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PHYSICOCHEMICAL CHARACTERIZATION AND STORAGE STABILITY ASSESSMENT OF DIETARY FIBRE-ENRICHED FOOD PRODUCTS DEVELOPED FROM BANANA PSEUDOSTEM POWDER

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Abstract

The increasing demand for functional foods with enhanced nutritional profiles has prompted investigation of novel ingredients derived from agricultural byproducts. Banana pseudostem, traditionally discarded after fruit harvest, represents an underutilized biomass resource with potential applications in food fortification. This study investigated the physicochemical properties and storage stability of three food product categories (biscuits, crisps, and sweets) fortified with banana pseudostem powder at substitution levels of 10%, 20%, and 30%. The study proposed the objectives, to comprehensively characterize the physicochemical properties of banana pseudostem powder and evaluate the impact of varying substitution levels on functional properties, quality parameters, and storage stability of developed food products over a 28-day period under ambient conditions (25 ± 2°C, 65 ± 5% relative humidity). In the study, banana pseudostem powder was characterized for water absorption capacity (WAC), oil absorption capacity (OAC), bulk density, and pH. Three product types were developed using composite flours with 0% (control), 10%, 20%, and 30% banana pseudostem powder substitution. Products were evaluated for moisture content, peroxide value, free fatty acid content, and microbiological quality (total plate count) at 7-day intervals during storage. Physicochemical changes were analyzed using standard AOAC methods, and statistical significance was determined using ANOVA and Tukey's HSD test ($p < 0.05$). The result indicated that banana pseudostem powder exhibited high water absorption capacity (4.50 ± 0.12 g/g), moderate oil absorption capacity (1.20 ± 0.08 g/g), bulk density of 0.42 ± 0.03 g/mL, and pH of 5.8 ± 0.2. Moisture uptake during storage increased proportionally with substitution level across all products, with biscuits showing increases from 3.0% (day 0) to 4.6% (day 28) for control and 4.5% to 7.3% for 30% substitution. Peroxide values remained below 5 meq/kg for all formulations throughout storage, indicating adequate oxidative stability. Free fatty acid content increased marginally but remained within acceptable limits (<2.0%). Total plate counts remained below 4 log CFU/g for all products. Crisps demonstrated higher moisture uptake rates (5.8% to 10.2% at 30% substitution) compared to biscuits and sweets due to higher surface-to-volume ratio and oil content. Statistical analysis revealed significant differences ($p < 0.05$) between substitution levels for all quality parameters. The study concluded that banana pseudostem powder incorporation significantly influences physicochemical properties and storage stability of food products in a dose-dependent manner. While all substitution levels maintained microbiological safety and oxidative stability within acceptable limits during 28-day ambient storage, higher fibre content increased hygroscopic nature, necessitating appropriate packaging solutions. The 10% substitution level demonstrated optimal balance between functional property modifications and storage stability maintenance. Enhanced packaging materials or modified atmosphere packaging may enable successful commercialization of products with higher substitution levels (20-30%) offering superior nutritional benefits.

Keywords: *Banana pseudostem; physicochemical properties; storage stability; shelf-life; water absorption; oxidative stability; food fortification*

1. Introduction

The development of functional foods incorporating novel ingredients requires comprehensive understanding of physicochemical properties that influence processing behaviour, product quality, and shelf-life stability (Elleuch *et al.,* 2011). Dietary fibre ingredients, while offering substantial nutritional benefits, often introduce complex interactions with food matrices that affect water binding, fat retention, textural properties, and susceptibility to deteriorative reactions during storage (Brennan and Cleary, 2005). Systematic characterization of these functional properties and their evolution during storage represents essential knowledge for successful product commercialization and quality assurance.
Banana pseudostem powder, derived from agricultural waste biomass, has emerged as a promising functional ingredient due to its exceptional dietary fibre content (35-45% dry weight basis) and substantial mineral composition (Mohapatra *et al.,* 2010; Padam *et al.,* 2014). However, the incorporation of high-fibre ingredients into conventional food matrices frequently results in modifications to processing characteristics, textural attributes, and storage behaviour that must be carefully evaluated to ensure product quality and safety (Dhingra *et al.,* 2012). The hygroscopic nature of dietary fibre components, particularly cellulose and hemicellulose, increases moisture absorption from the environment, potentially affecting textural properties and microbial stability (Raghavendra *et al.,* 2006). Additionally, the presence of unsaturated fatty acids in plant materials introduces concerns regarding oxidative rancidity during storage, which can compromise sensory quality and nutritional value (Shahidi and Zhong, 2010).
Physicochemical properties including water absorption capacity (WAC), oil absorption capacity (OAC), bulk density, and pH fundamentally influence ingredient functionality in food systems. WAC reflects the ability of ingredients to bind and retain water through hydrogen bonding with hydroxyl groups, affecting dough consistency, batter viscosity, and final product moisture content (Raghavendra *et al.,* 2006). OAC indicates fat-binding potential, relevant for emulsion stability, flavour retention, and textural characteristics in products containing lipid components (Wang and Kinsella, 1976). Bulk density affects packaging efficiency, handling properties, and volumetric measurements during formulation (Barbosa-Cánovas *et al.,* 2005). The pH of ingredients influences enzymatic activity, chemical stability, and potential interactions with other formulation components.
Storage stability assessment represents a critical component of food product development, as deteriorative changes during shelf-life can compromise safety, nutritional value, and sensory acceptability (Labuza and Szybist, 2001). Moisture migration between product and environment affects textural properties, with excessive moisture gain potentially supporting microbial growth while moisture loss causes undesirable hardening or staleness (Bell and Labuza, 2000). Lipid oxidation, proceeding through free radical mechanisms, generates off-flavors, reduces nutritional quality through degradation of unsaturated fatty acids and fat-soluble vitamins, and produces potentially harmful secondary oxidation products (Shahidi and Zhong, 2010). Microbiological stability must be maintained throughout intended shelf-life to ensure consumer safety and comply with regulatory standards (ICMSF, 1986).
Previous research on banana pseudostem utilization has primarily focused on nutritional characterization and initial product development, with limited systematic investigation of physicochemical properties and comprehensive shelf-life evaluation across multiple product categories and substitution levels. Existing studies have documented compositional attributes but have not thoroughly examined functional properties that govern processing behaviour or monitored quality deterioration patterns during extended storage under realistic conditions. Furthermore, comparative assessment across different food matrices (baked, fried, confectionery) would provide valuable insights into matrix-specific stability challenges and optimal formulation strategies.
This research addresses identified knowledge gaps through systematic physicochemical characterization of banana pseudostem powder and comprehensive evaluation of storage stability in three distinct product categories developed at multiple substitution levels. Specific objectives include: (1) determination of functional properties (WAC, OAC, bulk density, pH) of banana pseudostem powder; (2) assessment of moisture content evolution during 28-day ambient storage; (3) monitoring of lipid oxidation through peroxide value and free fatty acid measurements; (4) evaluation of microbiological stability via total plate count determination; and (5) comparative analysis of stability patterns across product types and substitution levels to establish optimal formulation parameters for commercial applications.

2. Materials and Methods

2.1 Raw Materials and Powder Preparation

Fresh banana pseudostems (*Musa paradisiaca*) were procured from local agricultural farms within 24 hours of fruit harvest. The outer fibrous layers were manually removed to expose the tender inner core, which was thoroughly washed with potable water to eliminate surface contaminants. The cleaned material was sliced into uniform pieces (0.5 cm thickness) using stainless steel blades to facilitate uniform drying. Thermal processing was conducted in a hot air circulation oven (Model: Lab Companion OF-22GW, Korea) maintained at 60 ± 2°C with periodic temperature monitoring using calibrated thermocouples. Drying continued for 12-14 hours until samples achieved constant weight, corresponding to final moisture content below 8%. The dried material was ground using a high-speed laboratory grinder (Model: Mixer Grinder MG3753, Philips, India) and sieved through 60-mesh stainless steel sieve (250 µm aperture) to obtain uniform particle size distribution. The resulting powder was packaged in food-grade high-density polyethylene (HDPE) containers with airtight sealing and stored in a temperature-controlled environment (25 ± 2°C) with silica gel desiccants to minimize moisture absorption prior to analysis and product formulation.

2.2 Physicochemical Characterization

Water absorption capacity was determined following the methodology of Raghavendra *et al.* (2006) with modifications. One gram of banana pseudostem powder was dispersed in 10 mL distilled water in pre-weighed centrifuge tubes, vortex-mixed for 30 seconds to ensure uniform dispersion, and allowed to stand at ambient temperature (25 ± 2°C) for 30 minutes with intermittent mixing every 10 minutes. The suspension was centrifuged at 3000 rpm for 20 minutes using a refrigerated centrifuge (Model: Sigma 3-16KL, Germany). The supernatant was carefully decanted, and the sediment was weighed. Water absorption capacity was calculated as grams of water absorbed per gram of dry sample using the formula: WAC (g/g) = (Weight of sediment - Weight of dry sample) / Weight of dry sample.

Oil absorption capacity followed similar methodology using refined vegetable oil (density 0.92 g/mL at 25°C) instead of water, according to Wang and Kinsella (1976). One gram of powder was mixed with 10 mL oil, equilibrated for 30 minutes with intermittent mixing, centrifuged at 3000 rpm for 20 minutes, and the absorbed oil was quantified gravimetrically after removing free oil. The formula used was: OAC (g/g) = (Weight of sediment - Weight of dry sample) / Weight of dry sample.

Bulk density was measured using the tapping method according to Barbosa-Cánovas *et al.* (2005). A known weight of powder (50 g) was transferred into a graduated cylinder (100 mL capacity), and the initial volume was recorded. The cylinder was subjected to 100 taps using a mechanical tapping apparatus, and the final volume was recorded. Bulk density was calculated as: Bulk density (g/mL) = Weight of powder / Tapped volume.

pH determination was conducted by preparing a 10% (w/v) suspension of banana pseudostem powder in distilled water. The suspension was stirred continuously for 30 minutes using a magnetic stirrer to achieve equilibration, and pH was measured using a calibrated digital pH meter (Model: Eutech pH 700, Singapore) with glass electrode. The pH meter was calibrated using standard buffer solutions of pH 4.0, 7.0, and 10.0 before measurements.

2.3 Product Development

Three product categories were developed representing different food matrices and processing methods. Composite flours were prepared by blending banana pseudostem powder with refined wheat flour at weight ratios of 0:100 (control), 10:90, 20:80, and 30:70, ensuring homogeneous distribution through thorough mixing for 10 minutes in a ribbon blender.

Biscuits were formulated using the cream method with the following ingredient proportions per 100 g composite flour: butter (40 g), powdered sugar (35 g), milk powder (5 g), baking powder (2 g), and vanilla essence (1 mL). Butter and sugar were creamed at medium speed for 5 minutes until light and fluffy. Dry ingredients were incorporated gradually with mixing until cohesive dough formed. The dough was sheeted to 5 mm thickness, cut into circular shapes (5 cm diameter), and baked in a pre-heated convection oven at 180 ± 5°C for 15-18 minutes until golden brown. Baked biscuits were cooled to ambient temperature on wire racks before packaging.

Crisps were prepared by mixing composite flour (100 g) with salt (2 g) and water (40-50 mL, adjusted based on dough consistency requirements). The dough was kneaded for 5 minutes to develop cohesive structure, rested for 15 minutes, sheeted to 2 mm thickness, and cut into rectangular shapes (3 cm × 5 cm). Deep frying was conducted in refined vegetable oil maintained at 180 ± 5°C for 3-4 minutes until golden and crisp. Fried crisps were drained on absorbent paper to remove surface oil and cooled before packaging.

Sweets were formulated using whole milk (500 mL), sugar (150 g), and composite flour (50 g). Milk was heated in a thick-bottomed pan, and sugar was dissolved completely. Composite flour was added gradually with continuous stirring to prevent lump formation. The mixture was cooked over medium heat with constant stirring until desired consistency (determined by ribbon stage test). The cooked mass was transferred to greased trays, cooled to 40-50°C, and shaped into uniform pieces (2 cm × 2 cm × 1 cm).

2.4 Storage Study Design

Products were packaged in food-grade metalized polyester pouches (thickness 75 μm) with heat sealing to prevent moisture and oxygen ingress. Packaging was conducted under ambient conditions without modified atmosphere. Packaged products were stored in a temperature-controlled chamber (Model: Sanyo MLR-351H, Japan) maintained at 25 ± 2°C and 65 ± 5% relative humidity, representing typical ambient storage conditions in tropical and subtropical regions. Storage period extended for 28 days, with sampling conducted at 7-day intervals (days 0, 7, 14, 21, 28). Three independent packages were analyzed at each sampling point for each formulation, representing biological replicates.

2.5 Quality Parameter Monitoring

Moisture content was determined gravimetrically using the hot air oven method (AOAC 925.09). Samples (5 g) were dried at 105 ± 2°C until constant weight (typically 4-6 hours), with moisture content calculated as percentage weight loss: Moisture (%) = [(Initial weight - Final weight) / Initial weight] × 100.

Peroxide value was determined using the iodometric titration method (AOAC 965.33). Fat was extracted from samples using petroleum ether in a Soxhlet apparatus. Five grams of extracted fat was dissolved in acetic acid-chloroform solution (3:2 v/v), saturated potassium iodide solution was added, and the mixture was titrated with standardized sodium thiosulfate solution using starch as indicator. Peroxide value was expressed as milliequivalents of peroxide per kilogram of fat using the formula: PV (meq/kg) = [(S - B) × N × 1000] / Sample weight (g), where S is sample titration volume, B is blank titration volume, and N is normality of sodium thiosulfate.

Free fatty acid content was determined by titration method (AOAC 940.28). Two grams of extracted fat was dissolved in neutral ethanol (50 mL) previously neutralized with 0.1 N sodium hydroxide using phenolphthalein indicator. The solution was titrated with standardized 0.1 N sodium hydroxide to the first permanent pink colour. Free fatty acid

content was calculated as oleic acid percentage: FFA (%) = (V × N × 28.2) / Sample weight (g), where V is titration volume and N is normality of sodium hydroxide.
Total plate count was determined following standard microbiological enumeration procedures (APHA, 2001). Samples (10 g) were homogenized with sterile 0.1% peptone water (90 mL) using a stomacher for 2 minutes. Serial dilutions (10^{-1} to 10^{-6}) were prepared, and appropriate dilutions were plated on Plate Count Agar using the pour plate technique. Plates were incubated at 35 ± 1°C for 48 hours, and colonies were counted using a Quebec colony counter. Results were expressed as $\log_{10}$ CFU/g.

2.6 Statistical Analysis
Data were analysed using three-way analysis of variance (ANOVA) with product type, substitution level, and storage time as independent variables. Statistical computations were performed using SPSS Statistics version 28.0 (IBM Corporation, Armonk, NY, USA). Homogeneity of variance was verified using Levene's test, and normality was assessed using Shapiro-Wilk test. When ANOVA indicated significant effects ($p < 0.05$), post-hoc mean comparisons were conducted using Tukey's Honestly Significant Difference (HSD) test at $\alpha = 0.05$ significance level. Pearson correlation analysis was performed to assess relationships between quality parameters. All experiments were conducted in triplicate, and results are presented as mean ± standard deviation.

3. Results and Discussion

3.1 Physicochemical Properties of Banana Pseudostem Powder

The physicochemical characterization of banana pseudostem powder revealed functional properties that fundamentally influence its behaviour in food systems and impact on final product characteristics (Table 1). These properties derive from the unique structural and compositional features of banana pseudostem tissue, particularly the abundance of dietary fibre components and their associated hydroxyl groups, porosity, and surface area characteristics.

Table 1. Physicochemical properties of banana pseudostem powder

Property	Value	Unit
Water Absorption Capacity (WAC)	4.50 ± 0.12	g water/g powder
Oil Absorption Capacity (OAC)	1.20 ± 0.08	g oil/g powder
Bulk Density	0.42 ± 0.03	g/mL
pH (10% w/v suspension)	5.8 ± 0.2	-

The water absorption capacity of 4.50 ± 0.12 g water/g powder substantially exceeds that of refined wheat flour (1.5-2.0 g/g) and whole wheat flour (2.5-3.5 g/g), reflecting the exceptional hydrophilic nature of banana pseudostem fibre components (Raghavendra *et al.,* 2006). This elevated WAC originates from multiple mechanisms including hydrogen bonding between water molecules and hydroxyl groups present in cellulose and hemicellulose structures, capillary absorption into the porous network of fibre matrix, and physical entrapment of water within the three-dimensional structure of fibre aggregates (Elleuch *et al.,* 2011). The high WAC has significant implications for product formulation, as increased water binding affects dough rheology, batter consistency, and final product moisture distribution. Products incorporating banana pseudostem powder require formulation adjustments, typically necessitating 15-25% increased water addition at 20-30% substitution levels to maintain equivalent processing characteristics compared to control formulations.
The oil absorption capacity of 1.20 ± 0.08 g oil/g powder, while lower than WAC, indicates moderate fat-binding potential relevant for products containing lipid components such as biscuits and fried crisps. OAC derives primarily from physical entrapment of oil in capillary networks of fibre structure and surface adsorption onto hydrophobic regions of fibre molecules (Wang and Kinsella, 1976). This property influences fat distribution in dough systems, emulsion stability in batter formulations, and oil retention in fried products. The moderate OAC suggests that banana pseudostem powder incorporation would not substantially increase fat content of fried products through excessive oil absorption during frying, maintaining relatively stable lipid profiles across substitution levels as observed in the developed crisps.
Bulk density of 0.42 ± 0.03 g/mL reflects the low-density, high-porosity nature of the fibrous powder. This relatively low bulk density compared to wheat flour (0.55-0.65 g/mL) affects volumetric measurements during ingredient scaling and influences packaging efficiency. The porous structure contributing to low bulk density also relates to the high surface area available for water and oil interactions, contributing to the elevated WAC and OAC values observed. From a practical perspective, the low bulk density necessitates weight-based rather than volume-based ingredient measurement for reproducible formulations, and results in larger package volumes for equivalent weight of material compared to conventional flours.
The pH of 5.8 ± 0.2 indicates mildly acidic character typical of plant tissues, influenced by organic acids, phenolic compounds, and buffering capacity of mineral components. This pH range is generally compatible with most food formulations and does not require neutralization or pH adjustment for typical applications. The slightly acidic pH may contribute beneficially to shelf-life by creating conditions less favourable for certain spoilage microorganisms while not significantly affecting sensory properties or chemical stability of developed products.

3.2 Moisture Content Evolution During Storage

Moisture content represents a critical quality parameter influencing textural properties, microbial stability, and chemical reaction rates during storage. Monitoring across all product types revealed systematic moisture uptake throughout the 28-day storage period, with magnitude directly proportional to banana pseudostem powder substitution level (Tables 2-4, Figures 1-3).

Table 2. Moisture content changes (%) in biscuits during 28-day storage at 25°C, 65% RH

Storage Day	Control (0%)	10% Substitution	20% Substitution	30% Substitution
Day 0	3.0 ± 0.2^{a}	3.5 ± 0.2^{b}	4.0 ± 0.2^{c}	4.5 ± 0.3^{d}
Day 7	3.5 ± 0.2^{a}	4.2 ± 0.3^{b}	4.8 ± 0.3^{c}	5.5 ± 0.3^{d}
Day 14	4.0 ± 0.3^{a}	4.8 ± 0.3^{b}	5.5 ± 0.4^{c}	6.2 ± 0.4^{d}
Day 21	4.3 ± 0.3^{a}	5.3 ± 0.4^{b}	6.0 ± 0.4^{c}	6.8 ± 0.5^{d}
Day 28	4.6 ± 0.3^{a}	5.7 ± 0.4^{b}	6.5 ± 0.4^{c}	7.3 ± 0.5^{d}

Note: Values represent mean ± SD (n=3). Different superscript letters within same row indicate significant differences ($p < 0.05$).

Biscuits demonstrated moderate moisture uptake patterns, with control formulation increasing from 3.0% (day 0) to 4.6% (day 28), representing a 53% relative increase. The 10% substitution showed moisture increase from 3.5% to 5.7% (63% increase), 20% substitution from 4.0% to 6.5% (63% increase), and 30% substitution from 4.5% to 7.3% (62% increase). Statistical analysis revealed significant differences ($p < 0.05$) between substitution levels at all time points, with moisture uptake rate increasing with fibre content. However, all formulations maintained moisture levels below critical thresholds for microbial growth (generally >15% for bakery products) and remained within ranges typical for commercially acceptable biscuit products (Bell and Labuza, 2000).

The moisture uptake mechanism in fibre-enriched biscuits involves multiple processes. Hygroscopic fibre components, particularly hemicellulose with abundant hydroxyl groups, actively bind atmospheric water vapor through hydrogen bonding (Brennan and Cleary, 2005). The porous structure created by fibre incorporation provides increased surface area for moisture adsorption and capillary condensation within void spaces. Moisture migration occurs from the environment through packaging materials (despite metalized polyester's relatively low water vapor transmission rate) and from regions of higher to lower water activity within the product matrix. The rate of moisture uptake correlates with the hygroscopic nature of the fibre and the water activity gradient between product and storage environment.

Table 3. Moisture content changes (%) in crisps during 28-day storage at 25°C, 65% RH

Storage Day	Control (0%)	10% Substitution	20% Substitution	30% Substitution
Day 0	2.5 ± 0.2^{a}	3.2 ± 0.2^{b}	3.8 ± 0.3^{c}	4.2 ± 0.3^{d}
Day 7	3.8 ± 0.3^{a}	5.2 ± 0.4^{b}	6.5 ± 0.4^{c}	7.8 ± 0.5^{d}
Day 14	4.5 ± 0.3^{a}	6.2 ± 0.4^{b}	7.8 ± 0.5^{c}	9.0 ± 0.6^{d}
Day 21	5.0 ± 0.4^{a}	6.8 ± 0.5^{b}	8.5 ± 0.6^{c}	9.8 ± 0.6^{d}
Day 28	5.8 ± 0.4^{a}	7.5 ± 0.5^{b}	9.2 ± 0.6^{c}	10.2 ± 0.7^{d}

Note: Values represent mean ± SD (n=3). Different superscript letters within same row indicate significant differences ($p < 0.05$).

Crisps exhibited more substantial moisture uptake compared to biscuits, attributed to higher surface-to-volume ratio of thin, flat product geometry and oil content facilitating moisture migration. Control crisps increased from 2.5% to 5.8% moisture (132% increase), while 30% substitution increased from 4.2% to 10.2% (143% increase). The accelerated moisture uptake in crisps has direct implications for textural quality, as water softens the crisp structure, reducing the characteristic crunchiness that represents the primary textural attribute of this product category (Katz and Labuza, 1981). Products approaching 10% moisture begin to lose crisp texture, transitioning toward soft or chewy characteristics considered defects in fried snack products. This suggests that crisps with higher substitution levels (20-30%) require enhanced barrier packaging, possibly incorporating desiccant sachets or modified atmosphere packaging to extend shelf-life while maintaining textural quality.

Table 4. Moisture content changes (%) in sweets during 28-day storage at 25°C, 65% RH

Storage Day	Control (0%)	10% Substitution	20% Substitution	30% Substitution
Day 0	12.0 ± 0.5^{a}	13.5 ± 0.6^{b}	15.0 ± 0.6^{c}	16.5 ± 0.7^{d}
Day 7	12.8 ± 0.6^{a}	14.5 ± 0.6^{b}	16.2 ± 0.7^{c}	17.8 ± 0.8^{d}
Day 14	13.5 ± 0.6^{a}	15.2 ± 0.7^{b}	17.0 ± 0.7^{c}	18.8 ± 0.8^{d}
Day 21	14.0 ± 0.6^{a}	15.8 ± 0.7^{b}	17.5 ± 0.8^{c}	19.5 ± 0.9^{d}
Day 28	14.5 ± 0.7^{a}	16.2 ± 0.7^{b}	18.2 ± 0.8^{c}	20.0 ± 0.9^{d}

Note: Values represent mean ± SD (n=3). Different superscript letters within same row indicate significant differences ($p < 0.05$).

Sweets, being milk-based confectionery products with inherently higher initial moisture content (12-16.5% at day 0), showed absolute moisture increases smaller than crisps but significant relative to their initial values. The control formulation increased from 12.0% to 14.5% (21% increase), while 30% substitution increased from 16.5% to 20.0% (21% increase). The higher initial moisture content of sweets reflects the presence of milk solids and the cooking process used in preparation. Despite higher absolute moisture levels, the sugar content in sweets (approximately 25-30%) reduces water activity through solute binding, providing preservation effect and maintaining microbiological stability even at moisture contents that would support microbial growth in less concentrated systems (Chirife and Buera, 1994).

3.3 Lipid Oxidation Stability

Lipid oxidation represents a major deteriorative pathway in foods containing fats and oils, proceeding through free radical mechanisms that generate hydroperoxides (measured as peroxide value) and their subsequent breakdown products including free fatty acids, aldehydes, ketones, and other compounds contributing to off-flavours and rancidity (Shahidi and Zhong, 2010). Monitoring of peroxide value and free fatty acid content provides insight into oxidative and hydrolytic rancidity development during storage.

Table 5. Peroxide value (meq/kg) changes in crisps during 28-day storage

Storage Day	Control (0%)	10% Substitution	20% Substitution	30% Substitution
Day 0	0.8 ± 0.1^{a}	0.9 ± 0.1^{a}	1.0 ± 0.1^{a}	1.1 ± 0.2^{a}
Day 7	1.5 ± 0.2^{a}	1.6 ± 0.2^{a}	1.8 ± 0.2^{ab}	2.0 ± 0.2^{b}
Day 14	2.2 ± 0.3^{a}	2.4 ± 0.3^{ab}	2.7 ± 0.3^{bc}	3.0 ± 0.3^{c}
Day 21	2.8 ± 0.3^{a}	3.2 ± 0.3^{ab}	3.5 ± 0.4^{bc}	3.9 ± 0.4^{c}
Day 28	3.2 ± 0.4^{a}	3.8 ± 0.4^{ab}	4.2 ± 0.4^{bc}	4.6 ± 0.5^{c}

Note: Values represent mean ± SD (n=3). Different superscript letters within same row indicate significant differences ($p < 0.05$). Acceptable limit for fried products: <5 meq/kg.

Peroxide value measurements for crisps, the product category with highest lipid content (28-30%) and therefore greatest susceptibility to oxidative deterioration, remained well below the generally accepted threshold of 5 meq/kg for consumer acceptability throughout the 28-day storage period. Initial peroxide values ranged from 0.8 to 1.1 meq/kg immediately after preparation, reflecting minimal oxidation during frying when conducted under controlled temperature conditions. Progressive increases during storage showed dose-dependent patterns, with 30% substitution reaching 4.6 meq/kg by day 28 compared to 3.2 meq/kg for control.

The slightly elevated peroxide formation in higher substitution formulations may reflect pro-oxidant effects of certain fibre-associated components or trace metal contaminants that can catalyse lipid oxidation reactions. However, the magnitude of differences between formulations remained relatively small, and all products maintained acceptable oxidative stability. This favourable stability profile suggests that banana pseudostem powder does not introduce substantial pro-oxidant factors that would compromise shelf-life under the tested storage conditions. The relatively low peroxide values despite 28-day ambient storage likely reflect the antioxidant properties of phenolic compounds naturally present in banana pseudostem tissue, which have been documented to exhibit free radical scavenging activity (Padam et al., 2014).

Free fatty acid content, reflecting hydrolytic rancidity from lipase activity or chemical hydrolysis, increased modestly during storage but remained below 2.0% (as oleic acid) for all formulations, well within acceptable limits for fried products (<3.0%). The limited free fatty acid formation indicates adequate inactivation of lipase enzymes during processing and minimal moisture-mediated hydrolysis during storage. The combination of low peroxide values and limited free fatty acid accumulation demonstrates that lipid stability does not represent a limiting factor for shelf-life of banana pseudostem powder-fortified products under ambient storage conditions.

3.4 Microbiological Stability

Microbiological safety represents an absolute requirement for food products, and shelf-life must ensure total plate counts remain within regulatory limits throughout the intended storage period. Total plate count monitoring across all products revealed excellent microbiological stability, with counts remaining below 4 log CFU/g throughout the 28-day storage period (Table 6).

Table 6. Total plate count (log CFU/g) in biscuits during 28-day storage

Storage Day	Control (0%)	10% Substitution	20% Substitution	30% Substitution
Day 0	<2.0	<2.0	<2.0	<2.0
Day 7	2.1 ± 0.2	2.2 ± 0.2	2.3 ± 0.2	2.4 ± 0.3
Day 14	2.5 ± 0.3	2.7 ± 0.3	2.9 ± 0.3	3.1 ± 0.3
Day 21	2.8 ± 0.3	3.1 ± 0.3	3.3 ± 0.4	3.5 ± 0.4
Day 28	3.2 ± 0.4	3.5 ± 0.4	3.7 ± 0.4	3.9 ± 0.4

Note: Values represent mean ± SD (n=3). Acceptable limit: <4 log CFU/g for shelf-stable bakery products.

Initial total plate counts immediately after processing were below detection limits (<2.0 log CFU/g or <100 CFU/g), indicating effective heat treatment during baking or frying that eliminated vegetative microbial cells. The slight increases during storage reflect post-processing contamination from handling, packaging, and storage environment rather than survival and growth of microorganisms present during processing. The rate of microbial count increase showed slight correlation with substitution level and moisture content, consistent with the relationship between water activity and microbial growth potential.

All formulations maintained total plate counts well below the generally accepted limit of 10^4 CFU/g (4 log CFU/g) for shelf-stable bakery and confectionery products throughout the 28-day storage period. The highest count observed was 3.9 log CFU/g for 30% substitution biscuits at day 28, representing approximately 8,000 CFU/g, still providing substantial safety margin below regulatory thresholds. Similar patterns were observed for crisps and sweets, with all products demonstrating adequate microbiological stability.

The favourable microbiological stability despite increasing moisture content reflects multiple preservation factors operating synergistically. The low water activity maintained even after moisture uptake (estimated at 0.4-0.6 for biscuits and crisps, 0.7-0.8 for sweets based on moisture-sorption isotherm relationships) limits microbial growth. The sugar content in all products, particularly sweets, reduces water activity through solute binding. The metalized polyester packaging provides barrier against external microbial contamination. The combination of these factors ensures microbiological safety throughout the intended shelf-life.

3.5 Comparative Stability Assessment Across Products

Comparative analysis across product types reveals matrix-specific stability challenges and opportunities. Biscuits demonstrated most favourable overall stability profile, with moderate moisture uptake rates, excellent oxidative stability (lowest lipid content minimizes oxidation potential), and robust microbiological stability. The baked structure provides mechanical strength that resists texture degradation even with moisture absorption, maintaining acceptable quality throughout 28-day storage at all substitution levels.

Crisps presented the greatest stability challenges, primarily related to moisture-induced textural degradation. The defining characteristic of crisps (crispness) is highly sensitive to moisture content, with loss of crunch occurring as moisture increases above 8-10%. The rapid moisture uptake observed, particularly for higher substitution levels, suggests that extended shelf-life (>28 days) would require enhanced packaging solutions. However, oxidative stability remained adequate, and microbiological safety was well maintained.

Sweets occupied an intermediate stability position. Higher initial moisture content and continued moisture uptake did not compromise quality as severely as in crisps because the expected texture is soft and pliable rather than crisp. The sugar content provides preservation effect through water activity reduction. Oxidative stability concerns are minimal due to lower fat content compared to crisps. The primary quality issue for sweets involves potential texture changes from moisture migration causing either excessive softness or surface crystallization, neither of which presented as major defects during the 28-day study period.

4. Conclusion

This comprehensive investigation of physicochemical properties and storage stability provides essential knowledge for successful commercialization of banana pseudostem powder-fortified food products. The functional properties characterized—notably high water absorption capacity (4.50 g/g), moderate oil absorption capacity (1.20 g/g), low bulk density (0.42 g/mL), and slightly acidic pH (5.8)—fundamentally influence processing behaviour and product quality, necessitating formulation adjustments particularly in water addition and mixing procedures.

Storage stability assessment over 28 days under realistic ambient conditions (25°C, 65% RH) demonstrated that all product formulations maintained safety and quality within acceptable limits. Moisture content increased in dose-dependent manner with substitution level across all products, reflecting the hygroscopic nature of dietary fibre. However, moisture levels remained below critical thresholds for microbial growth and quality deterioration. Peroxide values and free fatty acid content remained well within acceptable limits, indicating adequate oxidative and hydrolytic stability. Total plate counts remained below 4 log CFU/g, demonstrating microbiological safety throughout the storage period.

The 10% substitution level emerged as optimal for commercial applications when balancing nutritional enhancement with storage stability considerations. This level achieved substantial fibre enrichment while introducing minimal stability challenges, maintaining quality comparable to control formulations with standard packaging materials. The 20% substitution level approaches threshold acceptability from stability perspective, requiring careful packaging selection and potentially shortened shelf-life declarations. The 30% substitution level, while maximizing nutritional benefits, presents stability challenges particularly in moisture-sensitive products like crisps, necessitating enhanced barrier packaging or modified atmosphere packaging for extended shelf-life.

Product-specific recommendations include: (1) Biscuits demonstrate favourable stability across all substitution levels, suitable for conventional packaging with 28-day minimum shelf-life; (2) Crisps require enhanced moisture barrier packaging for substitution levels above 10%, with potential incorporation of desiccant sachets for 20-30% formulations; (3) Sweets exhibit adequate stability at all substitution levels with standard packaging, though surface moisture migration monitoring is recommended for extended storage beyond 28 days.

Future research directions should include extended shelf-life studies (6-12 months) to establish commercial shelf-life under various storage temperature and humidity conditions, investigation of modified atmosphere packaging and active packaging technologies to enhance stability at higher substitution levels, development of accelerated shelf-life testing protocols to predict long-term stability, and comprehensive sensory shelf-life assessment to correlate physicochemical

changes with consumer acceptability throughout storage. Additionally, investigation of antioxidant supplementation to enhance oxidative stability and exploration of moisture barrier coatings or film lamination to reduce hygroscopic moisture uptake would advance commercial applicability of these nutritionally enhanced products.

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