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Evaluation of Quality Parameters of High-Quality Cassava Flour Dried Using Nigerian Stored Products Research Institute (NSPRI) Parabolic-Shaped Solar Dryer

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Abstract

Cassava (*Manihot esculenta*) is a crucial staple crop widely consumed across tropical regions, particularly in sub-Saharan Africa, due to its adaptability and resilience to harsh climatic conditions. However, its high perishability necessitates immediate processing to prevent spoilage and potential toxin development. This study investigated the impact of solar drying on the quality attributes of High-Quality Cassava Flour (HQCF) using the NSPRI Parabolic-Shaped Solar Dryer (PSSD). The cassava variety of TME 419 was processed following standard procedures, including peeling, washing, grating, dewatering, drying, milling, and sieving. The drying process was carried out in the PSSD to reduce moisture content while preserving the nutritional and functional qualities of the final product. There was a significant reduction in moisture content from 66.83 ± 1.11% (wet basis) in freshly harvested cassava to 4.00 ± 1.00% (wet basis) in HQCF, improving its shelf-stability. The ash, crude fiber, and crude protein contents also decreased, while crude fat varied across processing stages. Vitamin analysis showed notable retention of Vitamin C (4.78 ± 0.1929 mg/100 g), Vitamin B1 (1.1633 ± 0.0929 mg/100 g), and Vitamin B9 (2.13 ± 0.0361 mg/100 g), demonstrating the effectiveness of the solar drying technology in preserving essential nutrients. Mineral analysis indicated low levels of magnesium, calcium, phosphorus, and zinc, similar to previously reported values. Functional properties, including bulk density (0.67 ± 0.02 g/ml), water absorption capacity (117.33 ± 6.51%), and swelling capacity (53.33 ± 5.77%), suggest that HQCF produced via solar drying is suitable for various food applications. The study confirms that solar drying using PSSD effectively reduces moisture content while maintaining the nutritional and functional qualities of the HQCF. This technology presents a sustainable approach to HQCF production. It could be concluded that a cost-effective green energy powered dryer like NSPRI PSSD has potential to produce HQCF that can compete favorably with other HQCF from other sources in terms of quality retention and food safety.

Categories: Food and Pharmaceutical Engineering, Agricultural Machinery and Automation, Bioprocess Engineering
Keywords: cassava, functional properties, hqcf, pasting properties, solar-drying, proximate composition, mathematical modelling, numerical simulation, machine learning, analysis

Introduction

Cassava (*Manihot esculenta*) is a vital root crop cultivated extensively across tropical regions, serving as a primary energy source for over 800 million people worldwide [1]. Its adaptability to diverse climatic conditions and resilience to drought make it indispensable for food security, particularly in sub-Saharan Africa [2]. However, cassava roots are highly perishable, because its roots undergo rapid physiological deterioration within 24-72 hrs after harvest, necessitating prompt processing to prevent spoilage and potential toxin development [3]. One of the effective preservation methods is transforming cassava into value-added products such as High-Quality Cassava Flour (HQCF), which extends shelf-life and enhances versatility in various culinary applications. The processing involves peeling, washing, grating, dewatering, drying, milling, and sieving. Notably, drying is a critical step that significantly influences the quality of the final product [4,5].

Solar drying has emerged as an efficient and sustainable technique for the production of some cassava value-added products that require drying [6]. Utilizing solar dryers will not only accelerate the drying process, but also ensures a cleaner product by minimizing contamination from insects, birds and other contaminating agents [7, 8]. A study has demonstrated that naturally ventilated screen solar dryers can reduce moisture content to less than 14.3% within 1.5 hrs depending on the agricultural material, outperforming traditional open-air drying methods [9]. Extending this identified potential of solar dryers, such as the Nigerian Stored Products Research Institute (NSPRI) parabolic-shaped solar dryer (PSSD), to the drying of unfermented cassava mash during HQCF production will reduce the production cost of such

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a product without compromising its quality and safety.

The economic significance of HQCF production extends beyond individual farmers to national economies. It offers income diversification opportunities, creates employment, and contributes to food security by providing a stable, non-perishable food source [10]. Moreover, HQCF can serve industrial purposes, such as in breweries and bakeries, thereby reducing reliance on imported wheat flour and strengthening local economies [11].

Investigating the impact of drying methods on the quality attributes of unfermented cassava mash is crucial. Research indicates that drying parameters, including temperature and air velocity, significantly affect the drying rate and quality of cassava flour [12]. For instance, reduced moisture removal time and higher drying temperatures have been associated with improved drying rates. Additionally, the choice of drying surface and bed depth can influence the efficiency of the drying process and the quality of the final product [13].

Therefore, the transformation of cassava roots into cassava flour such as HQCF using solar drying methods presents a sustainable approach to enhancing food security and economic growth. Understanding the effects of different drying approach on the quality of unfermented cassava mash is essential for optimizing processing methods and ensuring the production of high-quality cassava flour. Hence, this study investigated the effect of solar drying on quality attributes of dried unfermented cassava mash for the production of HQCF.

Materials And Methods

Description of NSPRI parabolic-shaped solar dryer

The NSPRI PSSD as shown in Figure *1* is an improved solar drying system designed with a parabolic-shaped frame covered with a UV-stabilized transparent material that traps and concentrates solar energy to enhance drying efficiency. It is equipped with a black body floor that absorbs and retains heat, with air vents and pneumatic aspirator for air flow and moisture removal. The PSSD operates on greenhouse effect, achieving higher temperatures and faster drying rates than traditional solar drying, while protecting products from rain, dusts, and pests.

FIGURE 1: NSPRI parabolic-shaped solar dryer

Procurement of cassava roots and preparation of high-quality cassava flour

Cassava (TME 419) was procured from an International Institute of Tropical Agriculture (IITA) certified farmer in Akinyele LGA, Ibadan Oyo state. The production of HQCF followed a systematic process that incorporated the PSSD developed by the NSPRI. According to the Food and Agriculture Organization [14], the process thus began with the harvesting and selection of cassava roots. Only mature and healthy cassava roots were chosen to ensure high starch content and minimize impurities.

Sample preparation

Following harvesting, cassava roots were peeled to remove the outer skin, which contains unwanted materials. After peeling, the cassava roots were washed thoroughly to ensure that soil and contaminants were removed. It has been indicated that thorough washing is necessary to maintain hygiene and product safety [15]. The next stage was grating, where the cleaned cassava roots were ground into a smooth fine mash. It has been observed that mechanical graters are commonly used in commercial production to increase efficiency [16]. After grating, bagging of the mash was done, then, dewatering process was carried out by pressing the grated pulp using hydraulic press to remove excess moisture which is crucial to reduce drying time and improve the final product's texture. Afterwards, pressed cassava cake was granulated into smaller granules manually by breaking down with clean hands and rubbing through a sieve, which is to facilitate even drying by increasing the surface area of the cassava particles [15].

The drying stage was then carried out using the NSPRI PSSD as shown in Figure *2*. Cassava should be dried until its moisture content falls below 12% to meet the industry standards [14]. After drying, the cassava granules were properly milled into fine flour to ensure a smooth and uniform product suitable for various applications. The next step involved sieving, where the flour was passed through mesh screens to achieve uniform particle size. This helped to improve the texture and consistency of the flour [14]. The flour was thus kept in moisture proof bags to maintain its quality during storage and transportation. According to IITA [15], proper packaging prevents contamination and extends the shelf life of the product. Figure *3* shows the flow chart for the processing operations carried out during the production of HQCF.

FIGURE 2: Drying of high-quality cassava flour using NSPRI PSSD

NSPRI, Nigerian Stored Products Research Institute; PSSD, Parabolic-Shaped Solar Dryer

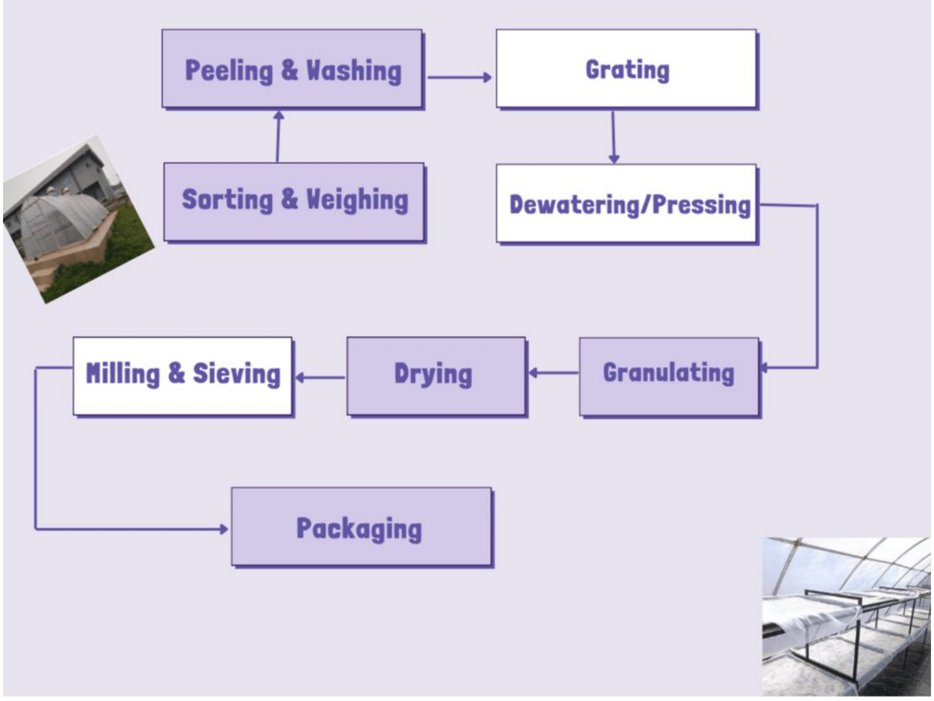

FIGURE 3: Process flow chart for the production of high-quality cassava flour

Determination of quality attributes of high-quality cassava flour

HQCF quality parameters are typically determined through a combination of physical, chemical, and microbial analyses. The methodology utilized to assess these parameters included:

(i) Physical Properties

Moisture Content: This was measured using the oven-drying method at 105°C until a constant weight is achieved using AOAC 925.10 standard [17].

Bulk Density: This was done by volumetric method using AOAC 2016.01 Standard [17].

(ii) Chemical Properties

Ash Content: Determined by incinerating a sample at 550°C and measuring the residue according to AOAC 923.03 [17].

Cyanide Content: Determined using titration or enzymatic methods to ensure safe consumption using AOAC 915.03 standard [17].

Fiber Content: Measured through enzymatic hydrolysis and fiber extraction techniques using AOAC 985.29 for fiber [17].

Fat Content: Extracted using Soxhlet apparatus with a solvent such as hexane using AOAC 2003.05 standard [17].

(iii) Functional Properties

Water Absorption Capacity (WAC): Measured by soaking a known amount of flour in water and calculating absorption using AACC 56-30 standard [18].

Swelling Power and Solubility: Determined by heating flour in water and measuring sediment and dissolved content using AACC 61-02 standard [18].

Oil Absorption Capacity: The Oil Absorption Capacity was determined using the AACC International

Approved Method 56-30 [18]. All analysis were conducted in triplicates and results were recorded as mean ± standard deviation.

Dispersibility: Dispersibility for HQCF samples were determined using AOAC 925.10 standard [17]. Analysis were performed in triplicates, and the results were expressed as the mean ± standard deviation.

(iv) Pasting Properties

Standard protocol as described by Newport Scientific (1998), the American Association of Cereal Chemists [18], and the International Organization for Standardization (ISO 6647-1:2020) was used.

The viscosity as part of pasting properties was determined using a Rapid Visco Analyser (RVA) in accordance with the standard method AACC 76-21.01 [18].

(v) Microbiological Analysis

Total Plate Count: Bacterial contamination was determined using ISO 4833-1:2013 standard [19].

Yeast and Mould Count: Assessment of fungal contamination using ISO 21527-2:2008 [20].

Coliform and *E. coli* Presence: To ensure hygiene and safety using ISO 4832:2006 standard [21].

Statistical analysis

Data obtained for proximate composition from the experiment were subjected to statistical analysis using One-way Analysis of Variance (ANOVA) to determine significant differences among the means of the three sample groups (Wholesome, Unfermented Cassava Mash, and High Quality Cassava Flour). When the ANOVA indicated significant differences $(p < 0.05)$, the means were separated using Tukey's Honest Significant Test (HSD) Post-hoc test to identify where the difference occurred.

All results were expressed as mean ± standard deviation of the three replicates. However, superscript letters (a, b, c) were used to denote statistically significant differences among mean in each column of the result of proximate composition for comparative statistical tests. Statistical analyses were performed using SPSS version 20.0 (IBM Corp, Armonk, NY, USA).

Results

Nutritional composition of freshly harvested cassava, unfermented cassava mash, and high-quality cassava flour (HQCF)

S/N	Sample ID	Moisture content (%)	Ash content (%)	Crude fat (%)	Crude fiber (%)	Crude protein (%)	Carbohydrate (%)
1	Wholesome	66.833 ± 1.109^a	7.430 ± 1.007^a	1.100 ± 0.050^b	5.850 ± 0.35^a	2.333 ± 0.404^a	14.787 ± 3.073^c
2	Unfermented cassava mash	49.550 ± 0.776^b	1.667 ± 0.289^b	3.883 ± 0.580^a	2.200 ± 0.347^b	1.367 ± 0.577^b	58.767 ± 0.653^b
3	HQCF	4.000 ± 1.000^c	1.667 ± 0.577^b	1.600 ± 0.529^b	2.333 ± 0.577^b	1.073 ± 0.89^b	89.327 ± 0.777^a

TABLE 1: Proximate composition of freshly harvested cassava, unfermented cassava mash, and HQCF

Note: Values are mean ± Standard Deviation. Means in the same column with different superscript letters (a, b, c) differ significantly $(P < 0.05)$ using one-way ANOVA and Tukey's HSD. ANOVA, Analysis of Variance; HSD, Honest Significant Test; HQCF, High-Quality Cassava Flour

Table *1* compares the proximate composition of freshly harvested cassava, unfermented cassava mash, and HQCF to determine the significance of changes due to processing and drying.

Result of vitamins of high-quality cassava flour

Vitamin composition	Vitamin content (µg/100 g)
Vitamin C	4.780 ± 0.193
Vitamin B1	1.163 ± 0.093
Vitamin B9	2.130 ± 0.036

TABLE 2: Vitamin contents of high-quality cassava flour

The vitamin content of HQCF produced using the NSPRI PSSD is presented in Table 2.

Result of some mineral contents of high-quality cassava flour

Table 3 presents result of some mineral contents of HQCF

Minerals composition	Mineral content (mg/100 g)
Mg	0.352 ± 0.001
Ca	0.207 ± 0.001
P	0.267 ± 0.002
K	0.583 ± 0.003
Zn	0.767 ± 0.006

TABLE 3: Mineral contents of the high-quality cassava flour

Result of the functional properties of high-quality cassava flour

Sample ID	Bulk density (g/ml)	Swelling capacity (%)	Oil absorption (%)	Water absorption (%)	Dispersibility (%)
HQCF	0.667 ± 0.022	53.333 ± 5.774	143.667 ± 3.215	117.333 ± 6.506	68.000 ± 1.000

TABLE 4: Functional properties of the HQCF

HQCF, High-Quality Cassava Flour

The functional properties of HQCF produced using the NSPRI PSSD are shown in Table 4.

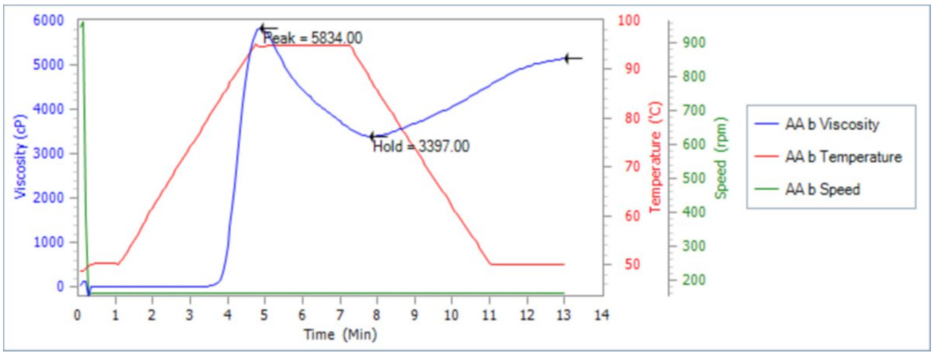

FIGURE 4: Graphical representation of pasting properties of HQCF produced using NSPRI PSSD (Replicate 1)

HQCF, High-Quality Cassava Flour; NSPRI, Nigerian Stored Products Research Institute; PSSD, Parabolic-Shaped Solar Dryer

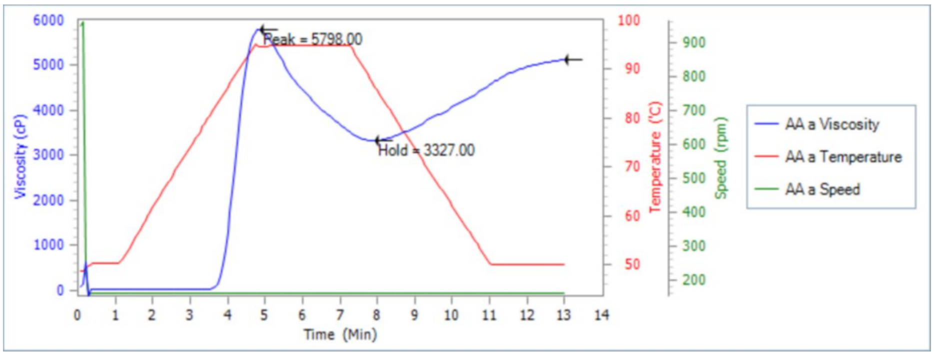

FIGURE 5: Graphical representation of pasting properties of HQCF produced using NSPRI PSSD (Replicate 2)

HQCF, High-Quality Cassava Flour; NSPRI, Nigerian Stored Products Research Institute; PSSD, Parabolic-Shaped Solar Dryer

Result of microbial qualities of the high-quality cassava flour

Sample ID	Total bacteria count	Total fungal count	Total Coliform count
HQCF R	NVG	NVG	NVG
	NVG	NVG	NVG
HQCF M	NVG	4	NVG
	NVG	7	NVG
HQCF D	5	NVG	NVG
	NVG	NVG	NVG
HQCF F	7	NVG	NVG
	3	NVG	NVG

TABLE 5: Microbial load of unfermented HQCF

HQCF R, Freshly harvested Cassava Roots; HQCF M, dewatered cassava mash; HQCF D, HQCF dried granules; HQCF F, HQCF flour; HQCF, High-Quality Cassava Flour; NVG, No Visible Growth

Discussion

Result of the proximate composition of raw cassava root, unfermented cassava mash and HQCF

Moisture Content

The moisture content of the freshly harvested cassava root as presented in Table *1* was 66.833 ± 1.109^{a}%, significantly higher than unfermented cassava mash (49.550 ± 0.776^{b}%) and HQCF (4.000 ± 1.000^{c}%). The first reduction in moisture content during the conversion of root to unfermented mash was due to the production processes that exposed the cells of the root for easier release of moisture. The second stage moisture reduction was as a result of the drying process which caused simultaneous heat and mass transfer. The significant reduction in the moisture content of the HQCF aligns with findings from studies [22], who reported moisture values ranging from 9.90% to 10.33% for HQCF dried under different conditions. The lower moisture content in this study suggests that the NSPRI PSSD is effective in achieving better moisture reduction of the crop, enhancing the shelf-life of the final product.

Ash Content

Wholesome freshly harvested cassava recorded an ash content of 7.430 ± 1.007^{a}% as indicated in Table *1*, which reduced significantly to 1.667 ± 0.289b% in unfermented cassava mash and remained at 1.667 ± 0.577^{b}% in HQCF. It was reported by researchers [22] that ash content value between 1.04% and 2.15% indicates that the HQCF produced in this study falls within an acceptable range. The reduction in ash content is expected as processing typically results in the loss of some mineral components through dewatering process.

Crude Fat

The crude fat content of freshly harvested cassava was 1.100 ± 0.050^{b}% as illustrated in Table *1*, which increased to 3.883 ± 0.580^{a}% in unfermented cassava mash before it decreased to 1.600 ± 0.529^{b}% in HQCF. Similar trends have been reported in literature according to studies [23], where fat content in HQCF was found to range between 0.50% and 2.10%. This variation could be attributed to the processing methods used, which may lead to the concentration or loss of lipids at different stages. The initial increase in crude fat may result from the relative concentration effect during water loss, while the subsequent reduction could be due to lipid degradation or leaching during fermentation and drying processes, as also suggested by previous studies [24].

Crude Fiber

Crude fiber content in wholesome cassava was 5.85 ± 0.35% as displayed in Table *1*, which decreased significantly in unfermented cassava mash (2.20 ± 0.35%) and remained significantly the same in HQCF (2.33 ± 0.58%). It was reported by researchers [22] that crude fiber values between 2.00% and 3.50% for

HQCF are typical, indicating that the values obtained in this study are within the earlier reported range in the literature. The decrease in crude fiber content during processing can be attributed to the breakdown of fibrous materials as a result of mechanical disintegration, fermentation, and sieving operations. This operation is desirable as it improves product's texture and overall quality of the flour [23].

Crude Protein

The result in Table *1* show that crude protein content in wholesome cassava was 5.850 ± 0.350^{a}%, which significantly reduced to 1.367 ± 0.577^{b}% in unfermented cassava mash and further to 1.073 ± 0.890^{b}% in HQCF. The protein content in this study is lower than the range (3.73-4.75%) reported by researchers [22]. This may be due to differences in cassava varieties, processing methods, or drying conditions.

This study demonstrated significant compositional changes in cassava during processing and drying using the NSPRI PSSD. The reduction in moisture, ash, crude fiber, and protein content aligns with literature values according to studies [23], confirming the effectiveness of the solar drying technology in production of HQCF.

Result of Vitamins of High-Quality Cassava Flour

The vitamin content of HQCF produced using the NSPRI PSSD is presented in Table *2*.

Vitamin C (Ascorbic Acid)

The Vitamin C content in the HQCF sample produced using NSPRI PSSD (4.78 mg/100g) is higher than the 2.08 mg/100 g reported in a study on sweet cassava flour [24] as shown in Table *2*. However, it is significantly lower than the 45 mg/100 g reported in another study [25]. The variations in Vitamin C content could be attributed to factors such as cassava variety, processing techniques, and the efficiency of the drying method used. Since Vitamin C is highly sensitive to heat and oxidation, thus the use of the NSPRI PSSD may have contributed to better retention compared to the findings of Haiqin et al. [24].

Vitamin B1 (Thiamine)

The HQCF sample contains 1.1633 mg/100 g of Vitamin B1 as illustrated in Table *1*, which is significantly higher than the 0.2 mg/100 g reported in cassava flour by Petite [25]. Additionally, a study on cassava-based fufu flour reported a much lower range of 0.06-0.08 mg/100gage flour according to Enyinna et al. [26]. This suggests that the NSPRI PSSD might have contributed to improved retention of Vitamin B1 compared to other traditional processing methods, or that the cassava variety used had naturally higher Thiamine content.

Vitamin B9 (Folate)

The Vitamin B9 content as summarized in Table *2* in the HQCF sample (2.13 mg/100g) is much higher than the 59 µg/100 g reported in cassava flour by Petite [25]. The large discrepancy could be due to differences in analytical methods, cassava variety, or possible fortification. Processing conditions, such as temperature control in solar drying, might have also contributed to higher folate retention compared to conventional drying methods.

The HQCF sample produced using NSPRI PSSD exhibited higher levels of Vitamin C, B1, and B9 compared to some previous studies, results are shown in Table *2*. The increased vitamin retention may be due to the drying technique used, as drying in the PSSD under controlled conditions can help preserve heat-sensitive nutrients better than traditional methods. However, variations in cassava species, environmental conditions, and processing parameters play a crucial role in determining the final nutrient composition of cassava flour.

Some Mineral Contents of High-Quality Cassava Flour

Understanding the mineral composition of HQCF is essential for assessing its nutritional value. Table *3* shows the result of some mineral composition present in the HQCF sample. The Mg content in the HQCF was notably low (0.035 ± 0.001 mg/100 g). This is significantly lower than the findings of Ndukwe et al. [27] that revealed the Mg level of 1.21 mg/100 g in cassava flour. This may be due to varietal difference or processing procedure. The Ca content recorded in the HQCF sample was 0.0207 ± 0.0006 mg/100 g. This is lower than the level (0.76 to 1.81 mg/100g) reported by Ndukwe et al. [27] in cassava flour. The phosphorus content in the HQCF sample was 0.0267 ± 0.0015 mg/100 g. The potassium content in the HQCF sample was 0.0583 ± 0.0025 mg/100 g. These are considerably low, and this is an indication that cassava is not a good source of phosphorus and potassium. The Zn content in the HQCF sample was 0.0767 ± 0.0058 mg/100 g, and this is relatively low compared to the Zn level of 3.59 mg/100 g reported for whole wheat flour. Studies have shown that drying cassava products using the PSSD leads to better preservation of nutritional content and reduction in drying time compared to traditional methods. The HQCF contains essential minerals but in lower concentrations compared to other flours like whole wheat or yellow corn flour. The use of NSPRI PSSD in drying cassava products can enhance the quality and nutrients retention in the flour.

Functional Properties of High-Quality Cassava Flour

The functional properties of HQCF produced using the NSPRI PSSD are illustrated in Table 4.

Bulk density: The bulk density of 0.67 g/ml recorded for the HQCF as shown in Table 4, aligns with findings of another study [28] that reported bulk density of 0.68 g/cm³ for TME 419 cassava variety, indicating that this value is within the expected range for cassava flours.

Swelling capacity: A swelling capacity of 53.33% indicates the HQCF's ability to absorb water and swell, which is essential for certain food applications according to studies [28]. The results are shown in Table 4. This value suggests a moderate ability to swell, which can influence the texture of food products.

Oil absorption capacity: The oil absorption capacity of 143.67% reflects the flour's ability to absorb oil, impacting the mouthfeel and flavor retention in food products, and the results are indicated in Table 4. This indicates that the samples could absorb up to 1.437 g of oil per gram of sample. The high value suggest that the flour has a good ability to bind and retain oil which can enhance flavor retention. Higher oil absorption is often desirable in products like baked goods to enhance palatability. It was observed by Ajayi [23] that sun-dried cassava flour exhibited higher oil absorption capacity compared to oven-dried samples, suggesting that drying methods can influence this property.

Water absorption capacity: With a water absorption capacity of 117.33% according to Table 4, this HQCF demonstrates a significant ability to absorb water, vital for dough formation and consistency in various food applications. It was found out by Akintunde [29] that water absorption capacities varied between 97.97 and 99.83 g water/g sample across different cassava varieties and drying methods, indicating that the NSPRI solar-dried HQCF has a comparatively higher water absorption capacity.

Dispersibility: A dispersibility of 68%, as presented in Table 4, indicates how well the flour can disperse in water, affecting its suitability in liquid-based food products. Similar results were gotten by Akintunde [29]. A higher dispersibility is generally preferred for products like soups and beverages to ensure a smooth consistency.

The functional properties of the HQCF produced using the NSPRI PSSD are comparable to those reported in other studies. The bulk density aligns with values from various cassava varieties, and the oil and water absorption capacities are within the ranges observed in other cassava-based flour studies. These properties suggest that the NSPRI solar-dried HQCF is suitable for diverse food applications, offering benefits in packaging, flavor retention, and product texture.

Result of the Pasting Properties of the High-Quality Cassava Flour

The graphical presentations of pasting properties of the HQCF produced using the NSPRI PSSD are displayed in Figures 4 and 5.

The pasting properties of the HQCF are crucial indicators of its functionality in various food applications. The HQCF samples exhibited the following pasting characteristics:

Peak Viscosity:

AA a: 5,798 cP

AA b: 5,834 cP

Hold (Trough) Viscosity:

AA a: 3,327 cP

AA b: 3,397 cP

Breakdown Viscosity:

AA a: 2,471 cP

AA b: 2,437 cP

Peak Viscosity: HQCF from various cassava genotypes was evaluated by [12] and it was reported that peak viscosities ranging from 295.6 to 467.0 Rapid Visco Units (RVU). Converting these values to centipoise (cP) using the factor 1 RVU ≈ 12 cP, the range was approximately 3,547 to 5,604 cP. The HQCF samples exhibited peak viscosities slightly above this range, indicating a strong swelling capacity and gelatinization potential.

Breakdown Viscosity: The same study observed breakdown viscosities between 187.7 and 336.8 RVU (approximately 2,252 to 4,042 cP). Similar result was gotten by Alamu et al. [22]. HQCF samples' breakdown viscosities (2,471 and 2,437 cP) fall within this range, suggesting comparable paste stability under heat and shear conditions.

Final Viscosity: It was reported by Alamu et al. [22] that final viscosities range from 137.6 to 210.8 RVU (approximately 1,651 to 2,530 cP). Final viscosity indicates the ability of starch to form a viscous paste or gel after cooking and cooling, essential for products requiring specific textural properties.

In summary, the HQCF samples demonstrated pasting properties that are consistent with, or slightly superior to, those reported in some of the existing literature. The high peak viscosities and moderate breakdown values suggest that HQCF has excellent gelatinization properties and reasonable stability, making it suitable for various food applications, such as baking and thickening agents.

Coliform load in HQCF samples at different levels of production:

Table *5* presents microbial load results for HQCF samples at different levels of production: HQCF R (HQCF raw cassava), HQCF M (HQCF dewatered cassava mash), HQCF D (HQCF dried granules), and HQCF F (HQCF flour). The results are recorded in terms of numerical values or NVG (No Visible Growth).

Bacterial load in HQCF samples at different levels of production:

HQCF R and HQCF M: No bacterial growth was observed (NVG) as shown in Table *5*, indicating good microbial quality and possibly effective processing and handling.

HQCF D: Bacterial counts of 5 CFU/g were recorded in one of the test repetitions, while the second repetition showed NVG.

HQCF F: Bacterial counts of 7 and 3 CFU/g were observed, which suggests some level of microbial contamination which might have resulted due to post-processing contamination, poor storage conditions, or environmental exposure.

According to Codex Alimentarius Commission [30], acceptable limits for total bacterial count in flour-based products should generally not exceed 10^3 to 10^4 CFU/g.

Fungal load in HQCF samples at different levels of production:

HQCF R, HQCF, and HQCF D showed NVG, indicating no fungal contamination. Also, HQCF M recorded fungal counts of 4 CFU/g and 7 CFU/g in different repetitions. The presence of fungi in HQCF M suggests exposure to moisture. The absence of fungi in the other samples suggests good drying conditions, preventing mold or fungal growth. Fungal contamination in cassava flour is a concern because certain molds can produce mycotoxins, such as aflatoxins, which are harmful to human health according to Adebayo-Tayo et al. [31].

Coliform load in HQCF samples at different levels of production:

Results from Table *5* indicate that all samples recorded NVG, which implies no coliform bacteria were detected. The absence of coliforms suggests proper hygiene practices during processing and handling. Coliform bacteria, such as *Escherichia coli*, indicate fecal contamination and poor sanitation. The results suggest that the HQCF samples are free from fecal contamination, making them microbiologically safe which is in line with results obtained by [32].

FAO/WHO standards recommend that cassava-based products should have bacterial counts below 10^3 CFU/g and fungal counts below 10^2 CFU/g. The recorded bacterial and fungal counts in the HQCF F and HQCF M are within acceptable limits, but indicate minor contamination. No coliforms were detected, aligning with food safety standards. It was reported by Adebayo-Tayo et al. [31] that cassava flour often harbors fungi and bacteria due to improper drying and/or handling. It was found out [32] that coliform presence in cassava products correlates with water quality and handling practices. It was highlighted by FAO [33] that mycotoxin contamination in cassava flour is a critical safety concern if storage conditions are poor.

Result of Microbial Qualities of the High-Quality Cassava Flour

Table *5* presents microbial load results for HQCF samples at different levels of production: HQCF R (HQCF raw cassava), HQCF M (HQCF dewatered cassava mash), HQCF D (HQCF dried granules), and HQCF F (HQCF flour). The results are recorded in terms of numerical values or NVG (No Visible Growth).

Bacterial load in HQCF samples at different levels of production:

HQCF R and HQCF M: No bacterial growth was observed (NVG), indicating good microbial quality and possibly effective processing and handling.

HQCF D: Bacterial counts of 5 CFU/g were recorded in one of the test repetitions, while the second repetition showed NVG.

HQCF F: Bacterial counts of 7 and 3 CFU/g were observed, which suggests some level of microbial contamination which might have resulted due to post-processing contamination, poor storage conditions, or environmental exposure.

According to Codex Alimentarius Commission [30], acceptable limits for total bacterial count in flour-based products should generally not exceed 10^3 to 10^4 CFU/g.

Fungal load in HQCF samples at different levels of production:

HQCF R, HQCF, and HQCF D showed NVG, indicating no fungal contamination.

HQCF M recorded fungal counts of 4 CFU/g and 7 CFU/g in different repetitions.

The presence of fungi in HQCF M suggests exposure to moisture. The absence of fungi in the other samples suggests good drying conditions, preventing mold or fungal growth. Fungal contamination in cassava flour is a concern because certain molds can produce mycotoxins, such as aflatoxins, which are harmful to human health, and this has been reported by Adebayo-Tayo et al. [31].

Coliform load in HQCF samples at different levels of production:

All samples recorded NVG, which implies no coliform bacteria were detected. The absence of coliforms suggests proper hygiene practices during processing and handling. Coliform bacteria, such as *Escherichia coli*, indicate fecal contamination and poor sanitation. The results according to [32], suggest that the HQCF samples are free from faecal contamination, making them microbiologically safe .

FAO/WHO standards recommend that cassava-based products should have bacterial counts below 10^3 CFU/g and fungal counts below 10^2 CFU/g. The recorded bacterial and fungal counts in the HQCF F and HQCF M are within acceptable limits, but indicate minor contamination. No coliforms were detected, aligning with food safety standards. It was reported by [31] that cassava flour often harbors fungi and bacteria due to improper drying and/or handling. It was found out by [32] that coliform presence in cassava products correlates with water quality and handling practices. It was highlighted by [33] that mycotoxin contamination in cassava flour is a critical safety concern if storage conditions are poor.

Further research may be done on artificial intelligence with the use of machine learning models to predict drying time and final moisture content of the dried product; product diversification and value addition especially fortification; and cost benefit analysis.

Conclusions

This study highlighted and demonstrated the effectiveness of the NSPRI PSSD in the production of HQCF with improved shelf stability and desirable functional properties. The drying process significantly reduced moisture content, ensuring longer storage life and preventing microbial contamination. The retention of essential vitamins (C, B1, and B9) and functional characteristics such as high-water absorption capacity and swelling power confirms the suitability of the HQCF for diverse food applications. Overall, the findings confirmed that solar drying can produce HQCF with desirable quality attributes, while remaining a viable, sustainable, and cost-effective technology (compared to flash dryer) that supports food security initiatives and economic development, particularly in the current economic situation in Nigeria. Future studies should focus on optimizing drying conditions to maximize nutrient retention while improving processing efficiency. These findings suggest that a cost-effective green energy powered dryer like NSPRI PSSD has potential to produce HQCF that can compete favorably with other HQCF from other sources in terms of quality retention and food safety.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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