductivity, high drying energy consumption, low overall efficiency, gross energy loss (<35%), extensive drying time, poor dried product quality, etc. (Motevali, Minaei, Banakar & Ghobadian, 2014; Yildiz & Izli, 2018). The desire to forestall these bottlenecks to preclude substantial energy demand, product quality, and efficiency decline, as well as efficient heat treatment has exhausted the increasing rate of application of microwaves for drying crops.

Drying process utilizes high energy compared to other production processes due to relatively low energy efficiency of dryers and high latent heat of water evaporation (Darvishi et al., 2013). Therefore, there is a major challenge for the drying industry to perform energy analysis to achieve optimum process conditions and reduction of energy utilization, having an understanding that energy analysis is practical in quantitative evaluation of energy requirements and energy losses in drying systems.

The energy demand and drying behaviour provides the optimum unit of drying air temperature, drying air velocity, and drying time for drying a given batch of sample product in order to prevent over drying which reduces the nutritional and economic values of the dried product (Nwakuba et al., 2016), high moisture laden root and tuber crop materials require high heat energy for optimal drying and safe storage. Hence, the energy required to dry root and tuber crops largely depends on the shape and size of the products (Nwakuba et al., 2016).

II. MATERIALS AND METHOD

Sample Preparation

Fresh tubers of white yam (Dioscorea rotundata), trifoliate yam (Dioscorea dumetorum), and cocoyam (Xanthosoma sagittifolium) were procured from Orie-Ugba market, a major metropolitan hub in Umuahia, Abia State, Nigeria. The samples were selected for their maturity, uniformity in size, and overall quality to ensure consistency in the experimental analysis. The tubers were then prepared by peeling, washing, and slicing into precise thicknesses of 3, 4, and 5 mm using a stainless-steel knife and a vernier caliper with 0.01 mm sensitivity. The samples were then sorted out and divided into three groups, whereby each group will consist of three (3) samples of the three (3) sample thickness (3, 4 and 5mm). These three groups will be subjected to microwave drying. In order to record the air velocity/ air speed, using an air flow meter, a variable resistor with a nobe was used to adjust the voltage needed, with a 13A, 0.5 hp AC motor which was connected to it, during operation the variable resistor is adjusted so that the fan slows down or accelerates until the exact speed is reached and recorded.

Experimental Procedure

The selected tuber samples: white yam (Dioscorea rotundata), trifoliate yam (Dioscorea dumetorum), and cocoyam (Xanthosoma sagittifolium), were sliced to thicknesses of 3, 4, and 5 mm, respectively. Each sample was placed in a pre-weighed moisture can and dried using a microwave dryer under controlled conditions: three temperature levels (40, 45, and 50 °C), three air velocities (2, 3, and 4 m/s), and the specified slice thicknesses. Moisture loss was monitored gravimetrically at 40-minute intervals using a digital balance (precision ±0.01 g). The mean of triplicate moisture content readings was used to establish the drying curve for each condition. At the conclusion of the primary drying phase which refers to the phase where free (unbound) moisture is removed. The process transitions to the secondary

drying phase once this unbound moisture has largely evaporated, the oven temperature was adjusted to 105 °C, and drying continued until a constant mass was achieved, indicating complete moisture removal. Final moisture content was determined on a dry basis by recording the weight loss after drying to equilibrium, following standard procedures (Yagcioglu et al., 1999).

Experimental Design
The experimental design was structured using a 3^3 factorial arrangement within a Central Composite Design (CCD) framework, facilitated by Design-Expert Software (v11.0). This approach enabled the systematic investigation of three critical factors: temperature (40, 45, 50 °C), slice thickness (3, 4, 5 mm), and air velocity (2, 3, 4 m/s); each at three levels, resulting in 27 core experimental runs, at the initial stage and further expanded to 60 runs, for effective evaluation, as shown in Table 3.1. Explaining further, for each drying method, there are three factors (temp, sample thickness, and air velocity) with three levels each: 40, 45, and 50°C; 3, 4, and 5 mm; 2, 3, and 4 m/s.

The effect of temperatures, thickness, and air velocity was analyzed and analysis of variance (AVONA) was used to determine the significant factors of the parameters in drying.

This CCD matrix allowed for the evaluation of linear, quadratic, and interaction effects of the independent variables on drying performance. The design incorporated replicate centre points to enhance statistical reliability and error estimation. Experimental responses, including specific energy, drying efficiency, drying time, and shrinkage were recorded and compiled, forming the basis for response surface analysis and process optimization under varying microwave drying conditions.

Table 1: A CCD experimental layout of input and output variables

Run	Temperature (°C)	Thickness (mm)	Air Vel. (m/s)	Sp. Energy (kJ/k g)	Drying Eff. (%)	Drying Time (min.)	Shrinkage (%)
1	45	4	2	1.16	85	760	30.33
2	50	3	4	0.72	80	940	21.67
3	40	3	2	2.28	75	520	25.56
4	45	3	3	1.29	83	700	26.6
5	50	3	2	1.47	77	970	32
6	40	4	3	1.16	85	520	29
7	45	4	3	1.16	85	760	26.6
8	50	5	4	2.28	75	1000	22.5
9	45	4	3	1.16	85	760	26.6
10	40	5	2	2.28	75	520	30
11	40	5	3	1.16	85	520	30.5
12	45	4	4	1.16	85	760	26.6
13	50	5	3	1.47	77	970	32
14	40	3	4	2.28	75	520	25.56
15	45	5	4	1.16	85	760	21.4
16	45	5	3	1.29	83	700	22.4
17	40	5	4	2.28	75	520	29
18	50	5	2	1.47	77	970	32
-	-	-	-	-	-	-	-
60	50	4	4	0.72	79	940	21.67

Moisture content determination
During the experiments, moisture content was measured by the gravimetric method using a digital balance (with a precision of 0.01g). The determination of the moisture content was carried out by the microwave drying method in accordance with AOAC (2000) at a temperature of 103°C for 10 hours at the Department of Agricultural and Bioresources Engineering laboratory, Michael Okpara University of Agriculture, Umudike, Abia State. Equation 3.1 was employed for moisture content determination of both white yam, trifoliate yam and Cocoyam. The moisture content (MC) in a product is designated on the basis of the weight of water (i.e., dry or wet basis). On dry basis (%) it can be calculated as follows (Ceylan et al., 2007; Haque & Langrish, 2005; Upadhyay et al., 2008):

$$\%MC\ (d.b) = \frac{W_w}{W_d} \times 100 \tag{1}$$

Where;
- MC (d.b) = moisture content at dry basis

- W_w = weight of wet sample (*g*)
- W_d = weight of dried sample (*g*)

The drying rate of the samples were calculated based on weight of water removed per unit time and per

kilogram of dry matter (solid) and expressed in units of kg kg^{-1} h^{-1}, as shown in Table 2

Table 2. Moisture ratio vs. Drying time of tubers: White yam, trifoliate yam, and Cocoyam under different drying conditions

Run	Drying time (min)	Temperature (ºC)	Air velocity (m/s)	MR of White yam (%)	MR of Trifoliate yam (%)	MR of Cocoyam (%)
1	0	45	3	1	1	1
2	40	45	3	0.935	0.974	0.99
3	80	45	3	0.857	0.94	0.97
4	120	45	3	0.704	0.896	0.95
5	160	45	3	0.502	0.85	0.92
6	200	45	3	0.244	0.798	0.88
7	240	45	3	0.102	0.722	0.84
8	280	45	3	0.001	0.632	0.78
9	320	45	3	0.001	0.524	0.72
10	360	45	3	0.001	0.39	0.65
-	-	-	-	-	-	-
60	2360	50	3	0.001	0.001	0.001

Drying Characteristics

(a) Product moisture content

Moisture content is a critical determinant of dried product quality and market value. It was measured gravimetrically using a digital balance (0.01g precision). The wet basis moisture content, commonly used for commercial purposes, expresses water weight as a percentage of the total sample mass, facilitating standardized product evaluation and trade (Hall, 1990).

This study preferred moisture content dried basis, and was calculated by dividing the weight of water by the weight of dry matter. This method provides a linear relationship ideal for drying kinetics analysis. Conversion between wet and dry basis values ensures consistency in data interpretation across different experimental and commercial contexts, using equations 2 to equation 3, as follow:

$$M.Cwb = \frac{W}{Ww + Wd} \qquad (2)$$

Where:

M.C$_{wb}$ = moisture content, wet basis, percent

W = weight (mass)

W$_w$ = weight of water, kg

W$_d$ = weight of dry matter, kg

However, the moisture content on a wet basis or dry basis can be converted from one to another using the following equation:

From wet basis to dry basis:

$$M.Cdb = \frac{MCwb}{100 - M.Cdb} \text{ X } 100 \qquad (3)$$

From dry basis to wet basis:

$$M.Cwb = \frac{MCwb}{100 + M.Cdb} \text{ X } 100 \qquad (4)$$

(b) Product drying constant

The drying constant described the mechanisms of heat and mass transport phenomena and examines the effect that certain process variables exert on moisture removal processes, as shown in equation 5 and Table 3.

The drying constant (k) is a function of diffusion coefficient (D) as presented by the following equation:

$$K = \frac{D\pi}{z} \qquad (5)$$

Where:

Z = a dimension character of product under consideration, m^2

D = diffusion coefficient, m^2/hr

Moisture Ratio (MR)

The moisture ratio shows the ratio of the moisture content (kg/kg dry matter) at any given time to the initial moisture content (kg/kg dry matter) (Both relative to the equilibrium moisture content) according O¨zbek and Dadali, (2007), and expressed in equation 3.

$$MR = \frac{M - Me}{Mo - Me} \qquad (6)$$

Where:

- M = Moisture content at time t (kg water/kg dry matter)
- M_O = Initial moisture content (kg water/kg dry matter)
- M_e = Equilibrium moisture content (kg water/ kg dry matter)

Effective moisture diffusivity

Moisture diffusivity is an important transport property needed in calculations and modelling of food drying, moisture adsorption/desorption during storage or dehydration (Okos *et al.*, 1992) as Table 3 shows drying time of tubers at varying temperatures, velocities and slice thicknesses.

Table 3. Drying time of tubers at varying temperatures, velocities, and slice thicknesses

Run	Temperature (ºC)	Air velocity (m/s)	Slice thickness (mm)	Drying time of white yam (min.)	Drying time of trifoliate yam (min.)	Drying time of cocoyam (min.)
1	40	2	2	430	910	960
2	40	2	2	410	890	950
3	40	2	2	410	880	950
4	40	2	3	400	730	950
5	40	2	3	400	730	950
6	40	2	3	400	730	950
7	40	2	3	390	720	950
8	40	2	3	390	530	950
9	40	2	3	390	530	940
10	40	2	3	380	470	940
-	-	-	-	-	-	-
60	50	4	5	100	140	140

Determination of Moisture Ratio (MR)

The moisture ratio (MR) was calculated as the ratio of instantaneous moisture content to the initial value, relative to equilibrium moisture content, as shown in Table 3. Equations 7 and 8 were applied to model MR over time for white yam, trifoliate yam, and cocoyam, enabling accurate tracking of drying kinetics under varying temperature, thickness, and air velocity conditions as shown in Table 3 (Babalis and Belessiotis, 2004).

$$MR = \frac{M - Me}{Mo - Me} \qquad (7)$$

Goyal, Kingsly, Manikantan & IIyas, (2014) stated that the equilibrium moisture content (Me) during thin-layer drying is often very small compared to the

product's moisture content during most of the drying period. The moisture ratio was further simplified according to Goyal *et al.* (2014) as:

$$MR = \frac{M}{Mo} \qquad (8)$$

Where;
Mt = the moisture content at any time, t
Mo = the initial moisture content
Me = the equilibrium moisture contents, respectively

Specific Energy consumption
Specific energy consumption is the energy required to remove a unit mass of water during drying, calculated as the ratio of total energy consumed to the mass of moisture evaporated. It was determined using Equations 9 to 10, incorporating parameters such as air velocity, air density, drying time, and temperature difference. Artificial dryers, though energy-intensive, are recognised for producing high-quality dried food products (Nwakuba et al., 2016). The total energy consumption for drying different yam tuber samples in the microwave dryer under varying air velocities, slice thicknesses, and temperatures is expressed in Equation 9 (Afolabi et al., 2014; Koyuncu *et al.*, 2007; Minaei et al., 2014; Nwakuba et al., 2016; Nwakuba et al., 2018) as:

$$E_T = Av\rho_a C_{pa}\Delta TDd \qquad (9)$$

Where: E_T is total energy consumption per batch (kWh); A is area of rack (m^2), v is air velocity (ms^{-1}), ρa is air density (kgm^{-3}), d is total drying duration per batch (h), ΔT is temperature difference between ambient and hot air (°C), and C_{pa} is specific heat of air ($kJkg^{-1}°C$).

The total energy consumption (E_T) for drying a batch of sliced yam samples at varying process conditions was obtained by adding the electrical energy (as measured by the arduino micro-processor), as shown in Table 4.4. The specific energy consumption is expressed in equation 10, and presented in Table 4.3 (Koyuncu et al., 2007; Motevali *et al.*, 2014; Afolabi *et al.,* 2014; Minaei *et al.*, 2014; Nwakuba *et al.*, 2018) as:

$$E_S = \frac{E_T}{M_0} \qquad (10)$$

Where: ES is specific energy consumption (kWhkg^{-1}); Mo is mass of moisture expelled (kg).
The energy consumption by microwave is expressed in equation 11:

$$Qt = \frac{P \times t}{60} \qquad (11)$$

Where, Qt represents total energy consumption in each drying bout, kWh; P is the microwave power, K_w and t is drying time, min, as expressed in equation 12.

$$\eta = \frac{m_w \lambda_w \times 100}{60 \times P_t} \qquad (12)$$

Where, η is the microwave drying efficiency, %; m_w is the mass of evaporated water, kg and λ_w is the latent heat of vaporization of water, kJ/kg. The latent heat of vaporization of water at the evaporating temperature of 100°C was taken as 2257 kJ/kg. The specific energy consumption was calculated as the energy needed to evaporate a unit mass of water (Mousa and Farid, 2002; Soysal *et al.*, 2006),

$$Q_S = \frac{60 \times 10^{-6} Pt}{M_w} \qquad (13)$$

Where, Qs is the specific energy consumption, MJ/kgH^{2}O.

Correlation Coefficient (R^2)
The correlation coefficient (R^2) serves as a fundamental statistical measure in assessing model adequacy, particularly in thin-layer drying analysis of tubers. It quantifies the proportion of variance in experimental moisture ratio explained by models such as Page, Midilli *et al.*, and Verma *et al.*, thereby confirming predictive reliability and experimental consistency, according to Equ.14

$$R^2 = \frac{\sum_{i=1}^{N}(MR_{exp} - MR_{pred})^2}{\sqrt{\left[\sum_{i=1}^{N}(MR_{exp} - MR_{pred})^2\right] * \left[\sum_{i=1}^{N}(MR_{exp} - MR_{pred})^2\right]}} \quad (14)$$

Reduced Chi-Square (X^2)

The reduced chi-square (χ^2) is a crucial goodness-of-fit indicator applied in evaluating thin-layer drying models, as it measures the deviation between experimental and predicted moisture ratios. Lower χ^2 values signify superior model accuracy, thereby enhancing reliability. Its application, according to Equation 15, validates model suitability under varying drying conditions.

$$\chi^2 = \frac{\sum_{i=1}^{n}(MR_{e,i} - MR_{p,i})^2}{n - \Omega} \quad (15)$$

Root Mean Square Error (RMSE)8

The root mean square error (RMSE) is a widely applied statistical parameter for assessing the accuracy of thin-layer drying models by quantifying deviations between experimental and predicted moisture ratios. Lower RMSE values indicate superior model performance. Mathematically, RMSE is expressed as shown in Equation 16:

$$E_{rms} = \sqrt{\frac{\sum_{i=1}^{n}(MR_{e,i} - MR_{p,i})^2}{n}} \quad (16)$$

Where, N = total no of observations, *MR exp, i* = experimental moisture ratio values and *MR pre, i* = predicted moisture ratio values.

The most appropriate thin-layer drying model is determined by selecting the one with the highest correlation coefficient (R^2) and the lowest chi-square (χ^2) and root mean square error (RMSE) values. Experimental drying curves are generated and subsequently fitted to ten models, with the most accurate representing product drying behaviour.

Fitting of drying models to experimental data (Goodness of fit)

The fitting of drying models to experimental data is essential for describing drying kinetics, which quantify the rate of moisture loss over time under controlled conditions. Thin-layer models, as shown in Table 4.5, were evaluated using correlation coefficient (R^2), root mean square error (RMSE), and reduced chi-square (χ^2), derived from Equations 14, 15, and 16, to determine model suitability.

For trifoliate yam, the Page and Modified Page models demonstrated strong predictive performance with R^2 values of 0.981 and 0.980 respectively, alongside relatively low RMSE and χ^2 values. However, the Midilli et al. model exhibited the highest accuracy (R^2 = 0.988, RMSE = 0.011, χ^2 = 0.0003), thus providing the best overall representation of the drying behaviour compared to other models.

The evaluation further revealed that models such as Newton and Wang & Singh performed poorly, with low R^2 and higher error indices, indicating limited capacity to describe drying kinetics. Conversely, the Two-Term and Midilli et al. models consistently provided superior fits across all tuber samples, thereby validating their robustness and suitability for kinetic analysis in microwave drying studies.

III. RESULTS AND DISCUSSIONS

This section presents empirical findings from microwave drying experiments on white yam, trifoliate yam, and cocoyam samples. The results addressed drying behaviour, energy demand, and the influence of process factors (temperature, air velocity, and slice thickness) at varying rates on product quality, providing a comprehensive analysis aligned with the study's objectives.

Initial moisture content of tuber samples

The initial moisture content of the tuber samples was determined gravimetrically and was found to be relatively high, ranging from 55 to 59% w.b. As illustrated in Figure 1, cocoyam had the highest average moisture content at 58.0% w.b., followed by trifoliate yam at 57.8% w.b., and white yam at 57.2% w.b., consistent with values reported for hygroscopic food materials (Cardoso & Da Silva Pena, 2014). These elevated moisture levels highlight the highly perishable nature of the tubers, emphasizing the need for prompt post-harvest processing. The findings are in agreement with Raju (2021), who reported that root and tuber crops generally exhibit moisture

contents above 55% w.b., rendering them highly prone to microbial spoilage in the absence of adequate drying.
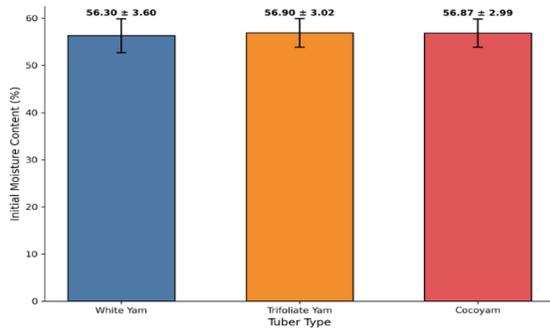

Figure 1: Initial moisture content (%) of tubers: White yam, trifoliate yam, and cocoyam.

Drying kinetics and moisture ratio curves
Figure 2 presents the moisture ratio (MR) drying curves for white yam, trifoliate yam, and cocoyam under various microwave drying conditions. The absence of a significant constant-rate period indicates that internal diffusion governed the process from the outset, which is characteristic of hygroscopic agricultural products.

The exponential decrease in MR over time confirms that drying occurred entirely within the falling rate period. Cocoyam demonstrated the most rapid moisture removal at 50 °C at 4 m/s, attributed to its favourable tissue structure, while trifoliate yam exhibited slower kinetics, consistent with patterns observed in similar root crops.
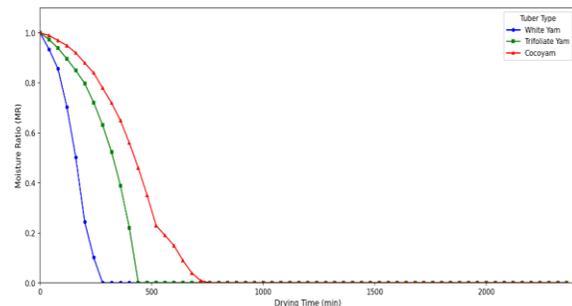

Figure 2: Moisture ratio vs. drying time of tubers: White yam, trifoliate yam, and cocoyam under different drying conditions.

Drying time under varying conditions
Figure 3 presents drying times for white yam, trifoliate yam, and cocoyam under varying

conditions. The results range from 100 to 960 minutes, demonstrating the substantial influence of process parameters on drying duration across tuber types. Drying time decreased significantly with elevated temperatures and reduced slice thickness, attributable to enhanced moisture diffusion and increased surface area-to-volume ratio. Higher air velocity further accelerated drying. These observations are consistent with established heat and mass transfer principles in food dehydration.
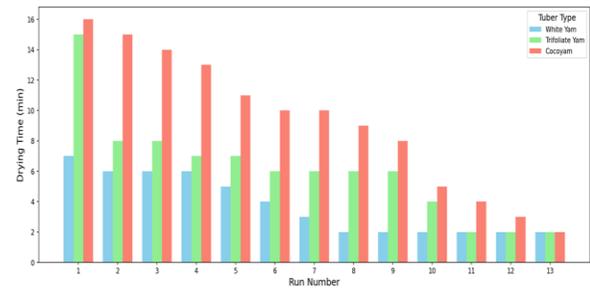

Figure 3: Drying time of tubers at varying temperatures, velocities, and slice thicknesses

Energy Consumption Analysis
Figure 4 presents the total energy demand, which increased with prolonged drying time and higher sample mass. White yam samples required the highest energy input (up to 3.00 kJ), due to its greater moisture content and density, followed by cocoyam and trifoliate yam. Variations in total energy consumption among tuber types reflect differences in physicochemical properties and drying kinetics. Energy demand was directly influenced by microwave exposure duration and initial moisture load, consistent with established principles of thermal processing for agricultural products.
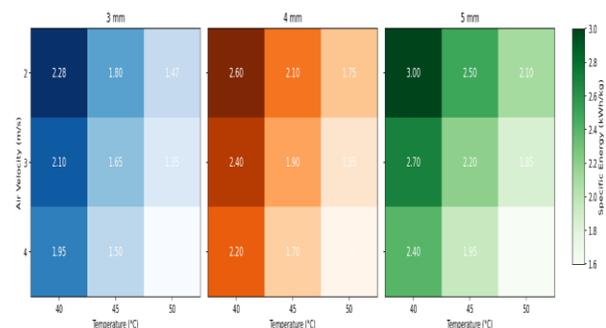

Figure 4: Total energy demand as a function of temperature, velocity, and thickness

The colour-coded heat map offers an intuitive visualization of specific energy demand across drying parameter combinations. Minimal consumption (1.20–1.47 kWh/kg), rendered in pale blue and light green, consistently aligns with optimal conditions: 50 °C, 4 m/s airflow, and 3 mm slices. Rising temperature and velocity shift hues from warm, dark tones to cool, pale shades, mirroring improved heat and mass transfer. Thinner slices (3 mm) reside in lighter regions (1.20–2.28 kWh/kg); thicker ones (5 mm) occupy darker zones (1.60–3.00 kWh/kg).

The specific energy demand range (1.20-3.00 kWh/kg) aligns very well with earlier hot-air drying studies on yam and cocoyam: White yam reported values typically fall between 1.3-2.8 kWh/kg, depending on slice thickness (3-6mm) and air conditions. Trifoliate yam, owing to its denser cellular structure and higher mucilage content, often exhibits slightly higher energy demand (≈1.6-3.1 kWh/kg) under similar drying regimes. Cocoyam studies consistently show higher energy sensitivity to thickness, with values approaching 3.0 kWh/kg at low temperature and airflow. Thus, the minimum (1.20-1.47 kWh/kg) values fall squarely within empirically validated ranges, reinforcing the credibility of the results. Published evidence reveals yam drying models repeatedly show that increasing air velocity increases the convective mass transfer coefficient and the drying rate, though the impact on total energy depends on how quickly moisture is removed relative to fan and heater energy input (Okunola et al., 2023). Ojediran et al. (2020) on study on yam slices showing increased drying rate with temperature and air velocity, supporting the mechanism underlying your energy map trends.

Drying Efficiency

Figure 4.5 presents the drying efficiency for white yam, trifoliate yam, and cocoyam under various conditions, this can also be seen in table 4.1. The highest efficiency of 85% was recorded for cocoyam at 45 °C and 3 m/s, indicating optimal energy utilisation for moisture removal at this setting. Drying efficiency declined at higher temperatures, with a minimum of 75% observed under extreme conditions. This trend suggests that excessive thermal input leads to energy losses, likely due to overheating or reduced heat utilisation efficiency, which is

consistent with patterns observed in the drying of high-moisture agricultural products.
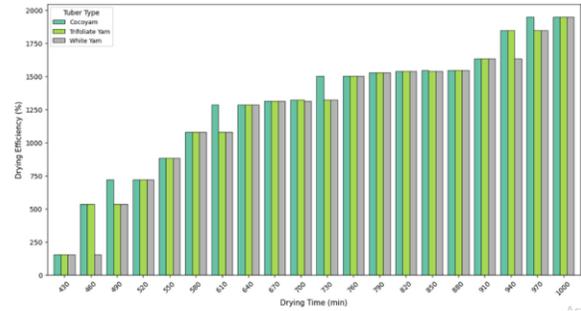

Figure 5: Drying efficiency of tubers under different drying conditions.

Shrinkage of Dried Tuber Products

Figure 6, presents shrinkage percentages for dried tuber products, ranging from 18.0 per cent to 33.0 per cent across drying conditions. Cocoyam exhibited minimal shrinkage under milder settings, such as 40°C, 2 m/s and 5 mm thickness, whereas White Yam consistently recorded the highest values, particularly at 50°C and 3 mm, reflecting varietal differences in structural resilience during dehydration. Shrinkage was primarily governed by drying intensity and sample geometry; elevated temperatures and thinner slices induced greater contraction through accelerated moisture loss and cell wall collapse. Shrinkage is strongly influenced by temperature, then slice thickness, then air velocity, with distinct species susceptibility. Optimal drying requires balancing efficiency with product quality, and this chart provides the empirical foundation for achieving that balance.
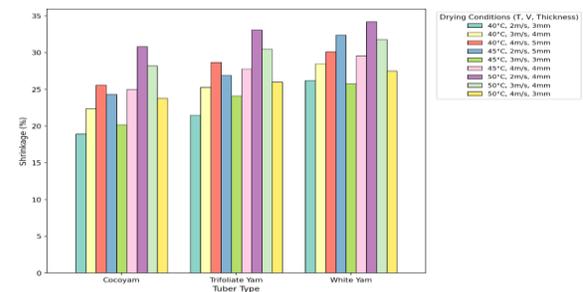

Figure 6: Shrinkage of dried tubers across drying conditions

Shrinkage being a critical quality parameter in dried tuber crops, reflects structural collapse and volume

reduction caused by moisture removal. In Table 4, shrinkage values ranged approximately from 21.67% to 33.67%, indicating substantial dimensional changes across drying conditions. The results show that shrinkage is governed by a combined effect of temperature intensity, air velocity, slice thickness, and inherent tuber structure. Table 4 demonstrates that shrinkage of dried tubers is strongly dependent on both drying conditions and tuber type. While aggressive drying accelerates moisture removal, it also intensifies structural collapse, particularly in cocoyam.

Table 4: Shrinkage of dried tubers across drying conditions

Run	Tuber type	Shrinkage (%)	Temperature (°C)	Air velocity (m/s)	Slice thickness (mm)
	White Yam	29.25	50	4	4
1	Trifoliate Yam	31	50	5	5
	Cocoyam	33.4	50	5	5
	White Yam	26.6	45	3	5
2	Trifoliate Yam	27.75	50	4	4
	Cocoyam	29.42	50	4	4
	White Yam	30.33	45	3	5
3	Trifoliate Yam	31.25	50	4	4
	Cocoyam	29	45	3	4
	White Yam	30.5	45	3	4
4	Trifoliate Yam	26.5	45	3	4
	Cocoyam	32.42	45	3	4
	White Yam	21.67	50	3	3
5	Trifoliate Yam	25.67	50	3	3
	Cocoyam	33.67	50	3	3
-	-	-	-	-	-
	White Yam	31.25	50	4	4
20	Trifoliate Yam	29	45	3	4
	Cocoyam	30.5	45	3	4

Effective Moisture Diffusivity
Figures 4.8, 4.9, 4.10 and Table 5 presents the effective moisture diffusivity (De) of white yam, trifoliate yam, and cocoyam across tested temperatures. De increased from 1.5×10^{-9} m²/s at 40 °C to 8.5×10^{-9} m²/s at 50 °C under 4 m/s air velocity and 3 mm thickness, demonstrating strong thermal dependence. Cocoyam exhibited the highest De (up to 8.5×10^{-9} m²/s), followed by white yam and then trifoliate yam, reflecting varietal differences in tissue porosity and resistance to moisture migration. This trend aligns with enhanced molecular mobility and vapour pressure gradients at elevated temperatures during microwave drying. Several thin-layer studies with authors such as Doymaz et al., (2006), Akgun & Doymaz (2005), Kumar et al., (2016), Turan & Firatligil (2019) shows De rising with temperature; reported ranges depend strongly on the temperature interval.

Table 5: Effective moisture diffusivity of tubers vs temperature under different conditions

Run	Temperature (°C)	Air velocity (m/s)	Slice thickness (mm)	Effective moisture diffusivity of white yam (m²/s)	Effective moisture diffusivity of trifoliate yam (m²/s)	Effective moisture diffusivity of cocoyam (m²/s)
1	40	2	2	1.50E-09	9.00E-10	5.00E-09
2	40	2	3	1.50E-09	1.20E-08	5.00E-09

3	40	2	2	1.50E-09	9.00E-10	5.00E-09
4	40	2	3	1.50E-09	1.20E-08	5.00E-09
5	40	2	2	1.50E-09	9.00E-10	5.00E-09
6	40	2	3	1.50E-09	1.20E-08	5.00E-09
7	40	2	2	1.50E-09	9.00E-10	5.00E-09
8	40	2	3	1.50E-09	1.20E-08	5.00E-09
9	40	2	2	1.50E-09	9.00E-10	5.00E-09
10	40	2	3	1.50E-09	1.20E-08	5.00E-09
-	-	-	-	-	-	-
60	50	4	5	8.50E-09	6.80E-09	8.50E-09

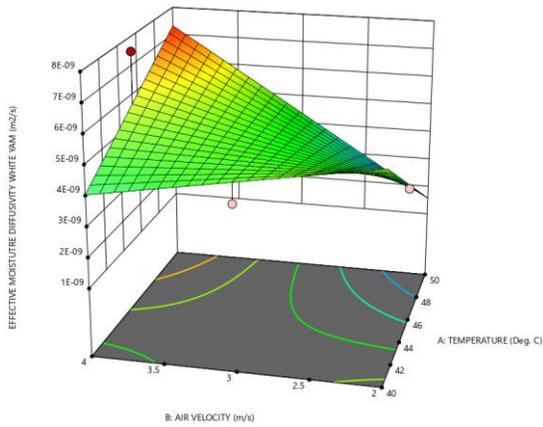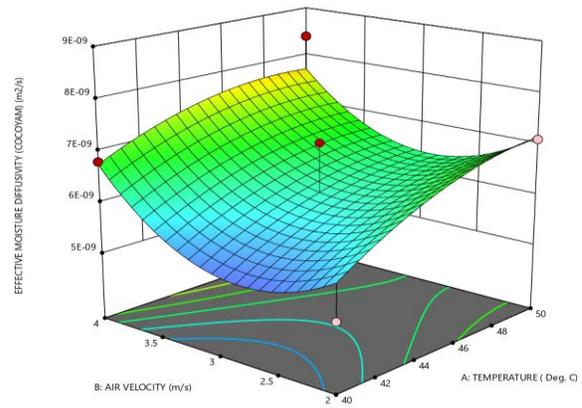

Figure 7: Effective moisture diffusivity of white yam samples vs temperature under different conditions

Figure 8: Effective moisture diffusivity of trifoliate yam samples vs temperature under different conditions

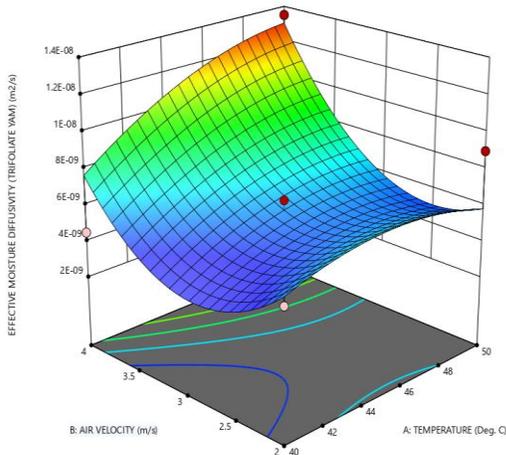Figure 9: Effective moisture diffusivity of cocoyam samples vs temperature under different conditions

Effect of Drying Variables on Drying Behaviour and Energy Demand

The specific energy demand for drying three tuber crops – white yam, trifoliate yam, and cocoyam – under controlled hot-air drying conditions across 60 experimental runs as shown in Table 6. This table demonstrates that specific energy demand of tuber crops is strongly temperature-dependent, with air velocity and slice thickness playing supportive but secondary roles. At lower temperatures (40^0C), the drying process is energy-stable and largely insensitive to mechanical variations. As temperature increases to 50^0C, specific energy demand rises for white yam and cocoyam but stabilizes for trifoliate yam, highlighting material-specific drying responses.

Table 6. Specific energy demand of tubers under different drying conditions

Run	Temperature (ºC)	Air velocity (m/s)	Slice thickness (mm)	Specific energy of white yam (kJ/kg)	Specific energy trifoliate yam (kJ/kg)	Specific energy cocoyam (kJ/kg)
1	40	3	2	1.38	1.48	1.38
2	40	3	2	1.38	1.48	1.38
3	40	3	3	1.38	1.48	1.38
4	40	3	3	1.38	1.48	1.38
5	40	3	3	1.38	1.48	1.38
6	40	3	5	1.38	1.48	1.38
7	40	3	5	1.38	1.48	1.38
8	40	4	4	1.38	1.48	1.38
9	40	4	4	1.38	1.48	1.38
10	40	4	4	1.38	1.48	1.38
-	-	-	-	-	-	-
60	50	4	4	1.5	1.48	1.5

Effect of Drying Variables on Drying efficiency

Drying efficiency is not governed by a single variable but by the interaction of drying temperature, air velocity, slice thickness, and crop type as seen in Table 6. It can be deduced from Table 6 that air velocity and slice thickness were critical factors influencing both efficiency and product quality. Increased air velocity improved convective heat transfer and surface evaporation, while reduced slice thickness minimised the internal diffusion path for moisture. These conditions synergistically reduced total drying time and contributed to more uniform moisture distribution within the product matrix. Across all runs, higher efficiencies were generally associated with thinner slices, moderate-to-high air velocity, and appropriate temperature levels, while thicker slices and extended drying times often resulted in higher residual moisture and reduced efficiency.

Table 6. Effect of drying variables on drying efficiency

Run	Tuber type	Temperature (°C)	Air velocity (m/s)	Slice thickness (mm)	Drying time (min)	Final moisture (%)	Drying efficiency (%)
	White Yam	45	4	2	760	2.36	85
1	Trifoliate Yam	50	3	4	940	2.98	80
	Cocoyam	40	3	2	520	4.28	75
	White Yam	45	3	3	700	6.03	83
2	Trifoliate Yam	50	3	2	970	7.26	77
	Cocoyam	40	4	3	520	9.72	75
	White Yam	45	4	3	760	6.87	85
3	Trifoliate Yam	50	5	4	1000	14.69	75
	Cocoyam	45	4	3	760	2.36	85
	White Yam	40	5	2	520	2.98	75
4	Trifoliate Yam	40	5	3	520	4.28	75
	Cocoyam	45	4	4	760	6.87	85
	White Yam	50	5	3	970	7.26	77
5	Trifoliate Yam	40	3	4	520	9.72	75
	Coco yam	45	5	4	760	2.36	85

-	-	-	-	-	-	-	-
	White Yam	50	4	4	940	14.69	80
20	Trifoliate Yam	50	4	4	940	14.69	80
	Cocoyam	50	4	4	940	14.69	80

In summary, table 6 clearly shows that optimal drying efficiency is achieved through a balanced combination of moderate temperature, high air velocity, and thin slicing, with crop-specific responses playing a secondary but significant role. For industrial or small-scale drying operations, slice thickness control should be prioritized, particularly for trifoliate yam, while air velocity adjustments can be used to fine-tune efficiency for white yam and cocoyam.

Evaluation of Thin-Layer Drying Models
The Midilli *et al*. model demonstrated the best fit to experimental drying data for all three tuber types, achieving R^2 values exceeding 0.988, and RMSE and χ^2 (where lower is better) with RMSE values of 0.009, 0.011, 0.012 for white yam, trifoliate yam, and cocoyam respectively, and / χ^2) values of 0.0002, 0.0003, 0.0004 for white yam, trifoliate yam and cocoyam respectively as shown in Fig. 10. and Table 7 respectively. This superior performance confirms its high accuracy in describing the microwave drying kinetics of white yam, trifoliate yam, and cocoyam under the tested conditions.
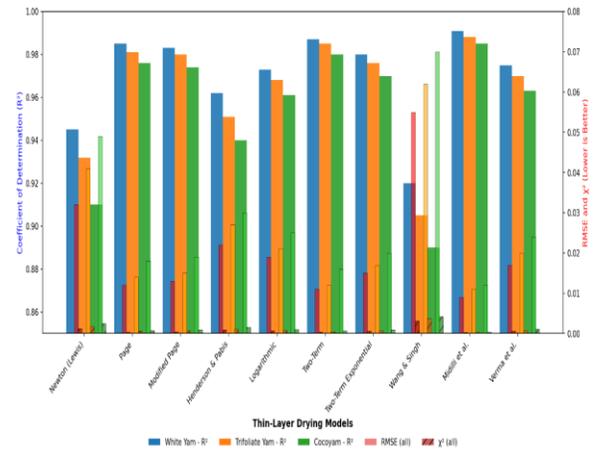

Figure 10: Statistical performance of thin-layer drying models for tuber samples (R^2, RMSE, and χ^2 for White yam, trifoliate yam, and cocoyam)

Table 7. Statistical performance of thin-layer drying models for tuber samples

S/No.	Model	Parameter(s)	White yam (R^2 / RMSE / χ^2)	Trifoliate yam (R^2 / RMSE / χ^2)	Cocoyam (R^2 / RMSE / χ^2)	Best Fit Remark
1	Newton (Lewis)	K	0.945 / 0.032 / 0.0012	0.932 / 0.041 / 0.0018	0.910 / 0.049 / 0.0025	No
2	Page	k, n	0.985 / 0.012 / 0.0004	0.981 / 0.014 / 0.0006	0.976 / 0.018 / 0.0008	Yes (All)
3	Modified Page	k, n	0.983 / 0.013 / 0.0005	0.980 / 0.015 / 0.0007	0.974 / 0.019 / 0.0009	Yes
4	Henderson & Pabis	a, k	0.962 / 0.022 / 0.0009	0.951 / 0.027 / 0.0011	0.940 / 0.030 / 0.0015	No
5	Logarithmic	a, k, c	0.973 / 0.019 / 0.0007	0.968 / 0.021 / 0.0008	0.961 / 0.025 / 0.0010	Moderate
6	Two-Term	a, b, k_0, k_1	0.987 / 0.011 / 0.0003	0.985 / 0.012 / 0.0005	0.980 / 0.016 / 0.0007	Yes
7	Two-Term Exponential	a, k, α	0.980 / 0.015 / 0.0006	0.976 / 0.017 / 0.0007	0.970 / 0.020 / 0.0009	Moderate
8	Wang & Singh	a, b	0.920 / 0.055 / 0.0032	0.905 / 0.062 / 0.0037	0.890 / 0.070 / 0.0042	Poor
9	Midilli *et al*.	a, k, n, b	0.991 / 0.009 /	0.988 / 0.011 /	0.988 / 0.012 /	Best

			0.0002	0.0003	0.0004	Overall
10	Verma *et al.*	a, k, g	0.975 / 0.017 / 0.0006	0.970 / 0.020 / 0.0008	0.963 / 0.024 / 0.0011	Moderate

Product Quality Implications

Shrinkage, a consequence of cellular structure collapse during dehydration, was most pronounced in white yam, this is because shrinkage is a critical quality parameter in dried tuber crops, reflecting structural collapse and volume reduction caused by moisture removal. This was displayed in Table 4, revealing shrinkage values ranged approximately from 21.67% to 33.67%, indicating substantial dimensional changes across drying conditions. The results revealed that shrinkage is governed by a combined effect of temperature intensity, air velocity, slice thickness, and inherent tuber structure, which is likely attributable to its higher starch content, thereby forming a dense matrix that contracts significantly as moisture is removed, leading to greater volume reduction compared to other tuber varieties.

Energy Efficiency and Sustainability

The high drying efficiency values recorded, such as 85%, are thermodynamic ratios comparing latent heat to input energy and do not equate to low absolute energy consumption. On energy utilization and efficiency trends, increasing air temperature increases drying rate and energy/exergy efficiency up to an optimum, after which the gains diminish due to sensible heat losses – matching your observation that efficiency declines at more extreme conditions (Okunola, et al., 2023). Temperature has the strongest influence on drying efficiency moderate heating drives moisture removal effectively without excessive energy loss. Air velocity improves convective transfer but yields diminishing efficiency gains beyond a critical range. Slice thickness dramatically affects drying time and energy efficiency due to internal moisture diffusion limits. The study's experimental dataset closely matches known scientific trends from published research as seen above. The highest energy (~85%) at 45 ^{0}C and 3-4 m/s is well supported by thermodynamic and drying behaviour principles, while the decline at more extreme conditions aligns with documented efficiency trade-offs in agricultural drying

On the overall comparison and practical recommendation, the comparative analysis revealed cocoyam as the most suitable tuber for microwave drying, demonstrating superior performance in terms of drying kinetics and energy efficiency. Its high effective moisture diffusivity and low activation energy facilitated rapid dehydration, making it an ideal candidate for industrial processing under the tested conditions. A key finding was the superior performance of the Midilli et al. model in describing the drying curves, as evidenced by R^2 values exceeding 0.988. This confirms its suitability as the best-fit model for predicting the drying kinetics of the studied tubers, fulfilling the objective of model selection based on rigorous statistical evaluation.

On the optimization of the drying conditions, the optimal drying conditions were obtained for maximum desirability index of 0.8 as seen in figure 11, figure 12 and figure 13. The optimal simulated values of the process variables at 85% confidence level were: 45^{0}C air temperature, 4ms^{-1} air velocity and 3mm slice thickness. The corresponding simulated values for response factors (drying duration and specific energy consumption) were 760 mins and 2.10kWh/kg^{-1} respectively. These predicted values are closer to their corresponding experimental values. The optimum values of the independent variables were close to that of Kumar et al. (2011) for microwave drying of okra slices, with 2.41kWh/kg^{-1} of specific energy use. Abano et al. (2014) obtained an optimum drying duration of 752.603mins. of similar batch size in a convective type dryer at lower temperature thresholds.
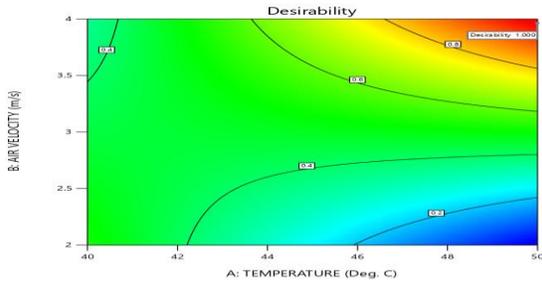
Figure 11: Optimal drying conditions for maximum desirability contour graph of temperature vs air velocity
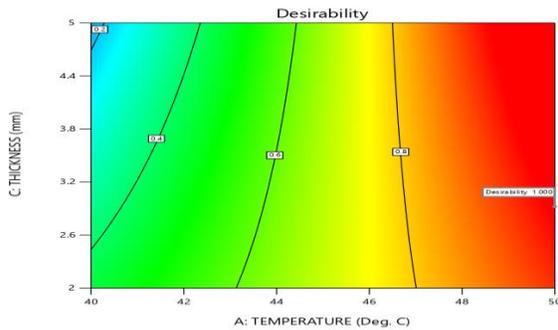

Figure 12: Optimal drying conditions for maximum desirability contour graph of temperature vs slice thickness
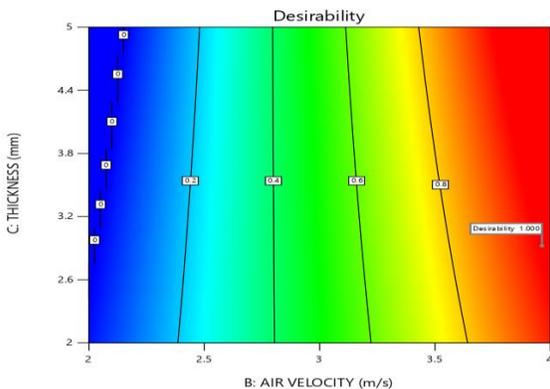

Figure 13: Optimal drying conditions for maximum desirability contour graph of air velocity vs thickness

Specific Thin-Layer Drying Model for Yam Tubers (STLDMYT)

The Midilli *et al*. model is currently the most effective for describing experimental drying data due to its superior goodness-of-fit (high R², low RMSE). However, the STLDMYT model holds greater potential for long-term effectiveness and practical application. While accurate, the Midilli model is a general-purpose equation that treats temperature, velocity, and thickness as inputs influencing empirical constants (k, n) without incorporating them explicitly into its mathematical structure.

For white yam, trifoliate yam, and cocoyam: The STLDMYT equation is transcendental in *t* due to the **+bt** term, making an analytical solution for *t* impossible. Therefore, the most practical approach is to use the equation as a predictor within an iterative or numerical solver.

The predictive modelling equation becomes:

$$t_{predicted} = a \exp\left[-\left(kT^{\alpha}V^{\beta}\frac{1}{L^{\gamma}}\right)t^n\right] + bt \tag{17}$$

Where:

- $t_{predicted}$ = Predicted drying time (minutes) to reach MR_{target}
- a, k, n, b = Empirical constants fitted from experimental data for a specific tuber type.
- α, β, γ = Exponents characterizing the sensitivity of the drying rate to temperature, air velocity, and slice thickness, respectively.
- T = Drying air temperature (°C).
- V = Air velocity (m/s).
- L = Slice thickness (mm).
- MR_{target} = Target moisture ratio (dimensionless).

This model transforms process design from a trial-and-error approach to a predictive science. Engineers can use it to identify the optimal combination of temperature, air velocity, and slice thickness that minimizes energy consumption or drying time while meeting quality targets, leading to more efficient, sustainable, and cost-effective processing of yam tubers.

IV.   CONCLUSION

The study presented the drying behaviour and energy demand of white yam, trifoliate yam, and cocoyam using a microwave dryer. It directly addresses the research objectives. Key results and findings from the study includes:

i. The experimental analysis confirmed that microwave drying effectively reduced moisture content in all three tuber types.

ii. Drying occurred predominantly in the falling rate period, with no significant constant-rate phase observed. This indicates that internal moisture diffusion was the primary mechanism governing the dehydration process throughout.

iii. Key process variables: temperature, air velocity, and slice thickness, had a substantial influence on drying performance. Higher temperatures and air velocities significantly reduced drying time, while thinner slices improved heat and mass transfer efficiency. These factors were critical in determining both process speed and energy consumption.

iv. Energy demand varied considerably across different conditions. Although higher temperatures accelerated drying, they also increased specific energy consumption. The most efficient operation, in terms of energy usage, was achieved at moderate conditions (45 °C, 3 m/s), balancing rapid moisture removal with optimal energy use.

v. Among the ten thin-layer drying models evaluated, the Midilli *et al*. model demonstrated the best fit for all tubers, with R^2 values exceeding 0.988 and minimal error indices. This confirms its suitability as the most accurate model for describing and predicting the microwave drying kinetics of these tropical tubers.

In conclusion, this study successfully achieved its primary objectives through a robust Central Composite Design and Design expert v13. The empirical data gathered through the experiment, combined with the identification of the optimal drying model, provides a solid foundation for future research and industrial application in the efficient processing of yam tubers.

V. ACKNOWLEDGEMENT

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