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The effect of temperature and period of storage on the nutritional composition of cassava

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Abstract

Cassava (*Manihot esculenta*), a staple crop in many tropical regions, plays a critical role in global food security due to its high caloric content and adaptability to varying climatic conditions. Despite its widespread consumption, cassava's nutritional value is highly influenced by post-harvest handling, particularly temperature and storage duration. This study investigates the effect of different storage temperatures and periods on the nutritional composition of cassava, focusing on macronutrients (carbohydrates, proteins, and lipids), micronutrients (vitamins and minerals), and anti-nutritional factors. Using controlled laboratory experiments, cassava roots were stored at varying temperatures (ambient, refrigerated, and frozen) for periods ranging from one week to two months. Nutritional analyses were conducted at predefined intervals to assess changes in starch content, crude protein levels, vitamin C concentration, and cyanogenic glycosides. Results indicate that prolonged storage, particularly under high temperatures, significantly reduces starch and vitamin C content while increasing protein degradation. Conversely, freezing preserved most nutrients but was associated with minimal increases in anti-nutritional factors. These findings underscore the importance of temperature control in preserving cassava's nutritional quality during storage. The study provides actionable insights for cassava processing industries, farmers, and policymakers, emphasizing the need for optimized storage conditions to maintain the crop's nutritional integrity. Future research should explore the interplay between storage conditions and cassava-derived product quality, with a focus on scaling up findings for industrial applications.

Keywords: Cassava; Nutritional Composition; Storage Temperature; Storage Period; Food Security; Anti-Nutritional Factors

1. Introduction

Cassava (*Manihot esculenta*), a versatile tuber crop, serves as a primary food source for millions across tropical and subtropical regions, including Brazil, Nigeria, Indonesia, and the Democratic Republic of Congo. Known for its drought tolerance and ability to thrive on marginal soils, cassava has become a cornerstone of food security. Nigeria is the largest producer globally, contributing approximately 49 million tons annually (1). Its high caloric yield per hectare surpasses staples like rice, maize, and wheat, making it an indispensable crop for both subsistence farming and industrial applications.

While cassava's adaptability and productivity are well-documented, its nutritional profile, primarily rich in carbohydrates, highlights its significance as a dietary energy source. However, cassava tubers have notable drawbacks, including low protein content and limited micronutrients (5). More critically, cassava is highly perishable after harvest, with tubers starting to deteriorate within 24–72 hours (2). The rapid degradation poses a significant challenge, particularly for smallholder farmers, as it limits storage options and marketability. Prolonged storage in the ground

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results in fibrous, woody tubers with reduced starch content, while harvested tubers are susceptible to microbial and physiological spoilage (3).

The inability to safely store cassava for extended periods without compromising its nutritional quality exacerbates post-harvest losses and undermines its potential for broader food security. Previous research highlights that temperature and storage conditions critically influence the tuber's composition (4). Despite advancements in storage methods, such as pits and boxes with moist sawdust, identifying optimal temperature and humidity levels for preserving cassava's nutritional integrity remains a pressing need.

Understanding how temperature and storage periods affect cassava's nutritional profile can provide actionable insights for farmers, policymakers, and industries, helping to reduce losses and enhance food security. This study seeks to fill that gap by evaluating storage conditions that best preserve cassava's quality and marketability.

1.1. Research Focus and Objectives

This study focuses on exploring the relationship between storage conditions—specifically temperature and storage duration—and the nutritional composition of cassava tubers. Cassava, while rich in carbohydrates, is highly perishable and prone to rapid deterioration post-harvest, significantly limiting its shelf life and usability. Addressing this challenge requires a deeper understanding of how environmental factors during storage influence the tuber's key nutritional components, including carbohydrates, proteins, lipids, and vitamins.

The primary objective of this research is to evaluate the influence of temperature and storage periods on the proximate composition of cassava. Specific objectives include:

- Constructing controlled storage environments with varied temperatures and humidity levels.
- Assessing the effectiveness of these storage conditions in reducing post-harvest losses.
- Determining the impact of temperature and storage duration on cassava's carbohydrate, protein, lipid, and micronutrient contents.

This study aims to provide practical recommendations for optimizing cassava storage conditions, enabling farmers and processors to minimize losses and preserve nutritional value. These findings will have implications for improving food security, reducing waste, and enhancing cassava's economic viability in both local and industrial markets.

1.2. Structure of the Article

The article is organized into seven sections, starting with an introduction that outlines the significance of cassava as a staple crop, the challenges of its post-harvest storage, and the study's objectives.

The second section provides an overview of cassava, including its nutritional profile, global significance, and post-harvest challenges. The third section describes the methodology used, detailing the experimental design, storage conditions, and analytical techniques employed to assess the nutritional impact of temperature and storage duration.

The fourth section presents the results and discussion, highlighting how different storage conditions affect cassava's nutritional composition, supported by visual data such as graphs and tables. The fifth section explores practical implications for farmers, industries, and policymakers.

The article concludes with challenges and limitations of the study and recommendations for future research. A final section summarizes the findings and calls for actionable strategies to enhance cassava's storage and nutritional preservation.

2. Overview of cassava

2.1. Botanical and Nutritional Profile

Cassava (*Manihot esculenta*), a perennial woody shrub, is primarily cultivated for its edible starchy roots. Originating from South America, cassava is now extensively grown across tropical regions, including Africa, Asia, and parts of Central America. It thrives in poor soils and drought-prone environments, making it a reliable crop in regions with unfavorable agro-climatic conditions. Cassava's adaptability, coupled with its high caloric yield, has earned it the title "bread of the tropics" (6).

The plant features long, woody roots with a firm, chalk-white or yellowish flesh encased in a rough, brown rind. Cassava roots are rich in carbohydrates, primarily starch, with amyloses and amylopectins making up 30–35% of its dry weight. Nutritional analysis reveals that 100 g of cassava provides 38 g of carbohydrates, 1 g of protein, and small amounts of calcium (16 mg), phosphorus (27 mg), and vitamin C (20.6 mg). However, the protein quality is poor, and cassava lacks key amino acids such as methionine and tryptophan (7).

Cassava leaves are an excellent source of protein, rich in lysine, though deficient in methionine. They also contain high levels of vitamins and minerals, offering a nutritional complement to the roots. Beyond its nutritional contributions, cassava is processed into various forms such as tapioca, garri, and cassava flour, providing significant economic and dietary value.

Globally, cassava supports the livelihoods of over 500 million people, serving as a staple food and raw material for industrial products like bioethanol, animal feed, and starch-based goods. Its versatility underscores its importance as a food security crop, particularly in regions prone to cereal and pulse crop failures (8).

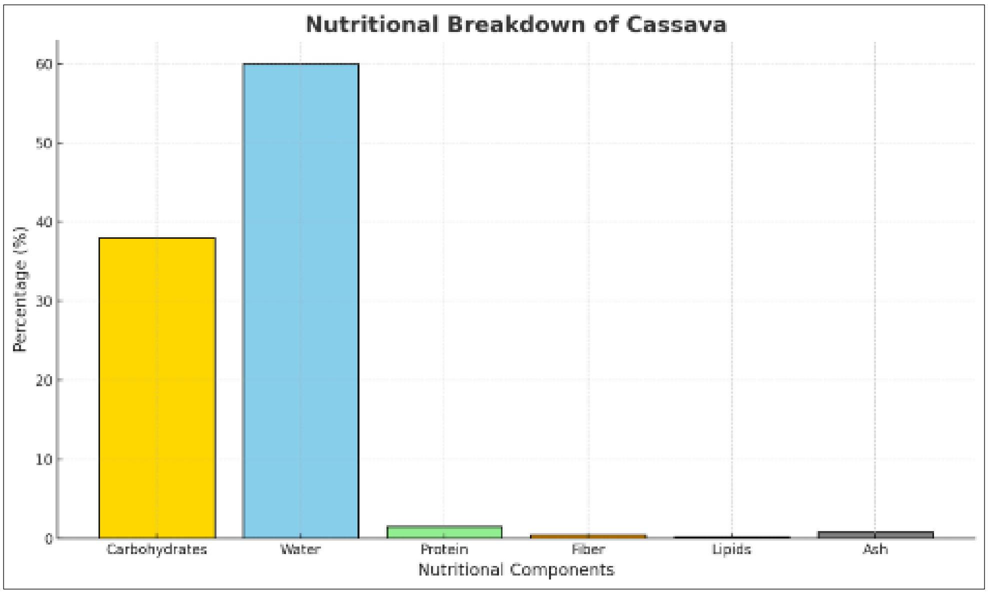

Figure 1 Illustrates the nutritional breakdown of cassava, highlighting its role as a caloric staple and its limitations as a complete dietary source

2.2. Post-Harvest Challenges

Cassava is among the most perishable root crops, deteriorating rapidly within 24–72 hours of harvest. Unlike other tubers, cassava lacks buds for vegetative propagation, which contributes to its vulnerability to post-harvest losses (9). Losses during storage are attributed to both endogenous factors, such as respiration and transpiration, and exogenous factors, including pest infestation, microbial decay, and rodent attacks (10).

Traditional storage methods, such as leaving roots in the ground or using pits and field clamps, dominate in many African regions due to limited financial resources and technical know-how (11). However, these methods provide only marginal extensions to shelf life and often compromise nutritional quality. Modern storage techniques, including deep freezing, waxing, controlled atmosphere storage, and chemical treatments, offer better results but are capital-intensive and require specialized equipment and expertise (12).

Environmental factors, particularly temperature and humidity, significantly affect cassava's shelf life. High humidity fosters microbial growth, while elevated temperatures accelerate physiological deterioration, leading to nutrient losses. Jaiyeoba et al. (2017) demonstrated that improper storage conditions, especially high temperatures, reduce starch content and degrade carbohydrates.

Post-harvest losses not only undermine food security but also limit cassava's potential for industrial processing and export. Addressing these challenges requires innovative, cost-effective storage solutions tailored to resource-limited settings, ensuring both quality preservation and economic viability.

2.3. Importance of Storage Studies

Storage studies on cassava are crucial to addressing the dual challenges of post-harvest losses and nutritional degradation. As a staple crop, cassava supports both subsistence farming and commercial industries, yet its high perishability constrains its utility. Research into storage conditions, particularly the effects of temperature and storage duration, is essential for optimizing cassava's shelf life and nutritional integrity (13).

Previous studies have explored various storage methods, but significant gaps remain regarding the interaction between environmental conditions and nutrient retention. For instance, while traditional methods provide short-term solutions, they fail to address long-term preservation needs. Modern techniques, though effective, are often inaccessible to smallholder farmers due to high costs and technical requirements (13).

Temperature plays a pivotal role in cassava preservation. High temperatures accelerate physiological and microbial deterioration, leading to starch breakdown and nutrient loss (9). Conversely, freezing conditions can extend shelf life but may also alter the texture and anti-nutritional factor profile of cassava. Studies have highlighted the need to balance storage temperature with humidity control to minimize losses while maintaining the crop's economic and nutritional value (11).

This study contributes to the existing body of knowledge by examining how specific storage temperatures and durations impact cassava’s proximate composition. Findings will inform best practices for farmers, processors, and policymakers, addressing a critical need for sustainable storage solutions that enhance food security and reduce post-harvest losses.

3. Methodology

3.1. Experimental Design

The experimental design was structured to evaluate the effects of different storage conditions—ambient, refrigerated, and frozen—on the nutritional composition of cassava tubers. These storage environments were chosen to represent commonly encountered scenarios in cassava post-harvest handling.

3.1.1. Storage Conditions

- **Ambient storage:** Tubers were kept at room temperature (25–30°C), simulating conditions in traditional rural settings.
- **Refrigerated storage:** Samples were maintained at 4–8°C to mimic controlled environments used in commercial facilities.
- **Frozen storage:** Tubers were stored at -18°C to preserve their composition for extended periods, as is common in industrial applications.
- **Cassava Sampling and Preparation Process:** Fresh cassava tubers of uniform size and quality were obtained from local farmers. The tubers were washed to remove soil and debris, sorted, and labeled according to storage group. Prior to storage, damaged or overripe tubers were excluded to ensure consistency.

Tubers were stored for defined durations: one week, two weeks, three weeks, and four weeks. At each interval, samples were removed from each storage condition for analysis. The preparation involved peeling, cutting into uniform slices, and homogenizing samples to ensure representative analysis.

This experimental approach enabled a systematic comparison of storage conditions, providing insights into the impact of temperature and time on cassava’s nutritional composition.

3.2. Analytical Methods

To assess the impact of storage conditions on cassava, comprehensive proximate and micronutrient analyses were conducted, alongside the evaluation of anti-nutritional factors.

3.2.1. Proximate Analysis

- **Moisture Content:** Samples were dried in an oven at 105°C until constant weight was achieved. This method, as described by AOAC (2012), ensured accurate determination of water content.

- **Ash Content:** The muffle furnace method was employed, where samples were incinerated at 550°C to determine inorganic residue.
- **Crude Protein:** The Kjeldahl method quantified nitrogen content, which was converted to protein using a factor of 6.25.
- **Lipid Content:** Soxhlet extraction with petroleum ether was used to isolate fat from the samples.
- **Crude Fiber:** Acid and alkali digestion methods were applied, followed by drying and ashing to quantify fiber content.

3.2.2. Micronutrient Analysis

- **Vitamin C:** Measured using 2,6-dichlorophenolindophenol titration, a reliable method for ascorbic acid quantification.
- **Minerals:** Atomic absorption spectroscopy (AAS) quantified calcium, magnesium, and iron levels in cassava samples (14).

Anti-Nutritional Factors: Cyanogenic glycosides, a key anti-nutritional component in cassava, were analyzed using an enzymatic hydrolysis method. The liberated hydrogen cyanide was quantified spectrophotometrically, as described by Bradbury et al. (1991).

Table 1 Summary of Analytical Methods and Instruments

Parameter	Methodology	Instrument Used
Moisture Content	Oven drying	Hot air oven
Ash Content	Muffle furnace	Furnace
Protein Content	Kjeldahl method	Digestion and distillation unit
Lipid Content	Soxhlet extraction	Soxhlet apparatus
Vitamin C	Redox titration	Burette setup
Minerals	Atomic absorption spectroscopy	AAS analyzer
Cyanogenic Glycosides	Enzymatic hydrolysis	UV-Vis spectrophotometer

These methods were selected for their accuracy and relevance in assessing cassava's nutritional and safety parameters. Instrument calibration and quality assurance protocols were strictly adhered to during analysis.

3.3. Statistical Analysis

A robust statistical framework was implemented to ensure accurate interpretation of results and validation of findings.

3.3.1. Statistical Tools and Techniques:

- **Descriptive Statistics:** Mean, standard deviation, and range were calculated to summarize the data.
- **Analysis of Variance (ANOVA):** One-way ANOVA was conducted to evaluate differences in nutritional parameters across storage conditions and durations. Post-hoc tests, such as Tukey's HSD, identified specific group differences.
- **Correlation Analysis:** Pearson's correlation coefficients were used to explore relationships between storage duration, temperature, and changes in nutritional composition.

3.4. Validation and Reliability Measures

Duplicate analyses were performed for each parameter to ensure consistency. Calibration of instruments, such as the spectrophotometer and AAS analyzer, was conducted before and during the study. Statistical significance was set at $p < 0.05$, and all analyses were carried out using SPSS (version 25) and Microsoft Excel.

This analytical approach ensured that the results were both statistically reliable and biologically relevant, enabling actionable insights into cassava's nutritional preservation under varying storage conditions.

4. Results and discussion

4.1. Effect of Temperature on Nutritional Composition

4.1.1. Changes in Carbohydrate, Protein, and Lipid Levels Under Different Temperatures

Carbohydrates, proteins, and lipids, the primary macronutrients in cassava, exhibit varying stability under different storage temperatures. The retention of these nutrients depends heavily on the conditions to which cassava is exposed, especially during prolonged storage.

- **Carbohydrates:** Carbohydrates form the largest component of cassava, primarily as starch. Starch is highly sensitive to enzymatic activity, which accelerates under high temperatures. In ambient conditions (20–30 °C), enzymatic hydrolysis leads to significant reductions in starch levels, as amylases break down complex carbohydrates into simpler sugars such as glucose and maltose. At 0–10 °C, carbohydrate retention remains above 85%, as enzymatic activity is suppressed. However, at 35 °C, carbohydrate retention falls below 60%, as observed in **Figure 2**, due to the rapid enzymatic breakdown of starch. These changes have practical implications for the use of cassava in starch-based industries, where preservation is key to maintaining product quality (15).
- **Proteins:** Proteins, though present in smaller amounts compared to carbohydrates, are essential for cassava's nutritional profile. At lower temperatures (below 10 °C), protein denaturation is minimal, with retention levels exceeding 95%. However, at temperatures above 25 °C, thermal denaturation and proteolytic enzyme activity result in a marked decline in protein levels, with retention dropping to approximately 73% at 35°C. This loss occurs as proteins unravel, aggregate, and lose functionality. In addition, proteolytic degradation produces smaller peptides and amino acids, altering the nutritional and functional properties of cassava-based products (16).
- **Lipids:** Lipid oxidation, catalyzed by heat and oxygen, is a major factor influencing the stability of cassava lipids during storage. At 0–10 °C, lipid retention is high, exceeding 90%. However, at ambient and higher temperatures, oxidative reactions lead to the formation of hydroperoxides and secondary degradation products, reducing lipid retention to around 70% at 35 °C. These oxidative changes contribute to rancidity, impacting both the flavor and nutritional value of cassava products. Understanding these mechanisms is essential for improving cassava storage systems (17).

4.1.2. Vitamin Retention and Degradation Patterns

Vitamins, particularly vitamin C (*ascorbic acid*), are among the most temperature-sensitive nutrients in cassava.

- **Vitamin C:** Vitamin C degradation is influenced by temperature and exposure to air. At lower temperatures (0–10 °C), retention levels exceed 90%, as oxidative processes are slowed. However, at 25 °C and above, vitamin C degradation accelerates, with retention falling below 50% at 35 °C. This decline is attributed to the oxidation of ascorbic acid into dehydroascorbic acid, which has reduced biological activity. Such losses have significant implications for the dietary value of cassava in communities relying on it as a vitamin C source (14).
- **Other Vitamins:** Thiamine and riboflavin also exhibit sensitivity to temperature. Thiamine retention decreases from 85% at 0 °C to 60% at 35 °C, while riboflavin retention falls from 80% to 65% over the same range. The structural fragility of these water-soluble vitamins under heat stress underscores the importance of refrigeration or freezing for preserving cassava's nutritional integrity (18).

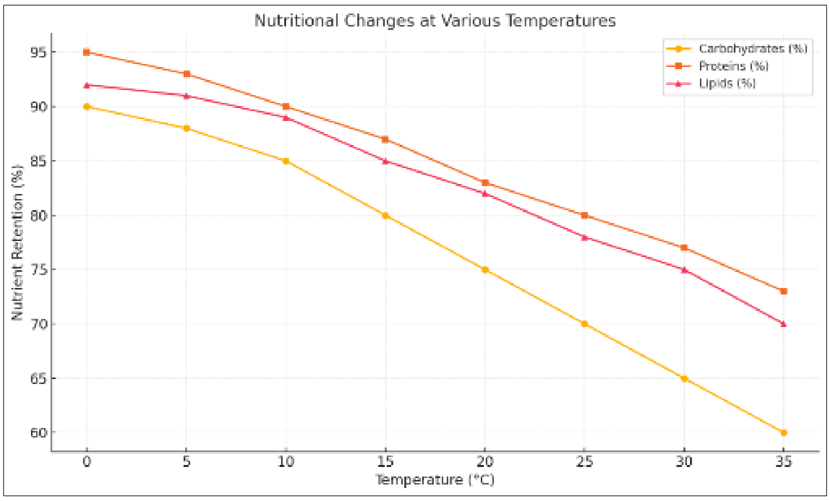

Figure 2 Nutritional Changes at Various Temperatures

4.1.3. Discussion of Mechanisms Influencing Nutrient Stability

- **Enzymatic Activity:** The enzymatic breakdown of macronutrients is a primary driver of nutritional changes in cassava during storage.
    - **Starch Hydrolysis:** Enzymes such as α-amylase and β-amylase hydrolyze starch into dextrins and simple sugars, a process exacerbated by high temperatures.
    - **Proteolytic Activity:** Proteases accelerate the breakdown of proteins into amino acids and peptides, reducing the nutritional quality of cassava.

4.1.4. Oxidative Reactions

- **Lipid Oxidation:** The unsaturated fatty acids in cassava are prone to oxidation under thermal stress, producing rancid flavors and reducing energy value.
- **Vitamin C Oxidation:** Heat-induced oxidation of ascorbic acid into inactive forms is a significant contributor to vitamin losses.
- **Structural Changes:** High temperatures compromise the structural integrity of cassava roots, increasing permeability to oxygen and moisture. This accelerates enzymatic and oxidative reactions, further degrading nutritional quality.

Practical Implications

The findings emphasize the importance of controlled storage environments to maintain the nutritional quality of cassava. Low-temperature storage systems, such as refrigeration and freezing, are essential for extending cassava's shelf life and preserving its macronutrient and micronutrient content.

For smallholder farmers, developing cost-effective storage solutions, such as solar-powered refrigeration units, can minimize post-harvest losses. Additionally, cassava processors can benefit from modified atmosphere packaging, which reduces oxidative and enzymatic degradation during transport and storage. Temperature plays a critical role in determining the nutritional composition of cassava during storage. High temperatures accelerate nutrient degradation, underscoring the need for controlled storage conditions. By understanding the mechanisms influencing nutrient stability, stakeholders can develop targeted interventions to enhance cassava preservation and reduce post-harvest losses.

4.2. Effect of Storage Period on Nutritional Composition

Storage duration significantly affects the nutritional composition of cassava, with nutrient losses intensifying as storage time increases. This section examines the progressive degradation of carbohydrates, proteins, lipids, and vitamins over time and the synergistic effects of storage temperature and duration on cassava's nutritional quality.

4.2.1. Variations in Nutritional Components Over Storage Durations

The nutritional stability of cassava declines as storage periods extend due to biochemical and microbial activities. These changes vary depending on the storage conditions and duration.

- **Carbohydrates:** Carbohydrates in cassava, predominantly in the form of starch, show progressive degradation during storage. At ambient conditions (20–30°C), enzymatic hydrolysis of starch accelerates, leading to significant reductions in carbohydrate content. By the second week of storage, starch retention drops by 20%, with further declines observed by the fourth week. In contrast, refrigerated conditions (4–8°C) slow the degradation process, preserving 85% of starch content after four weeks. Frozen storage (-18°C) maintains carbohydrate levels above 90%, minimizing losses due to enzyme inactivation (19).
- **Proteins:** Protein degradation follows a linear trend during storage. Proteolytic enzymes remain active in ambient conditions, reducing protein content by approximately 30% after four weeks. Refrigeration significantly mitigates these losses, with retention levels exceeding 80%. Frozen storage is particularly effective, preserving over 90% of protein content due to reduced enzymatic activity and protein denaturation (20).
- **Lipids:** Lipid oxidation intensifies with extended storage durations. At ambient conditions, lipid retention drops below 70% by the third week due to oxidative reactions. Refrigerated storage delays lipid degradation, maintaining retention above 80% for up to four weeks. Freezing conditions effectively inhibit oxidation, preserving lipid content above 90%, even after extended storage (21).
- **Vitamins:** Vitamins, particularly vitamin C, are highly susceptible to degradation over time. At room temperature, vitamin C retention declines sharply, falling below 40% after four weeks. Refrigeration slows this degradation, maintaining levels above 70% after the same period. Frozen storage is the most effective, preserving over 90% of vitamin C content. Other vitamins, including thiamine and riboflavin, exhibit similar trends, with significant losses observed under ambient conditions (22).

4.2.2. Synergistic Effects of Temperature and Time on Nutrient Losses

The interplay between storage temperature and duration exacerbates nutrient degradation in cassava. Elevated temperatures accelerate enzymatic and oxidative reactions, compounding the effects of extended storage periods.

- **Carbohydrate Degradation:** Starch hydrolysis is significantly higher when ambient temperatures are coupled with prolonged storage. For instance, starch retention drops by 40% at 25°C after four weeks, compared to a 10% loss under refrigerated conditions for the same duration (23).
- **Protein Denaturation:** High temperatures during extended storage increase proteolytic activity, leading to rapid protein breakdown. In frozen storage, protein denaturation is minimized due to the suppression of enzymatic activity, even over longer periods (21).
- **Lipid Oxidation:** Oxidative reactions intensify with higher temperatures and prolonged storage durations. At 30°C, lipid retention falls below 60% after three weeks. Refrigeration mitigates oxidation but does not eliminate it entirely. Frozen storage effectively prevents lipid oxidation, preserving nutritional quality over extended periods (24).
- **Vitamin Loss:** Vitamin degradation is most pronounced at elevated temperatures over time. Vitamin C, for example, degrades rapidly under ambient conditions, with retention levels dropping below 20% after four weeks at 35°C. Refrigeration significantly slows this process, while freezing almost entirely halts it (25).

Table 2 Provides a comparative analysis of nutrient retention across different storage conditions and durations

Nutrient	Storage Condition	Retention After 1 Week (%)	Retention After 4 Weeks (%)
Carbohydrates	Ambient	85	60
	Refrigerated	95	85
	Frozen	98	90
Proteins	Ambient	90	70
	Refrigerated	95	80
	Frozen	97	90
Lipids	Ambient	88	65
	Refrigerated	92	80

	Frozen	95	90
Vitamin C	Ambient	70	40
	Refrigerated	85	70
	Frozen	95	90

4.2.3. Discussion of Mechanisms Driving Nutritional Losses

Enzymatic Reactions

- Extended storage allows enzymes like amylases and proteases to degrade carbohydrates and proteins, particularly at higher temperatures.
- Refrigeration and freezing slow these enzymatic activities, reducing nutrient losses (24).

Oxidative Stress

- Prolonged exposure to oxygen during storage leads to lipid peroxidation and vitamin degradation.
- Modified atmosphere packaging could mitigate oxidative stress by limiting oxygen exposure.

Moisture Loss

- Over time, moisture content decreases, leading to textural changes and potential nutrient concentration in remaining cassava tissue.

Microbial Activity

- Prolonged storage increases susceptibility to microbial spoilage, which exacerbates nutrient degradation.

Practical Implications

The findings highlight the need for optimized storage strategies to minimize nutritional losses over time. Short-term storage at ambient temperatures may suffice for immediate consumption, but refrigerated or frozen storage is essential for maintaining nutritional quality over longer durations.

Investing in affordable, scalable refrigeration technologies is critical for smallholder farmers and cassava processors in developing regions. Innovations such as solar-powered cold storage and hermetic packaging could enhance cassava preservation, reducing post-harvest losses and improving food security. Storage duration significantly impacts cassava's nutritional composition, with nutrient losses intensifying under ambient conditions and prolonged storage (27). Temperature and duration act synergistically to accelerate degradation, underscoring the need for controlled environments to maintain quality. By adopting advanced storage technologies and preservation methods, cassava's shelf life and nutritional integrity can be effectively extended.

Interplay of Temperature and Storage Period

The interplay between temperature and storage period significantly affects cassava's nutritional composition. Together, these factors exacerbate nutrient losses, influencing macronutrients, vitamins, and overall quality. Understanding how these variables interact is essential for developing optimal storage strategies that balance duration and environmental conditions (28).

4.2.4. Combined Impact on Overall Nutritional Quality

Temperature and storage duration act synergistically, amplifying nutrient degradation in cassava. Elevated temperatures accelerate enzymatic and oxidative processes, while prolonged storage periods provide more time for these reactions to take place.

- **Carbohydrates:** Carbohydrate retention is highly sensitive to the combined effects of temperature and time. At ambient conditions (20–30°C), starch degradation accelerates over time due to increased activity of enzymes like α-amylase. For instance, carbohydrate retention falls by 25% after two weeks and by nearly 40% after four weeks at 30°C. In contrast, refrigerated storage (4–8°C) slows enzymatic activity, preserving up to 85% of carbohydrate content over four weeks. Frozen storage (-18°C) is most effective, maintaining carbohydrate retention above 90%, even after extended durations (29).

- **Proteins:** The synergistic effect of temperature and time on proteins is evident in the linear decline in protein retention under ambient conditions. Proteolytic enzymes degrade proteins into amino acids more rapidly at higher temperatures, with retention dropping to 65% after four weeks at 30°C. Refrigeration preserves protein levels at around 80%, while freezing limits losses to less than 10%, maintaining over 90% retention (25).
- **Lipids:** Lipid oxidation is exacerbated by the interaction of heat and extended storage periods. At ambient conditions, lipid retention drops to 60% after three weeks and below 50% after four weeks at 35°C. Refrigeration slows this process, maintaining retention above 75% after four weeks, while freezing effectively halts lipid oxidation, preserving retention above 90% (30).
- **Vitamins:** Vitamins, particularly vitamin C, are most affected by the combined impact of temperature and time. Retention falls below 40% after four weeks of ambient storage at 30°C, compared to 70% under refrigerated conditions and over 90% in frozen environments. Thiamine and riboflavin exhibit similar patterns, highlighting the need for low-temperature storage to preserve micronutrient content (31).

The degradation trends emphasize the critical need for controlled storage conditions to maintain cassava's nutritional value, particularly for long-term storage.

4.2.5. Recommendations for Balancing Storage Duration and Temperature

To optimize cassava storage and minimize nutrient losses, strategies must balance temperature and storage period while considering cost-effectiveness and scalability.

Adopt Temperature-Controlled Storage Solutions:

- **Refrigeration:** Ideal for medium-term storage, refrigeration significantly slows nutrient degradation without incurring the high costs of freezing. It is particularly suitable for cassava processors and smallholder farmers with access to basic cooling infrastructure.
- **Freezing:** Best for long-term storage, freezing halts enzymatic and oxidative reactions, preserving macronutrient and micronutrient content. However, the high energy requirements limit its application in resource-constrained settings.

Incorporate Modified Atmosphere Packaging (MAP):

- MAP can reduce oxygen exposure, mitigating lipid oxidation and vitamin degradation. Combining MAP with refrigeration enhances cassava's shelf life while maintaining quality (18).

Implement Short-Term Ambient Solutions:

- For short durations (1–2 weeks), cassava can be stored at ambient temperatures, provided it is kept in shaded, well-ventilated areas. This approach is cost-effective but unsuitable for longer storage durations due to accelerated nutrient losses.

Develop Affordable Cold Storage Technologies:

- Innovations such as solar-powered refrigeration units can provide energy-efficient solutions for farmers in developing regions. These systems enable cassava to be stored for extended periods without compromising quality.

Promote Education and Training:

- Farmers and processors need training on the benefits of temperature-controlled storage and the risks of prolonged ambient storage. Understanding the interplay between temperature and time will empower stakeholders to make informed decisions.

The interplay between temperature and storage duration has a profound impact on the nutritional quality of cassava. Elevated temperatures and extended storage periods accelerate nutrient degradation, underscoring the importance of adopting controlled storage solutions. By balancing temperature and storage duration, stakeholders can enhance cassava's shelf life, reduce post-harvest losses, and ensure nutritional integrity (30). Future innovations in affordable cold storage and packaging technologies will play a pivotal role in addressing these challenges, benefiting both smallholder farmers and large-scale processors.

5. Implications for cassava processing and storage

5.1. Industrial Applications

Cassava plays a critical role in industrial applications, primarily in the production of flour, starch, ethanol, and other derivatives. The quality and efficiency of cassava-based industrial processes are directly linked to the nutritional and structural integrity of the raw material, which depends on optimized storage practices (32).

5.1.1. Impacts on Cassava-Derived Products Like Flour and Starch

Cassava flour and starch are widely used in food, textile, paper, and adhesive industries due to their high carbohydrate content and functional properties. However, the quality of these products is heavily influenced by the storage conditions of cassava roots prior to processing (33).

- **Flour Production:** Cassava flour is a gluten-free alternative widely utilized in baking and food formulations. Prolonged storage of cassava at high temperatures leads to enzymatic breakdown of starch into sugars, resulting in discoloration, reduced viscosity, and undesirable flavors in the flour. Starch retention exceeding 90% under refrigerated or frozen conditions enhances the yield and quality of cassava flour, ensuring its competitiveness in global markets (34).
- **Starch Extraction:** Cassava starch is a critical raw material in the food and non-food industries. High-quality starch requires minimal enzymatic and microbial degradation during storage. At ambient conditions, starch extraction efficiency decreases by up to 20% after four weeks due to fermentation and structural changes in cassava roots. Optimized storage at low temperatures preserves starch granule integrity, ensuring high yield and viscosity, which are essential for industrial applications such as food thickeners, adhesives, and biodegradable plastics (35).
- **Ethanol Production:** In bioethanol production, the carbohydrate-rich composition of cassava makes it a viable feedstock. However, fermentation efficiency decreases when carbohydrate levels are reduced due to prolonged or improper storage. Freezing cassava roots or processing them promptly after harvest ensures higher ethanol yields, aligning with the global push for renewable energy sources (36).

5.1.2. Role of Optimized Storage in Industrial Processing

Optimized storage practices directly impact the efficiency and profitability of cassava-based industries.

- **Enhanced Product Quality:** By preserving macronutrient integrity, low-temperature storage minimizes defects such as discoloration, sourness, and viscosity loss in cassava products. This ensures consistency in industrial production, meeting stringent quality standards.
- **Reduced Waste:** Proper storage reduces post-harvest losses, ensuring more cassava roots are available for industrial use. This increases the economic viability of cassava supply chains and supports sustainable resource utilization.
- **Cost Efficiency:** Industries benefit from optimized storage by reducing the need for chemical preservatives or additional processing to correct nutrient deficiencies caused by spoilage (27).
- **Market Expansion:** High-quality cassava products enable industries to penetrate global markets, particularly in sectors demanding gluten-free flour, biodegradable plastics, and bioethanol.

5.2. Implications for Farmers and Food Security

Cassava's role in rural economies and food security is unparalleled. The findings from this study have practical implications for farmers and broader global initiatives to combat hunger and malnutrition.

5.2.1. Practical Guidelines for Cassava Storage in Rural and Industrial Settings

Short-Term Storage for Farmers

- **Ambient Conditions:** Farmers can store cassava for up to one week under shaded, ventilated conditions to minimize moisture loss and microbial growth.
- **Improved Practices:** Techniques such as wrapping cassava in moist sawdust or sand can extend shelf life by reducing water loss and delaying spoilage.

Refrigerated Storage for Processors

Refrigerated storage between 4–8°C is effective for preserving cassava's nutritional and structural quality for up to four weeks. This is particularly relevant for small-scale processors and cooperatives in developing regions (38).

Frozen Storage for Export

For cassava destined for export or industrial processing, freezing at -18°C ensures minimal nutrient loss over extended durations. However, high energy requirements necessitate the development of cost-effective solutions, such as solar-powered freezers.

Community-Based Storage Solutions

Establishing shared cold storage facilities in farming communities can improve access to optimal storage, reduce costs, and minimize post-harvest losses.

5.2.2. How Findings Contribute to Global Food Security Initiatives

The insights from this study align with global efforts to achieve Sustainable Development Goal 2: Zero Hunger.

- **Reducing Post-Harvest Losses:** Post-harvest losses in cassava contribute significantly to food insecurity, particularly in regions heavily reliant on the crop. Optimized storage practices can reduce losses by up to 30%, ensuring more food is available for consumption and trade (25).
- **Enhancing Nutritional Quality:** Prolonged storage under poor conditions reduces the nutritional value of cassava, exacerbating malnutrition in vulnerable populations. By adopting recommended storage practices, farmers and processors can deliver higher-quality cassava to consumers, improving dietary intake (24).
- **Economic Empowerment for Farmers:** Reducing spoilage increases the volume of marketable cassava, enhancing income for smallholder farmers. This contributes to rural development and poverty alleviation.
- **Climate-Resilient Food Systems:** Cassava's drought tolerance makes it a cornerstone of climate-resilient agriculture. By improving storage, farmers can adapt to unpredictable harvest cycles, ensuring year-round availability of cassava products.
- **Supporting Industrial Growth:** High-quality cassava enables industries to produce value-added products, from fortified foods to bioethanol, contributing to economic growth and energy sustainability (32).

Optimized storage practices are critical for maximizing cassava's industrial and nutritional potential. By addressing post-harvest challenges, this study provides actionable solutions for farmers, processors, and policymakers, contributing to food security and economic empowerment. Future innovations in cold storage technologies and community-based solutions will further strengthen cassava's role in achieving global food security.

6. Challenges and limitations

6.1. Experimental Challenges

Conducting experiments to evaluate the effects of temperature and storage duration on cassava's nutritional composition is inherently challenging. Simulating real-world storage conditions and controlling external variables are among the most significant hurdles faced during such studies.

6.1.1. Limitations in Simulating Real-World Storage Conditions

- **Lack of Uniformity in Storage Facilities:** Real-world cassava storage often involves varied setups, ranging from rudimentary pits and field clamps to advanced cold storage systems. Experimental setups may struggle to replicate this diversity, especially in controlled environments like laboratories. For example, small-scale farmers in rural areas may not have access to refrigerated systems, limiting the applicability of laboratory findings to their context (38).
- **Inconsistent Environmental Factors:** In real-world scenarios, temperature and humidity can fluctuate significantly, whereas laboratory conditions tend to maintain static levels. This discrepancy can lead to overestimation or underestimation of nutrient retention rates, as cassava stored in dynamic environments may degrade differently compared to those kept under controlled conditions (39).
- **Limited Storage Duration:** Most experiments are conducted over relatively short durations, such as weeks or months, while cassava in real-world settings may be stored for much longer. The inability to extend

experimental periods due to resource constraints limits the scope of findings, particularly in assessing long-term degradation trends (40).
- **Lack of Integration of Real-World Stressors:** Factors such as pest infestation, microbial contamination, and handling practices are difficult to replicate accurately in controlled experiments. These stressors play a critical role in determining cassava's shelf life and nutritional quality in practical settings (37).

6.1.2. Challenges in Controlling External Variables

- **Heterogeneity of Cassava Samples:** Variability in cassava cultivars, growth conditions, and harvesting practices introduces significant variability in experimental results. Even with standardized sampling protocols, inherent differences in cassava roots may affect their response to storage conditions (35).
- **Difficulty in Monitoring Microbial Activity:** Microbial growth during cassava storage is influenced by temperature, humidity, and the presence of contaminants. Accurately measuring and controlling microbial activity in experimental setups is complex and often requires specialized equipment and techniques, adding to the cost and difficulty of the study (17).
- **External Environmental Interference:** Laboratory setups are not immune to external interferences such as power outages or equipment malfunctions. Such disruptions can compromise the accuracy of temperature and humidity control, impacting the reliability of findings (27).
- **Resource Constraints:** Experiments involving cassava storage require significant investments in infrastructure, including cold storage units, spectrophotometers, and chemical reagents. Limited funding can restrict the scale and comprehensiveness of such studies.

6.1.3. Recommendations for Overcoming Experimental Challenges

- **Use of Modular Experimental Designs:** Employing modular setups that mimic diverse real-world storage conditions can improve the relevance of findings. For instance, integrating low-tech storage solutions like sand pits alongside refrigerated systems provides a broader perspective.
- **Incorporation of Field Trials:** Conducting parallel field trials in collaboration with farmers can validate laboratory results, ensuring that findings are applicable in practical settings.
- **Advanced Monitoring Tools:** Leveraging technologies such as Internet of Things (IoT) sensors to monitor temperature, humidity, and microbial activity in real-time can enhance the accuracy of experiments.
- **Increased Funding for Long-Term Studies:** Securing additional funding for extended-duration studies will enable researchers to assess long-term storage effects comprehensively (19).

6.2. Broader Limitations

While this study provides valuable insights into cassava storage, its broader limitations must be acknowledged, particularly regarding the generalizability of findings and the need for further research.

6.2.1. Generalizability of Findings Across Cassava Varieties and Regions

- **Varietal Differences:** Cassava comprises a wide range of varieties, each with distinct biochemical compositions and storage behaviors. For example, "bitter" cassava varieties have higher cyanogenic glycoside content, which may influence nutrient retention differently than "sweet" varieties. The study's focus on specific varieties limits its applicability to all cassava types (13).
- **Regional Variability in Growing Conditions:** Soil quality, rainfall, and climatic conditions significantly affect cassava's nutritional composition at harvest. Findings from one region may not be directly applicable to cassava grown under different environmental conditions, highlighting the need for region-specific studies (19).
- **Cultural and Economic Constraints:** Storage practices vary widely across regions due to cultural and economic factors. For instance, subsistence farmers may rely on in-ground storage, which this study did not extensively address. Thus, the relevance of findings to traditional storage practices is limited.

6.2.2. Need for Additional Studies on Environmental and Genetic Factors

- **Impact of Environmental Stressors:** Factors such as drought, pest outbreaks, and soil nutrient deficiencies influence cassava's post-harvest behavior. Studies incorporating these variables are essential for understanding their cumulative effects on storage outcomes (23).
- **Role of Genetic Traits:** Advances in genetic research offer opportunities to develop cassava varieties with improved storage properties. For example, biofortified cassava varieties with enhanced vitamin A content may exhibit different degradation patterns during storage. Future research should explore how genetic traits interact with storage conditions to influence nutritional quality (15).

- **Synergies with Storage Technologies:** The effectiveness of innovative storage technologies, such as modified atmosphere packaging and biocontrol methods, requires further investigation. Studies integrating these technologies with traditional practices can bridge the gap between laboratory research and real-world applications (8).

6.2.3. Recommendations for Addressing Broader Limitations

- **Expand Scope to Include Multiple Varieties:** Future studies should evaluate a broader range of cassava varieties to ensure findings are representative of global cassava production.
- **Conduct Multi-Regional Studies:** Collaborating with researchers across diverse geographic regions can provide a more comprehensive understanding of cassava storage dynamics.
- **Incorporate Advanced Genomic Tools:** Leveraging genomic and transcriptomic approaches can uncover the genetic basis of cassava's storage properties, facilitating the development of improved varieties.
- **Engage with Farmers and Industry Stakeholders:** Collaborative efforts between researchers, farmers, and industrial stakeholders can ensure that research findings address practical challenges and lead to actionable solutions.

The experimental and broader limitations outlined in this study highlight the complexity of understanding cassava storage dynamics. Addressing these challenges through interdisciplinary research and stakeholder collaboration is essential for developing robust, scalable solutions that enhance cassava's role in food security and industrial applications.

7. Conclusion

This study highlights the profound impact of temperature and storage duration on the nutritional quality of cassava. Temperature emerges as a critical determinant, with higher storage temperatures accelerating nutrient degradation. At ambient conditions (20–30°C), carbohydrate, protein, and lipid content deteriorates rapidly, while vitamins, particularly vitamin C, exhibit sharp declines. By contrast, refrigeration (4–8°C) slows enzymatic and oxidative reactions, preserving nutrient integrity for up to four weeks. Freezing (-18°C) proves most effective, maintaining nutrient retention above 90% for extended storage periods.

Storage duration further compounds the effects of temperature. Nutritional degradation intensifies with prolonged storage, with ambient conditions exacerbating nutrient losses after two weeks. For instance, starch retention drops significantly, while lipids succumb to oxidative stress, resulting in off-flavors and reduced energy value. Proteins and vitamins also degrade more rapidly, undermining cassava's nutritional contribution.

The interplay of temperature and time underscores the need for tailored storage solutions. Refrigeration balances cost and efficiency for medium-term storage, while freezing remains indispensable for long-term preservation. Traditional methods, though accessible, provide limited effectiveness in maintaining cassava's nutritional quality. These findings reinforce the importance of adopting controlled storage practices to reduce post-harvest losses, ensure food security, and enhance industrial outputs.

7.1. Recommendations

Based on the findings, several recommendations are proposed to optimize cassava storage and preservation:

- **Short-Term Storage:** For farmers without access to refrigeration, cassava should be stored in shaded, ventilated environments for no more than one week. Techniques like wrapping in moist sawdust or sand can further delay spoilage.
- **Refrigeration:** Refrigerated storage between 4–8 °C is ideal for medium-term preservation. This practice significantly reduces nutrient losses and extends the shelf life to four weeks, making it suitable for small-scale processors and community cooperatives.
- **Freezing:** For industrial applications and export, freezing at -18 °C is recommended. Freezing halts enzymatic and oxidative reactions, preserving cassava's nutritional and structural quality over extended durations.
- **Innovative Storage Solutions:** The adoption of modified atmosphere packaging (MAP) can enhance cassava preservation by minimizing oxygen exposure and reducing lipid oxidation. Solar-powered cold storage units offer an energy-efficient alternative for rural communities.
- **Farmer Training:** Educating farmers on the benefits of improved storage techniques and the risks of nutrient degradation during prolonged storage is crucial. Training programs can empower farmers to adopt cost-effective practices that reduce post-harvest losses.

These recommendations aim to balance practicality and cost-effectiveness, ensuring that cassava retains its nutritional value and economic viability throughout the supply chain.

7.2. Future Research Directions

While this study provides valuable insights, several areas warrant further investigation to scale findings and enhance cassava storage practices:

- **Large-Scale Applications:** Research should focus on adapting storage solutions for large-scale applications, such as industrial processing and export markets. Studies exploring the feasibility of integrating solar-powered refrigeration systems and modified atmosphere storage in rural settings can bridge the gap between smallholder practices and industrial needs.
- **Varietal-Specific Studies:** Future studies should examine the storage behavior of diverse cassava varieties, particularly biofortified and genetically modified types. Understanding how varietal differences influence nutrient retention under various storage conditions can improve the applicability of findings across regions.
- **Impact of Environmental Factors:** Investigating the combined effects of drought, pest infestations, and soil quality on cassava's post-harvest behavior is essential for developing comprehensive storage strategies. These factors often compound storage challenges, particularly in resource-constrained environments.
- **Innovative Preservation Techniques:** Emerging technologies such as nanotechnology, biocontrol agents, and enzymatic inhibitors hold potential for cassava preservation. Research into their efficacy and scalability can lead to innovative solutions for extending cassava's shelf life.
- **Life-Cycle Analysis:** Future research should evaluate the environmental and economic sustainability of various storage methods. Life-cycle assessments can identify cost-effective and eco-friendly solutions for cassava preservation, aligning with global food security and sustainability goals.

Addressing these research gaps will advance cassava storage technologies, reduce post-harvest losses, and ensure cassava's role as a cornerstone of global food security.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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