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Quality assessment of dried cassava slices: A freeze-drying approach

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Abstract

This research evaluates the quality of freeze-dried cassava slices under varying conditions of temperature, drying time, thickness, and vacuum pressure. Fresh cassava slices of three thicknesses (2 mm, 3.5 mm, and 5 mm) were subjected to freeze drying at primary drying temperatures of -15°C, -20°C, and -25°C, secondary drying temperatures of 40°C, 50°C, and 60°C, with vacuum pressures of 0.12 mbar, 0.16 mbar, and 0.2 mbar respectively. The results showed that moisture content decreased with increased drying temperature and time, while thicker slices retained higher moisture. Notably, the study found that the optimal combination of primary and secondary drying temperatures significantly reduced moisture content while preserving the nutritional quality of cassava slices. The findings highlight the potential of freeze drying as an effective preservation method for cassava, thus providing valuable insights into process optimization for improved product quality including colour of the freeze-dried product. It further explores the potential of freeze-drying technology to improve the shelf life and quality of cassava, a staple food in many developing countries. This study contributes to the knowledge base by presenting robust and practical guidelines for scaling up freeze drying technology in cassava processing. Also, it underscores the necessity of precise control over certain drying parameters to achieve the desired quality attributes in the final product hence, making them appealing and beneficial for consumption. This study has significant implications for the food processing industry especially in regions where cassava is a major dietary component as effective moisture diffusivity obtained in the freeze-drying process ranged from 10^{-11} to 10^{-10} m^2/s, activation energy obtained was within range therefore, aligning with that of agricultural products.

Keywords: Cassava; Freeze drying; Quality assessment; Moisture content; Nutritional preservation

1. Introduction

Cassava (*Manihot esculenta Crantz*), a crucial crop in tropical and subtropical regions, is a significant source of carbohydrates for millions of people [1]. It is also rich in vitamins C, which is essential for immune function, antioxidant protection, skin health and providing about 20% of daily value (DV) for vitamin C per 100grams; several vitamins B such as B1, B9 and B6 required for brain health and energy metabolism. In addition, it contains copper necessary for neurotransmitter synthesis, iron metabolism and energy production; fibre aiding in digestion and maintenance of healthy gut. In its role as a mainstay of the diet, cassava also plays a pivotal role in the industrial sector, finding application in the production of various food products, animal feed, and starch-based derivatives [2]. Cassava is widely consumed in various forms, including fresh, dried, and as processed products. However, its high perishability due to elevated moisture content limits its shelf life and industrial applications.

Drying is a method used to preserve cassava, but traditional methods, such as sun drying and oven drying, often degrade the quality of the product. The most conventional method used for drying is achieved by open sun drying which is not suitable for large scale production of cassava due to lack of ability to control the drying conditions, contamination of dust and insect or rodent infestation. In recent times, it is observed that drying could be done by using a hot-air oven [3]. Industrial and home usage of the oven is increasing and the primary use in the home is reheating while tempering,

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cooking, drying and pasteurization are the main applications in the industry [4]. Dehydrated foods and the dried components of many formulated or manufactured foods are now common articles of commerce and drying is becoming a standard processing operation [5]. Drying technology is now well defined and done with the aid of well tested types and sizes of equipment to produce billions of pounds of dry product annually. Drying extends product shelf life by reducing moisture that inhibits microbial growth and spoilage. Drying cassava adds to economic value by serving as a pathway to preserve products like tapioca and cassava flour widely used in food industries. Factors that influence the rate and total drying time include the characteristics of the products, mainly the geometry and particle size, spatial distribution of the products relative to heat transfer medium (drying air), features of the drying equipment, surface area, physical attributes of the drying medium or environment, temperature, air velocity, dryness of air, time, and atmospheric pressure [6].

Freeze drying operates on the principles of sublimation where frozen products are directly dehydrated. It involves two major stages, the primary drying (freezing) and secondary drying (desorption) stage thus, freezing, and drying temperatures respectively. The moist in the sample gets frozen to solid and then gets removed directly via sublimation (turning the ice into vapour). During the secondary drying phase, the vacuum pump creates a low-pressure condition necessary for the removal of solvents thereby resulting in product appearing dry. The solvent removed during this desorption stage is termed "bound". Furthermore, the vacuum pump creates a free vapour route for migrating condensable molecules by eliminating air from the chamber [7]. The three basic components of a freeze dryer include the product chamber, vacuum pump, and condenser.

Freeze drying is an effective alternative that preserves nutritional, structural, and sensory properties by removing moisture under low temperature and vacuum. The advantage of freeze drying is linked to its long preservation period due to 95% - 99.5% moisture removal [8]. Other benefits include minor contamination due to aseptic process, minimal loss in volatile chemicals, heat-sensitive nutrient, and fragrant components thus, less changes in the overall properties of the product since microbe growth and enzyme effect cannot occur at low temperatures [9]. In addition, constituents of the material dried remain homogeneously dispersed and sterility (i.e. absence of living microorganisms such as bacteria) of product can be achieved and maintained [10],[11]. The three methods of freeze drying commonly used are bulk drying, manifold drying and batch drying [11]. However, the effectiveness of freeze drying depends on several factors, including drying temperature, vacuum pressure, time, and sample thickness. Dried cassava is lightweight thus easy to store, transport to regions with limited access to it. Freeze-dried cassava can be used in various culinary applications such as thickening agents, flour for baking and as a base for some traditional dishes. Freeze drying cassava enhances the usability and economic potential of products aside preserving its nutritional benefits.

Quality assessment of agricultural products generally ensures that the end products meet predetermined standards for visual appeal, nutritional value and sensory attributes hence contributing to consumer satisfaction and market competitiveness [2]. It involves the proximate analysis of key constituents like protein, fat, moisture content, ash content and carbohydrates.

Hence, investigating the quality of cassava slices under varying freeze-drying conditions to predict the moisture content in order to obtain high quality cassava products promotes food security.

2. Material and methods

2.1 Sample Preparation

The cassava samples were sorted, peeled using a sterilized knife, washed with deionized water, and sliced using a thickness slicer to a thickness of 2mm, 3.5mm and 5mm. The slices were then freeze-dried.

2.2 Freeze Drying Procedure

A freeze dryer was used for the experiment. Secondary drying temperatures were set at 40°C, 50°C, and 60°C with corresponding vacuum pressures of 0.12 mbar, 0.16 mbar, and 0.2 mbar maintained in the vacuum pump at each temperature to ensure effective drying throughout the process. The freezing temperatures ranged from -25°C to -15°C. Drying times varied depending on the temperature and slice thickness as the freeze-dried cassava samples were monitored and weighed at every thirty minutes interval until constant weight was obtained.

2.3 Analytical Methods

2.3.1 Colour Analysis

The colour of fresh and freeze-dried cassava samples were analyzed using a colorimeter, measuring parameters L, a, and b as described by Alamu [12]. Samples were prepared by slicing and cleaning to ensure a contamination-free surface. The colorimeter was calibrated using standard white and black reference materials, with settings adjusted to illuminant D65 and a 10° observer angle. Measurements were taken at multiple points on the sample, and the data were used to calculate total colour difference (TCD) and whiteness index (WI) as in the equations below:

$$TCD = [(L^0 - L)^2 + (a^0 - a)^2 + (b^0 - b)^2]^{0.5} \quad \text{……………… (1)}$$

$$WI = 100 - [(100 - L)^2 + a^2 + b^2]^{0.5} \quad \text{………… (2)}$$

Where, L^0, a^0 and b^0 = fresh sample reading, L indicates lightness, a represents the red-green axis, and b represents the yellow-blue axis.

2.3.2 Moisture Content Determination

Moisture content was determined following AOAC standard [13]. Fresh cassava slices were weighed, freeze-dried at 40°C, 50°C, and 60°C, and the weight loss calculated. The percentage moisture content was obtained using:

$$\%\ M.C = \frac{W - W_d}{W_d} \times 100 \ \text{(dry basis) ………… (3)}$$

$$\%\ M.C = \frac{W - W_d}{W} \times 100 \ \text{(wet basis) ………… (4)}$$

Where, % M.C = percentage moisture content, W = weight of the fresh cassava sample, and W_d = weight of dried cassava sample.

2.3.3 Ash Content Determination

Ash content was determined by incinerating 10 g of the sample in a muffle furnace at 600°C for 3 hours. The percentage ash content was calculated as:

$$\text{Ash (\%)} = \frac{\text{Weight of ash}}{\text{Weight of sample}} \times 100 \ \text{……………… (5)}$$

2.3.4 Crude Fat Determination

Crude fat content was extracted using petroleum ether in a Soxhlet apparatus. After extraction, the solvent was evaporated, and the residue was weighed. The amount of cude fat was determined using:

$$\text{Crude Fat (\%)} = \frac{\text{Weight of fat}}{\text{Weight of sample}} \times 100 \ \text{……………… (6)}$$

2.3.5 Crude Fiber Determination

Crude fiber was determined by digesting the sample in sulfuric acid and sodium hydroxide solutions. The percentage crude fiber was calculated as:

$$\text{Crude Fiber (\%)} = \frac{\text{Loss in weight on ignition}}{\text{Weight of sample}} \times 100 \ \text{……………… (7)}$$

2.3.6 Crude Protein Determination

Protein content was determined via the Kjeldahl method. The nitrogen content was measured and converted to protein using a conversion factor:

$$\text{Protein (\%)} = \text{\%Nitrogen} \times 6.25 \ \text{……………… (8)}$$

2.3.7 Determination of Carbohydrate

Carbohydrate content was estimated by using the equation below:

$$\text{Carbohydrate (\%)} = 100 - (\text{Protein} + \text{Crude Fat} + \text{Ash Content} + \text{Crude Fiber}) \ \text{…………… (9)}$$

2.4 Effective Moisture Diffusivity

The effective moisture diffusivity (D_{eff}) measures the rate at which moisture moves through a material during drying. It is a vital parameter in the design and optimization of drying processes [14]. Effective diffusivity is also a key parameter in mathematical and kinetic models as it describes the drying kinetics during freeze drying. Models like the Fickian diffusion model utilize D_{eff} to predict moisture content changes over time [14]. The understanding of effective diffusivity helps optimize freeze drying conditions such as pressure and temperature. From Fick's diffusion equation for slab geometry objects, Equation (10) can be used to calculate effective moisture diffusivity.

$$MR = \frac{M_t - M_e}{M_o - M_e} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-(2n+1)\pi^2\frac{D_{eff}t}{4L^2}\right) \ldots\ldots\ldots\ldots (10)$$

Where, D_{eff} = effective moisture diffusivity (m^2/s), L = half-thickness of the sample, t = drying time and n = number of terms in the series

2.5 Activation Energy

Activation energy can be interpreted as the energy barrier that must be overcome in order to activate moisture diffusion [15]. In cassava drying studies, the determination of activation energy is crucial for optimizing drying conditions and predicting the impact of temperature on the drying kinetics as higher activation energy values implies greater sensitivity of the drying process to temperature changes [16]. Activation energy can be obtained as a relationship between the effective diffusivities and temperature therefore, assumed in the Arrhenius form as in Equation 11:

$$D_{eff} = D_o\exp\left[\frac{-E_a}{RT}\right] \ldots\ldots\ldots\ldots\ldots\ldots (11)$$

Where D_o = pre-exponential factor of the Arrhenius equation (m^2/s), E_a = is the activation energy (kJ/mol), R = universal gas constant (8.314 kJ/mol K), and T = the absolute temperature (K).

3 Results and discussion

3.1 Moisture Content Trends

Moisture content decreased with drying time across all experimental conditions. At 40°C, 2mm slices reduced from 74.34 ± 0.02% to 10.04 ± 0.02% within 570 minutes, while at 60°C, the same slices achieved 8.93 ± 0.04% in 420 minutes. Thicker slices (5 mm) retained more moisture compared to thinner slices at all temperatures, confirming the influence of thickness on drying efficiency.

3.2 Effect of Temperature on Drying Kinetics of Cassava Slices

Higher drying temperatures accelerated moisture removal, resulting in shorter drying times. At 60°C, the time to reach a final moisture content of 8.93, 9.92 and 10.01% for 2mm, 3.5mm and 5mm respectively was significantly less compared to 40°C. This aligns with previous findings that higher temperatures increase the rate of moisture diffusion [17]. However, the freeze-drying process revealed significant effects of temperature and thickness on the drying characteristics of cassava slices. Moisture content decreased with increasing drying temperature (40°C to 60°C) across all slice thicknesses (2mm, 3.5mm, and 5mm). Thinner slices (2mm) achieved the lowest moisture content and required shorter drying times due to more efficient mass transfer, while thicker slices required longer drying times due to higher density and reduced surface area-to-volume ratio.

Samples dried at 60°C exhibited the fastest drying times and lowest moisture content, with drying times ranging from 420 to 540 minutes. Conversely, samples dried at 40°C retained higher moisture content and required longer drying times (570–660 minutes). Thus, establishing findings that higher drying temperatures accelerate moisture loss and reduce drying time [1]. The drying rate was highest at the initial stage and declined as the moisture content decreased, governed by diffusion-based mass transfer as shown in Figures 1 - 3.

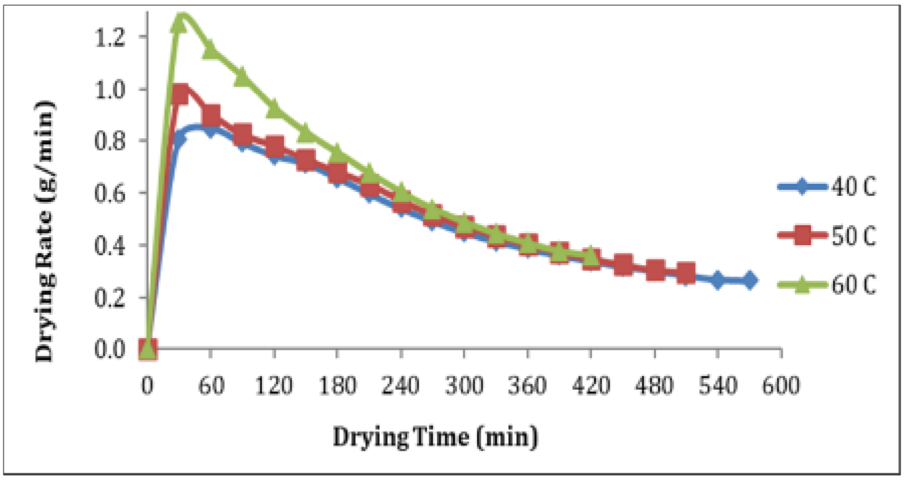

Figure 1 Drying rate curve at different temperatures for 2 mm

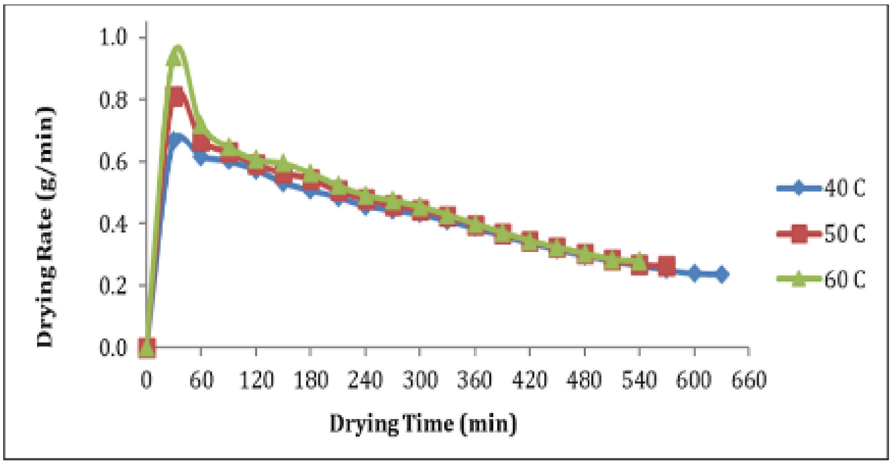

Figure 2 Drying rate curve at different temperatures for 3.5 mm

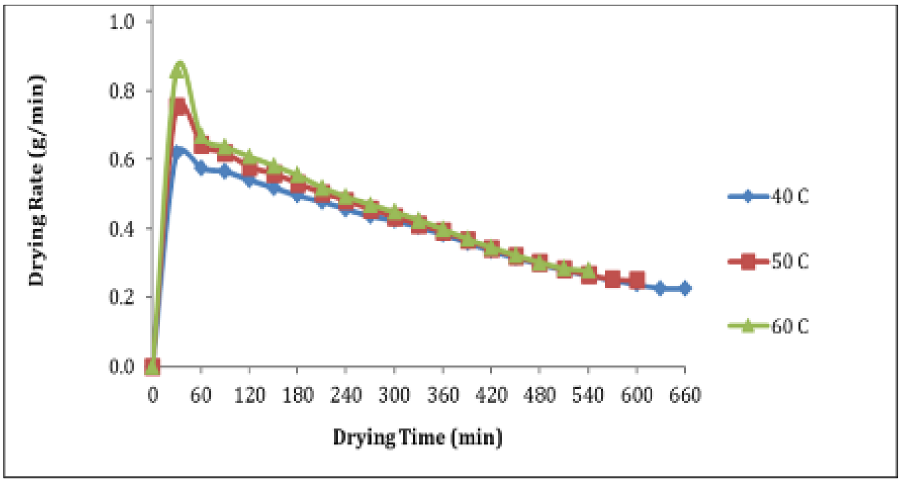

Figure 3 Drying rate curve at different temperatures for 5 mm

3.3 Quality Retention

3.3.1 Colour Analysis

Colour retention was influenced by drying temperature, with 40°C yielding the least colour change (low Total Colour Difference [TCD] values) across all thicknesses. Higher temperatures (50°C and 60°C) caused slight darkening and increased yellow hue due to oxidative and enzymatic browning. Colour retention across all drying temperatures preserved lightness (L*) and whiteness index (WI) was observed to be close to the fresh samples as in Table 1.

Table 1 Colour Analysis of Fresh and Freeze-dried Cassava Slices

Samples	L*	a*	b*	WI	TCD
Thickness – 2 mm					
C_{FR}	91.11	0.00	0.80	91.07	0.00
C_{40^oC}	88.99	0.00	1.00	88.94	2.13
C_{50^oC}	88.95	0.00	1.40	88.86	2.24
C_{60^oC}	88.89	0.00	2.00	88.71	2.52
Thickness – 3.5 mm					
C_{FR}	90.95	0.00	1.00	90.89	0.00
C_{40^oC}	88.87	0.00	1.20	88.81	2.09
C_{50^oC}	88.82	0.00	1.80	88.68	2.28
C_{60^oC}	88.77	0.00	2.30	88.54	2.54
Thickness – 5 mm					
C_{FR}	89.95	0.00	1.20	89.88	0.00
C_{40^oC}	88.80	0.00	1.70	88.67	1.25
C_{50^oC}	88.76	0.00	1.90	88.60	1.38
C_{60^oC}	88.74	0.00	2.80	88.40	2.01

Where,

C_{FR} = Fresh cassava sample
C_{40^oC} = Cassava freeze-dried at secondary temperature of 40 °C
C_{50^oC} = Cassava freeze-dried at secondary temperature of 50 °C
C_{60^oC} = Cassava freeze-dried at secondary temperature of 60 °C

3.3.2 Nutritional Integrity

Freeze-dried samples processed at 40 °C retained more nutritional components on proximate analysis, suggesting minimal nutrient loss due to reduced thermal exposure. Sublimation under constant vacuum pressure and uniform secondary drying temperatures ensured product integrity and minimized nutrient degradation. The proximate analysis obtained is as presented in Table 2.

3.3.3 Moisture Content

Moisture content ranged from 8.93% to 10.27% for all dried samples, with thinner slices exhibiting the lowest moisture content, highlighting their superior drying efficiency. Lower drying temperatures retained more moisture, while higher temperatures reduced moisture content, extending the shelf life of cassava slices.

3.3.4 Crude Fibre

Crude fibre content was highest in thicker slices (5mm) but decreased slightly with increasing drying temperature. Samples dried at 40 °C retained the most fibre, irrespective of thickness, suggesting that low-temperature freeze-drying minimizes fibre loss.

3.3.5 Crude Fat

Crude fat content was minimal across all samples but decreased with increasing drying temperature. The 2mm slices had the lowest fat content, while 40 °C freeze-dried samples retained higher fat levels compared to those processed at 50 °C and 60 °C.

3.3.6 Crude Ash Content

Ash content increased with temperature for 2mm and 3.5mm slices, reflecting better mineral retention at higher drying temperatures. However, 5mm slices exhibited higher ash content at 40 °C, indicating variability in mineral preservation linked to slice thickness.

3.3.7 Crude Protein

Protein content decreased with increasing drying temperature, with 40 °C dried samples retaining the most protein. Thinner slices preserved protein content better than thicker slices due to reduced exposure to thermal degradation.

3.3.8 Carbohydrate Content

Carbohydrate content increased with drying temperature and was highest in thinner slices due to faster drying rates and reduced oxidation. This demonstrates the effectiveness of freeze-drying in preserving cassava's carbohydrate-rich composition.

3.3.9 Moisture Content and Drying Time

Initial moisture content decreased as drying temperature increased, with thicker slices exhibiting lower initial moisture content on a wet basis. Final moisture content was inversely proportional to drying temperature and directly proportional to slice thickness. Higher temperatures (60 °C) significantly reduced drying time, affirming the positive correlation between temperature and drying efficiency as in Figures 4 – 6.

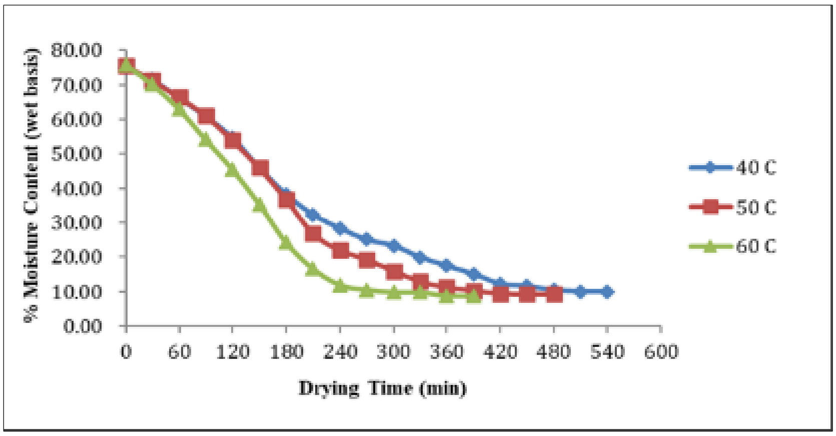

Figure 4 Drying time curve for 2mm

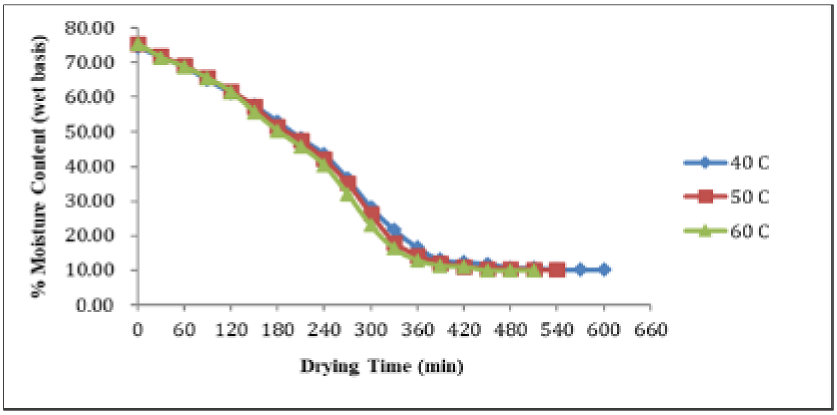

Figure 5 Drying time curve for 3.5mm

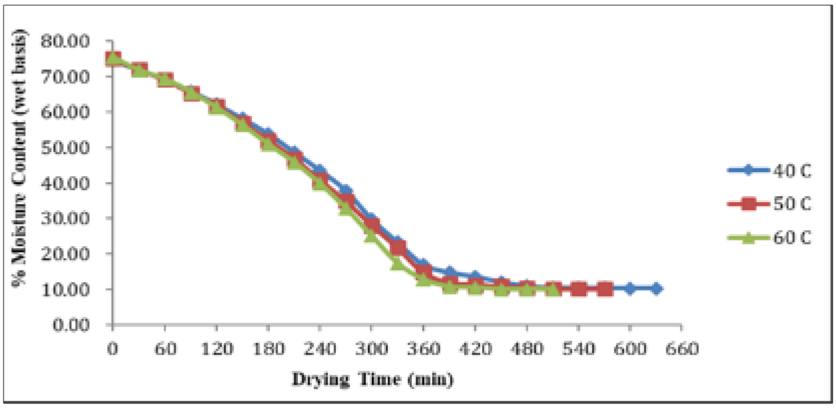

Figure 6 Drying time curve for 5mm

Table 2 Summary of the Proximate Composition of Cassava Slices

Samples	% Moisture	% Crude Fibre	% Crude Fat	% Ash Content	% Crude Protein	% Carbohydrate
Thickness – 2 mm						
CFR	74.34 ± 0.02	0.28 ± 0.02	0.34 ± 0.01	0.32 ± 0.01	1.55 ± 0.02	87.44 ± 0.05
C40oC	10.04 ± 0.02	0.36 ± 0.02	0.22 ± 0.02	0.16 ± 0.01	1.44 ± 0.03	87.78 ± 0.04
C50oC	9.22 ± 0.03	0.33 ± 0.02	0.17 ± 0.02	0.22 ± 0.02	1.36 ± 0.03	88.70 ± 0.04
C60oC	8.93 ± 0.04	0.31 ± 0.02	0.09 ± 0.01	0.26 ± 0.01	1.14 ± 0.03	89.27 ± 0.03
Thickness – 3.5 mm						
CFR	74.87 ± 0.02	1.28 ± 0.02	1.19 ± 0.02	0.67 ± 0.02	1.79 ± 0.02	84.78 ± 0.03
C40oC	10.19 ± 0.02	1.34 ± 0.02	1.04 ± 0.03	0.73 ± 0.02	1.42 ± 0.03	85.28 ± 0.04
C50oC	10.02 ± 0.03	1.32 ± 0.01	0.92 ± 0.02	0.99 ± 0.02	1.15 ± 0.03	85.60 ± 0.03
C60oC	9.92 ± 0.03	1.30 ± 0.02	0.68 ± 0.02	1.06 ± 0.02	0.87 ± 0.03	86.17 ± 0.04
Thickness – 5 mm						
CFR	75.25 ± 0.02	2.43 ± 0.02	1.22 ± 0.02	2.76 ± 0.01	1.83 ± 0.02	81.44 ± 0.04
C40oC	10.27 ± 0.02	2.51 ± 0.01	1.07 ± 0.02	2.80 ± 0.02	1.52 ± 0.03	81.83 ± 0.04
C50oC	10.10 ± 0.03	2.48 ± 0.01	0.92 ± 0.02	2.62 ± 0.02	1.31 ± 0.03	82.58 ± 0.04
C60oC	10.01 ± 0.02	2.43 ± 0.02	0.73 ± 0.02	2.41 ± 0.02	1.13 ± 0.03	83.29 0.03

3.4 Effective Moisture Diffusivity

Moisture content of cassava at the initial stage of the drying process influences effective diffusivity. Thus, effective moisture diffusivity obtained in the freeze-drying process ranged from 10^{-11} to 10^{-10} m^2/s from a plot of natural logarithm of moisture ratio against time. It is observed that at high temperature, a high value of effective moisture diffusivity is obtained. Thus, effective moisture diffusivity (D_{eff}) increases with increase in temperature. Similar observation had been reported for increase in diffusivity coefficient as drying temperature increases [18],[19],[20]. Effective moisture diffusivity for dried food material ranges from 10^{-11} to 10^{-9} m^2/s and increases with increase in thickness and temperature [17].

3.5 Activation Energy

In cassava drying studies, the determination of activation energy is crucial for optimizing drying conditions and predicting the impact of temperature on the drying kinetics as higher activation energy values implies greater sensitivity of the drying process to temperature changes [16]. The values of respective activation energy and Arrhenius constant were estimated to be 19.24kJ/mol and 2.88 × 10^{-11} m^2/s, 19.41kJ/mol and 1.02 × 10^{-10} m^2/s and 19.81kJ/mol and 2.08 × 10^{-10} m^2/s for thickness 2mm, 3.5mm and 5mm respectively for the cassava freeze drying process. Thus, corresponding with the value of 19.92 kJ/mol for sweet potatoes [21], 15.53 and 26.98 kJ/mol for treated and untreated cassava [20], [22], [23] respectively. The activation energy levels obtained in this study are consistent with the recognized range for food materials, which spans from 12.7 to 110 kJ/mol [24].

4 Conclusion

The study showed that thinner slices ensured uniform drying and consistent nutrient profiles. The importance of optimizing freeze-drying parameters for effective moisture removal and nutrient retention was confirmed. The findings align with existing literature, emphasizing that vacuum pressure at varying temperatures facilitates moisture removal through sublimation during primary drying (freezing temperature) and efficient desorption during secondary drying [7]. Thinner slices and higher drying temperatures led to faster drying, reduced moisture content, and better carbohydrate retention. Hence, freeze drying is an effective drying method that preserves quality and nutritional content for freeze-drying of 2mm, 3.5mm, and 5mm cassava slices. Additionally, the study highlighted the significance of reducing primary (freezing) drying temperature to enable proper freezing and subsequent sublimation throughout the drying process.

It further demonstrated that freeze drying effectively preserves cassava quality while minimizing moisture content. Notably, changes were relatively consistent across different thicknesses and drying temperatures, with the most significant impact of freeze drying the cassava observed in moisture and carbohydrate content. The findings provide a foundation for scaling up freeze drying applications in cassava processing, contributing to improved preservation techniques for perishable crops.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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