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Packaging material and storage temperature effects on physicochemical, textural and microbial stability of jackfruit pulp pomace powder fortified millet-based muffins

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Abstract

The valorization of agro-industrial by-products in functional bakery products offers opportunities to improve nutritional quality while promoting sustainable food production; however, information on their shelf-life stability remains limited. This study investigated the combined effects of packaging material and storage temperature on the quality and shelf life of muffins fortified with finger millet flour, sorghum flour and jackfruit pulp pomace powder over 15 days. Storage progressively reduced moisture, water activity, pH, total phenolic content, antioxidant activity, texture quality and sensory acceptability, while peroxide value and microbial counts increased. These changes were significantly influenced by packaging material and storage temperature, with refrigerated laminated aluminium foil pouches providing the greatest retention of phenolic compounds (96.5%) and antioxidant activity (96.8%), the slowest textural deterioration and the lowest microbial growth. Based on microbiological safety and sensory acceptability, refrigerated laminated aluminium foil packaging extended the shelf life of the muffins to 14 days, compared with 7 days for room low-density polyethylene and polypropylene packaging. The findings demonstrate that combining high-barrier packaging with refrigerated storage effectively preserves the quality and extends the shelf life of jackfruit pulp pomace powder-fortified millet muffins, supporting their commercial application as sustainable functional bakery products.

Keywords: By product, packaging, refrigerated storage, shelf life, sensory evaluation

1. Introduction

Increasing consumer demand for healthier and functional foods has stimulated the development of bakery products enriched with nutrient-dense ingredients as alternatives to conventional refined wheat flour [26]. Among these alternatives, millets have gained considerable attention owing to their climate resilience and superior nutritional composition, particularly their high dietary fibre, mineral and phenolic antioxidant contents [7]. Finger millet (*Eleusine coracana*) is especially valued for its exceptional calcium, dietary fibre and polyphenol content [8, 12], whereas sorghum (*Sorghum bicolor*) contributes additional dietary fibre, minerals and desirable functional properties in bakery products [4]. Consequently, composite millet flour systems have emerged as promising ingredients for developing nutritionally enhanced bakery products.

The sustainable valorization of agro-industrial by-products has also become an important strategy for reducing food-processing waste while improving the nutritional quality of foods [13]. Fruit-processing residues are particularly valuable because they retain substantial amounts of dietary fibre and bioactive phytochemicals despite being discarded during processing [31]. Jackfruit (*Artocarpus heterophyllus* L.) is naturally rich in dietary fibre and phytochemicals [23] and its processing by-products preserve much of this nutritional value [21]. Among these, jackfruit pulp pomace powder (JPPP), obtained after juice extraction, is a promising yet underutilized functional ingredient. Incorporating JPPP into bakery products therefore offers the dual benefits of nutritional enhancement and sustainable utilization of fruit-processing residues.

Muffins are widely used as carriers for functional ingredients because their batter system readily accommodates composite flours and fibre-rich materials without major processing modifications. Previous studies have developed functional muffins using composite millet flours and various plant-derived ingredients, including proso millet, kodo millet, lotus flower flour and banana peel powder [5, 9, 15, 20, 30]. These formulations improved nutritional composition and antioxidant potential; however, most investigations have focused primarily on product development and immediate post-baking quality. Information regarding the shelf-life stability of such functional muffins remains limited, despite shelf life being a key determinant of commercial feasibility, distribution and consumer acceptance. During storage, bakery products undergo progressive physicochemical, biochemical and microbiological changes that collectively determine shelf life. Moisture migration and starch retrogradation deteriorate crumb structure and texture [28], whereas oxidative reactions reduce phenolic compounds and antioxidant capacity while promoting lipid oxidation [2]. Concurrent changes in pH and microbial growth further limit product safety and shelf life [27]. Consequently, shelf-life evaluation requires the integrated assessment of multiple quality attributes rather than a single quality parameter. The extent of these quality changes is largely influenced by packaging material and storage temperature. Packaging materials with superior barrier properties minimize oxygen and moisture transfer, thereby improving moisture retention, oxidative stability and overall product quality during storage [19]. Likewise, refrigerated storage slows moisture migration, starch retrogradation, oxidative deterioration and microbial proliferation compared with room storage [30]. Although the individual effects of packaging and storage temperature have been widely investigated for bakery products, their combined influence on the shelf-life stability of JPPP-fortified composite millet muffins has not been systematically evaluated. Addressing this knowledge gap is essential for the successful commercialization of sustainable functional bakery products. The present study aimed to evaluate changes in the physicochemical, antioxidant, textural, microbiological and sensory attributes of the optimized millet muffin during storage under different

packaging materials and storage conditions to identify the most suitable storage system for maintaining product quality and shelf life.

2. Materials and Methods

2.1 Raw materials and reagents

Fully ripe jackfruits (*Artocarpus heterophyllus* L.) were obtained from a local market in Vadodara, Gujarat, India. Jackfruit pulp pomace powder (JPPP), prepared from the pomace generated during juice extraction, was used as one of the ingredients in the composite flour blend for muffin preparation. Finger millet flour, sorghum flour, jaggery powder, ripe bananas, skimmed milk powder, melted butter, baking powder, baking soda and food-grade vinegar were purchased from local retail markets in Dahod, Gujarat, India. All chemicals and reagents used for physicochemical, antioxidant and microbiological analyses were of analytical grade.

2.2 Preparation of millet-based muffins

The muffins were prepared according to the formulation presented in Table 1, using a 100 g composite flour blend consisting of jackfruit pulp pomace powder (JPPP), finger millet flour and sorghum flour. All dry ingredients, including the composite flour blend, skimmed milk powder, baking powder and baking soda, were passed through a fine sieve twice and thoroughly mixed to ensure uniform distribution.

Jaggery powder was dissolved in the required quantity of water and whipped using a hand-held electric beater until a stable foam was obtained. Mashed ripe banana pulp and vinegar were subsequently added and mixed thoroughly. The premixed dry ingredients were gradually incorporated into the liquid mixture with continuous mixing to obtain a smooth and homogeneous batter.

The batter was transferred into a cone-fitted plastic dispensing jar and dispensed uniformly into greased paper muffin moulds. Baking was carried out in a rotary bakery oven (CS Aerotherm, Bengaluru, India) at 170 ± 2 °C for 20–22 min. After baking, the muffins were cooled to room temperature for approximately 1 h, packaged in the respective packaging materials and stored under the designated conditions for subsequent quality evaluation.

Table 1: Formulation of millet-based muffins prepared using a 100 g composite flour blend

Ingredients	Quantity
Jackfruit pulp pomace powder	16.96 gm
Finger millet flour	42.08 gm
Sorghum flour	40.96 gm
Jaggery powder	60 gm
Melted butter	50 ml
Baking powder	½ tsp
Baking soda	¼ tsp
Skim milk powder	20 gm
Banana pulp	40 gm
Water	75 ml
Vinegar	5 ml

Note: The composite flour blend (100 g) consisted of JPPP, finger millet flour and sorghum flour in the proportions shown above.

2.3 Packaging and storage conditions

A 3×2 factorial experimental design was adopted to evaluate the combined effects of packaging material and storage temperature on the shelf-life of the developed

muffins. The experiment comprised three packaging materials, namely low-density polyethylene (LDPE), polypropylene (PP) and laminated aluminium foil pouches (LAFP) and two storage conditions: room temperature and

refrigerated storage (4-7 °C), resulting in six treatment combinations as shown in Table 2. Each treatment was prepared in triplicate.

After cooling to room temperature, the muffins were individually packaged in the respective packaging materials and heat-sealed using an impulse sealer. The packaged samples were appropriately labelled and stored under the designated storage conditions. Quality evaluations were performed at 0, 4, 7, 10, 12, 14 and 15 days of storage. The samples were analyzed for physicochemical, antioxidant, microbiological and sensory attributes using the methods described in the subsequent sections. Storage evaluation for a treatment was discontinued once the product exceeded acceptable microbiological limits or failed sensory acceptability criteria.

Table 2: Experimental treatments used for the storage study

Treatment	Packaging material	Storage condition
T ₁	LAFP	Refrigerated
T ₂	LAFP	Room Temperature
T ₃	PP	Refrigerated
T ₄	PP	Room Temperature
T ₅	LAFP	Refrigerated
T ₆	LAFP	Room Temperature

2.4 Physicochemical analysis

2.4.1 Moisture content

Moisture content was determined according to AOAC Official Method 925.10 [3]. Approximately 5 g of finely ground muffin sample was weighed into a pre-dried and pre-weighed moisture dish and dried in a hot-air oven (NOVA Instruments Pvt. Ltd., Ahmedabad, India) at 105±2 °C until a constant mass was obtained. The samples were cooled in a desiccator to room temperature before weighing and the moisture content was expressed as percentage on a wet basis (% w.b.).

2.4.2 pH

The pH of the muffin samples was determined according to a previously described method [14] with slight modifications.. A 10% (w/v) aqueous suspension was prepared by homogenizing 10 g of finely ground muffin sample with 90 mL of distilled water. The suspension was allowed to equilibrate for 30 min at room temperature before measuring the pH using a calibrated digital pH meter (Model LT-11, Labtronics, Panchkula, India). The instrument was calibrated with standard buffer solutions of pH 4.0 and 7.0 prior to analysis.

2.4.3 Water activity

Water activity (a_w) was measured using a digital water activity meter (LABSWIFT, Novasina AG, Switzerland) at 25±2 °C, following a previously described procedure [11]. Finely ground muffin samples were placed in the sample cup to approximately half of its capacity and equilibrated inside the sealed measurement chamber until a stable reading was obtained. The recorded values were expressed as water activity.

2.4.4 Color (L*, a* and b*) values

Crust and crumb colour were measured using a portable colourimeter (NH310, 3nh Technology Co., Ltd., China) previously described method [17]. The instrument was calibrated with the manufacturer's standard white calibration

tile before analysis. Colour values were recorded in the CIE L*, a* and b* colour space. Crumb colour was measured on the freshly exposed interior surface after horizontally slicing the muffins, while crust colour was measured directly on the upper surface. Three readings were taken at different locations for both crust and crumb and the mean values were reported.

2.5 Instrumental texture analysis

Texture profile analysis (TPA) was performed as previously described [16] using a TA-HD Plus Texture Analyzer (Stable Micro Systems, Surrey, UK) equipped with a 5 kg load cell and a 75 mm flat cylindrical probe (P/75). Crumb samples (approximately 25 mm in height) were obtained from the centre of each muffin after removing the upper crust. The samples were subjected to a double-compression cycle to 50% deformation, with pre-test, test and post-test speeds of 2.0, 1.0 and 2.0 mm/s, respectively. A trigger force of 0.98 N and a 5 s interval between the two compression cycles were maintained throughout the analysis. Texture parameters, including hardness (gf), springiness, cohesiveness and chewiness, were obtained from the force-time curves.

2.6 Biochemical analysis

2.6.1 Total phenolic content

Total phenolic content (TPC) was determined according to a previously described Folin-Ciocalteu colorimetric method [18]. Muffin samples (0.5 g) were extracted with 10 mL of 80% (v/v) methanol using a tube rotator (Model SLM-TR-100, Sahil Scientific Co., Ambala, India) for 4 h at room temperature, followed by centrifugation at 8,000 rpm for 10 min (REMI R-4C, Mumbai, India). An aliquot (0.2 mL) of the supernatant was reacted with diluted Folin-Ciocalteu reagent and 20% (w/v) sodium carbonate solution. After incubation for 30 min at room temperature, the absorbance was measured at 620 nm using a visible spectrophotometer (Labman, Chennai, India). Catechol was used as the calibration standard and the results were expressed as mg catechol equivalents (CE) per 100 g sample.

2.6.2 Antioxidant activity (FRAP)

Ferric reducing antioxidant power (FRAP) was determined as previously described [29]. Muffin samples (1.0 g) were extracted with 10 mL of 60% (v/v) aqueous methanol containing 0.1% HCl using a tube rotator for 4 h at room temperature and centrifuged at 8,000 rpm for 10 min. Fresh FRAP reagent was prepared by mixing 0.3 M acetate buffer (pH 3.6), 10 mM TPTZ solution in 40 mM HCl and 20 mM FeCl₃·6H₂O in the ratio of 30:2:2 (v/v/v). The extract (0.2 mL) was mixed with 2.8 mL methanol and 3.0 mL FRAP reagent, incubated for 10 min at room temperature and the absorbance was recorded at 593 nm using the same spectrophotometer. Antioxidant activity was expressed as mg FeSO₄ equivalents (FSE) per 100 g sample.

2.7 Sensory evaluation

Sensory evaluation was conducted using a 15-member semi-trained panel comprising faculty members and postgraduate students. Prior to evaluation, informed consent was obtained from all panellists. Muffin samples were coded with random three-digit numbers and presented in a randomized order at room temperature under uniform lighting conditions. Drinking water and puffed rice were provided between

samples for palate cleansing. The panellists evaluated appearance, colour, aroma, texture, taste and overall acceptability using a 9-point hedonic scale (9 = like extremely; 1 = dislike extremely) according to previously described [24]. The mean overall acceptability (OA) score was used to assess the sensory quality of muffins during storage and samples with an OA score of ≥ 5 were considered acceptable.

2.8 Shelf-life indicator

2.8.1 Peroxide value

Peroxide value (PV) was determined according to the AOAC Official Method [3]. Approximately 5 g of muffin sample was mixed with 30 mL of an acetic acid-chloroform (2:1, v/v) solution and kept in the dark for 30 min. Saturated potassium iodide (KI) solution (0.5 mL) was added, followed by 30 mL of distilled water. The liberated iodine was titrated against 0.1 N sodium thiosulfate using 1% starch solution as the indicator. A reagent blank was analyzed simultaneously. The peroxide value was expressed as milliequivalents of active oxygen per kilogram of sample (meq O₂/kg).

2.8.2 Microbiological analysis

Microbiological quality was evaluated by determining the aerobic plate count (APC) following the standard method as previously described [24]. All analyses were performed under aseptic conditions in a laminar airflow chamber (Khera Instruments Pvt. Ltd., New Delhi, India). Muffin samples (1 g) were aseptically homogenized with 9 mL of sterile distilled water to obtain a 10⁻¹ dilution, followed by the preparation of appropriate serial dilutions. Aliquots (1 mL) from suitable dilutions were transferred into sterile Petri dishes and approximately 15-20 mL of molten nutrient agar (HiMedia Laboratories Pvt. Ltd., Mumbai, India) maintained at 45±2 °C was added using the pour plate technique. After solidification, the plates were incubated at 37±1 °C for 24 h. Plates containing 30-300 colonies were enumerated using a digital colony counter and the results were expressed as colony-forming units per gram (CFU/g).

3. Results and Discussion

3.1 Moisture Content

The moisture content of the developed millet-based muffins decreased progressively during storage under all packaging materials and storage conditions (Fig 1a). Freshly baked muffins had an initial moisture content of 26.50% (w.b.), which declined throughout storage, with a comparatively faster reduction under room conditions than under refrigeration. Among the packaging materials, laminated aluminium foil pouches (LAFP) were more effective in limiting moisture loss than polypropylene (PP) and low-density polyethylene (LDPE), reflecting their superior barrier properties against water vapour transmission.

The decline in moisture content is a common phenomenon in bakery products and is primarily associated with moisture redistribution between the crumb and the surrounding environment, leading to crumb firming and staling during storage. In contrast, high-barrier packaging restricts moisture transfer and thereby slows these deteriorative

changes, while refrigerated storage further reduces the rate of moisture migration. Similar results reported for waxy whole wheat flour muffins [1], Nelumbo nucifera dried flower flour-fortified muffins [5] and composite millet-palm jaggery muffins [9], where a gradual decline in moisture content was similarly attributed to moisture redistribution and staling during storage.

3.2 Water activity

Water activity (aw) of the developed millet-based muffins gradually decreased throughout storage under all packaging materials and storage conditions (fig 1b). Freshly prepared muffins exhibited an initial aw of 0.88, which progressively declined during storage. The reduction was comparatively greater under room storage than under refrigerated conditions, while muffins packaged in LAFP consistently maintained higher aw values than those packaged in PP and LDPE.

Water activity reflects the availability of free water for microbial growth and other deteriorative reactions rather than the total moisture present. The gradual decline in aw indicates a reduction in free water as storage progressed due to moisture redistribution within the muffin matrix. The comparatively slower decline observed in LAFP-packaged muffins suggests that high-barrier packaging was more effective in limiting moisture exchange with the surrounding environment. Similar reductions in water activity during storage have been reported for waxy whole wheat flour muffins [1]. Likewise, a decline in water activity was observed in banana peel-fortified muffins [15] and khaboos bread [25] during storage, attributing the change to the gradual conversion of free water into a more tightly bound form within the product matrix.

3.3 pH

The pH of the muffins showed only a slight but consistent decline during storage (Fig 1c). Fresh muffins had an initial pH of 6.65, which remained comparatively stable in T₁ (6.58 after 14 days) under refrigeration, whereas larger reductions occurred in T₃ (6.52 after 12 days) and T₅ (6.46 after 12 days). At room temperature, pH decreased more rapidly, reaching 6.53 in T₂ by Day 10 and 6.47 and 6.41 in T₄ and T₆, respectively, by Day 7.

The change in pH is principally governed by the accumulation of acidic metabolites during storage. The greater reduction observed in LDPE and PP coincided with faster microbial proliferation, suggesting that metabolic production of organic acids became increasingly important as storage progressed. Lower storage temperature effectively delayed these reactions, while the more stable package environment provided by LAFP further moderated pH changes. Similar storage-dependent reductions in pH have been reported for muffins and sponge cakes, where the pH decline was associated with organic acid formation during storage and improved pH stability was demonstrated when oxygen availability was restricted [9, 10]. The limited pH variation observed in the present study further indicates that biochemical deterioration remained well controlled throughout the acceptable storage period, particularly in refrigerated LAFP packages.

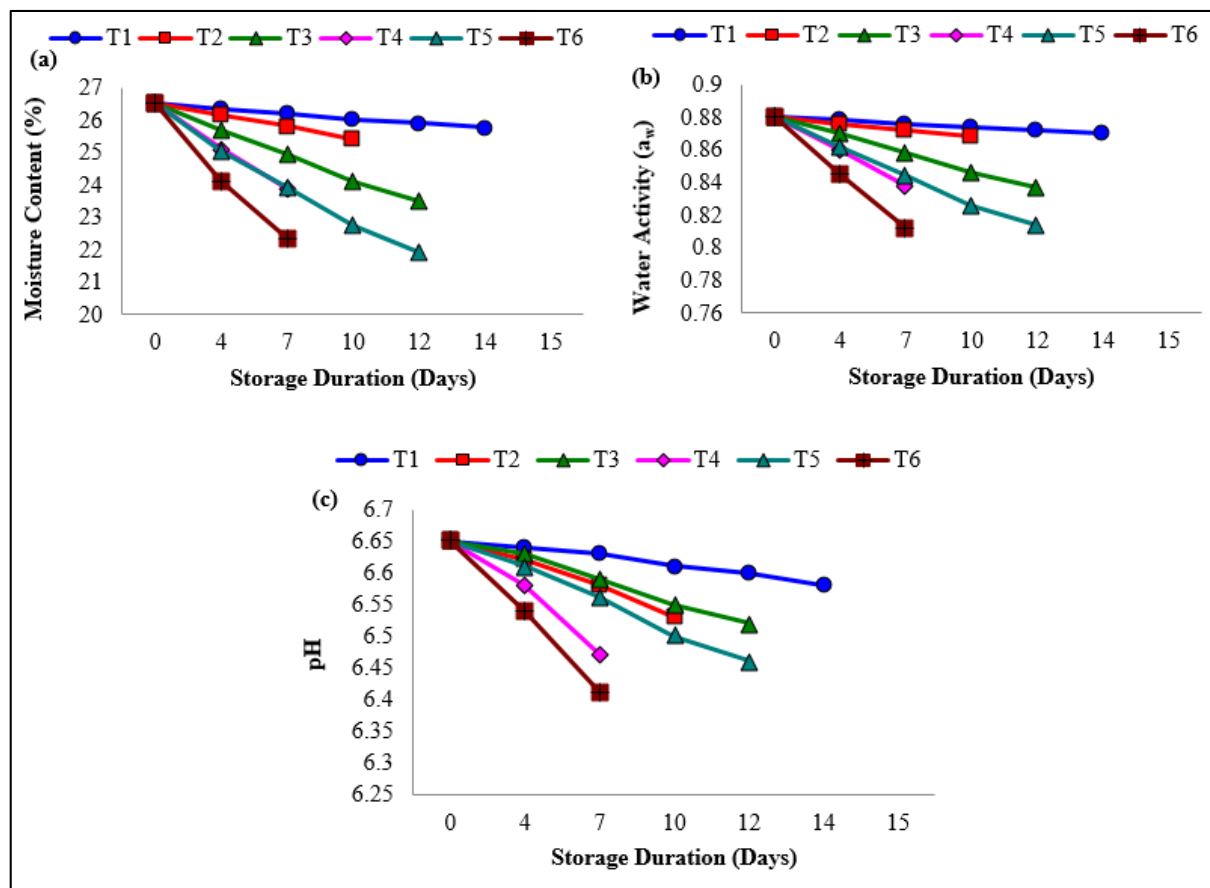


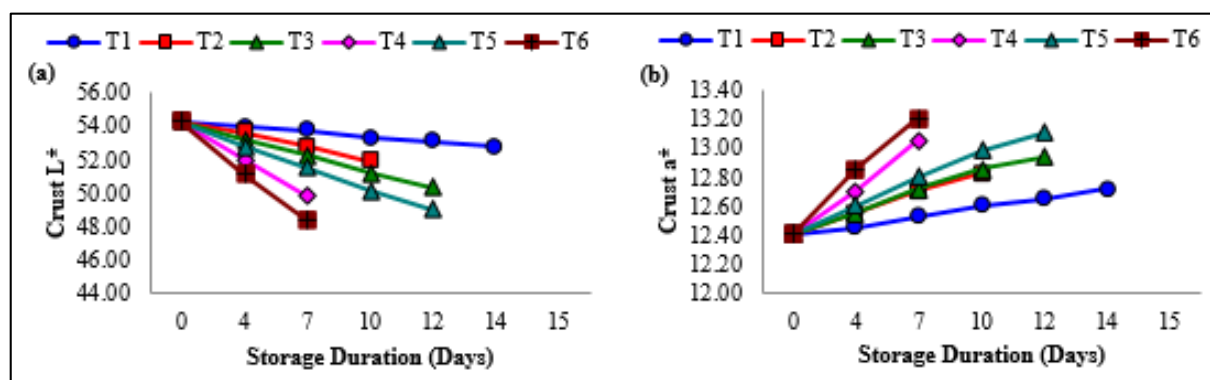
Fig 1: (a) Moisture content, (b) water activity and (c) pH of muffins during storage

3.4 Crust and crumb Colour (L^* , a^* and b^*)

The colour attributes of the crust and crumb changed progressively throughout storage, with considerably greater variation observed in the crust than in the crumb (Fig 2a-f). Crust lightness (L^*) decreased gradually, accompanied by slight increases in redness (a^*) and yellowness (b^*), indicating progressive surface darkening. These changes were more pronounced under room storage, whereas muffins packaged in LAFP exhibited the least variation in colour attributes. In contrast, only marginal changes were observed in crumb colour, with L^* , a^* and b^* remaining comparatively stable irrespective of packaging material and storage condition.

The greater susceptibility of the crust to colour deterioration is attributed to oxidative changes and the continued

development of browning pigments initiated during baking. Because the crust is directly exposed to oxygen and light, these reactions become more evident at the product surface than within the protected crumb matrix, which undergoes less thermal browning during baking and remains less susceptible to subsequent colour changes. The improved colour stability of LAFP-packaged muffins is likely due to the excellent oxygen and light barrier properties of the laminate, which limited oxidative pigment degradation and slowed storage-induced browning. These observations are consistent with previous studies reporting significant changes in muffin colour attributes during storage^[30] and greater colour stability in the crumb than in the crust of fortified muffins^[5].



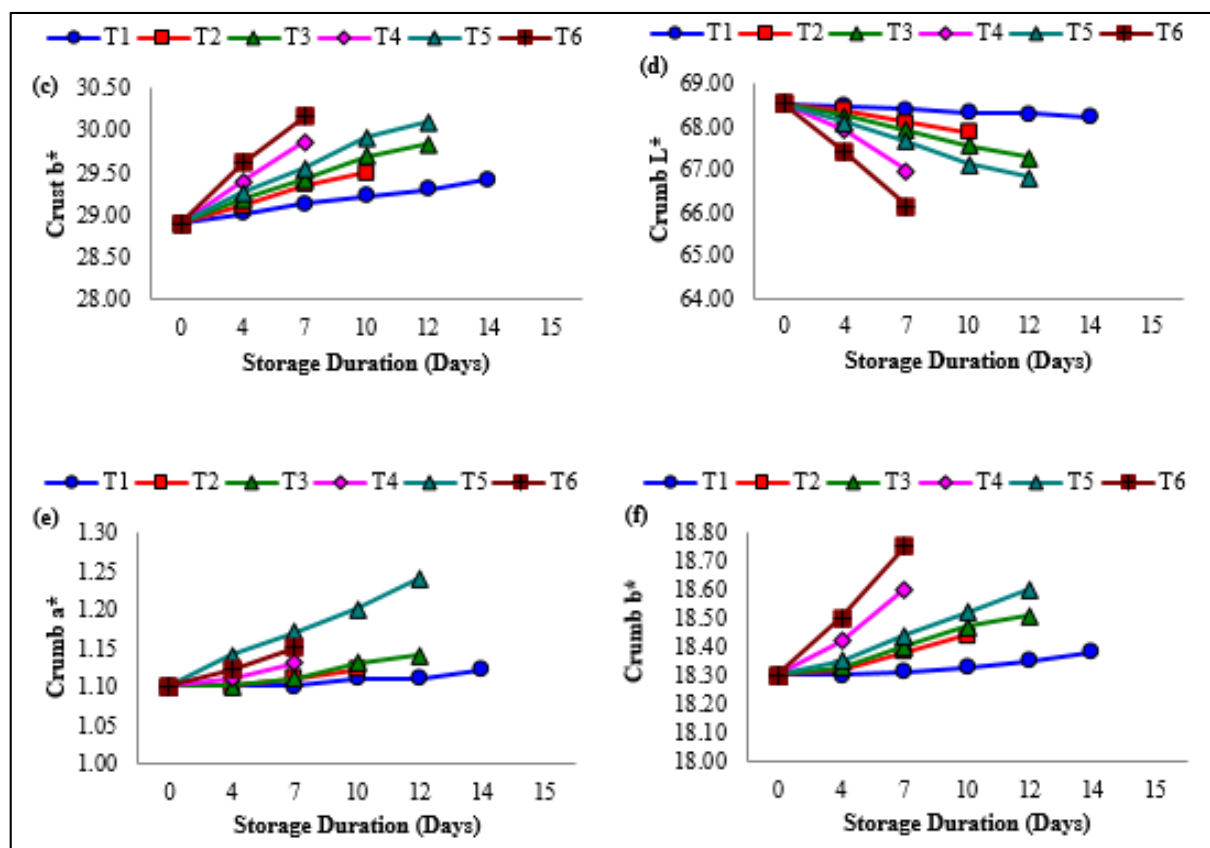


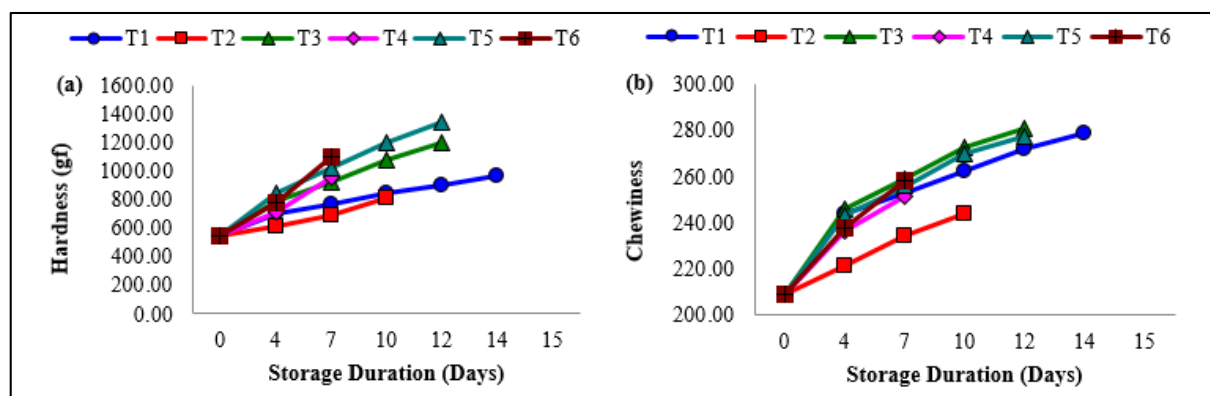
Fig 2: Crust and crumb colour dynamics (L^* , a^* and b^*) during storage

3.5 Changes in texture profile during storage

Storage progressively altered the textural characteristics of the developed muffins, as reflected by increased hardness and chewiness together with decreased springiness and cohesiveness (Fig 3a-d). Although these changes occurred under all treatments, their extent depended on both the packaging material and storage temperature. Texture deterioration was slower under refrigerated storage than under room conditions irrespective of the packaging material. Likewise, among the packaging materials, LAFP consistently preserved the textural attributes better than PP and LDPE, indicating that both storage temperature and package barrier properties influenced the rate of crumb staling.

The simultaneous increase in hardness and chewiness together with the reduction in springiness and cohesiveness reflects progressive structural changes within the crumb during storage. These changes are mainly associated with

starch retrogradation, redistribution of moisture within the crumb matrix and gradual strengthening of starch-protein interactions, which collectively produce a firmer and less elastic crumb. Packaging with superior barrier properties slows these changes by reducing moisture exchange with the surrounding environment, while refrigerated storage delays physicochemical reactions responsible for crumb firming. Consequently, textural deterioration progressed more slowly in refrigerated samples, particularly when packaged in LAFP. Comparable storage-induced changes in texture have been reported for banana peel powder-enriched muffins, where hardness and chewiness increased while springiness and cohesiveness decreased throughout storage^[15]. Similar trends were also reported in resistant starch-enriched muffins^[6], confirming that crumb firming and loss of elasticity are characteristic manifestations of bakery product staling.



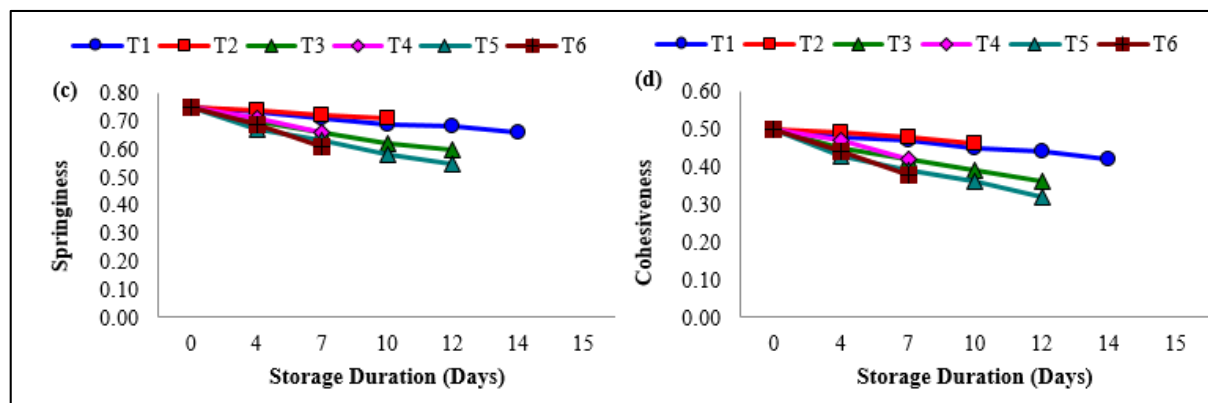


Fig 3: Texture profile analysis parameters during storage

3.6 Antioxidant activity (FRAP)

Ferric reducing antioxidant power gradually declined during storage under all packaging materials and storage conditions (Table 3). Fresh muffins exhibited an initial antioxidant activity of 262.77 mg FSE/100 g, which decreased to 254.35, 236.40 and 225.10 mg FSE/100 g under refrigerated storage and to 249.20, 230.10 and 215.30 mg FSE/100 g under room storage in LAFP, PP and LDPE packages, respectively. The decline was consistently slower under refrigerated storage, while PP exhibited intermediate behaviour between LAFP and LDPE.

The reduction in antioxidant activity reflects the progressive oxidation of phenolic compounds and other redox-active constituents during storage, thereby lowering the ferric reducing capacity of the product. The superior oxygen barrier provided by LAFP limited oxidative deterioration more effectively than PP and LDPE, whereas lower storage temperature further retarded oxidation. Similar decreases in antioxidant activity during storage have been reported in millet-based muffins^[30] and wheat bread enriched with nut oil cakes^[22], confirming that antioxidant depletion is a common phenomenon in bakery products during storage.

2.7 Total phenolic content

A progressive reduction in total phenolic content was

observed throughout storage regardless of packaging material and storage condition (Table 3). The initial TPC of 217.67 mg CE/100 g decreased to 210.15, 193.10 and 184.20 mg CE/100 g in muffins stored under refrigeration and to 205.80, 189.60 and 175.25 mg CE/100 g under room conditions in LAFP, PP and LDPE packages, respectively. Across both storage conditions, phenolic retention followed the order LAFP > PP > LDPE.

The decrease in TPC is mainly attributed to oxidative degradation of phenolic compounds together with their interactions with proteins and other food constituents, resulting in reduced extractable phenolics during storage. Oxygen exposure and light further accelerate degradation of individual phenolic compounds, whereas packaging materials with lower oxygen permeability effectively retard these reactions. Comparable declines in phenolic content have been reported in local breads containing sourdough and potato puree^[32] and wheat bread enriched with nut oil cakes^[22]. These authors further demonstrated that depletion of phenolic compounds diminished antioxidant capacity and oxidative stability during storage. Likewise, the decline in TPC observed in the present study closely paralleled the reduction in FRAP antioxidant activity, indicating that phenolic compounds contributed substantially to the antioxidant potential of the developed muffins.

Table 3: Antioxidant activity and total phenolic content: Day 0 vs terminal acceptable day

Treatment	FRAP (mg FSE/100 g)	Retention (%)	TPC (mg CE/100 g)	Retention (%)
T ₁ (d-14)	262.77→254.35	96.8	217.67→210.15	96.5
T ₂ (d-10)	262.77→249.20	94.9	217.67→205.80	94.5
T ₃ (d-12)	262.77→236.40	90.0	217.67→193.10	88.7
T ₄ (d-7)	262.77→230.10	87.6	217.67→189.60	87.1
T ₅ (d-12)	262.77→225.10	85.7	217.67→184.20	84.6
T ₆ (d-7)	262.77→215.30	81.9	217.67→175.25	80.5

3.8 Overall acceptability

Overall acceptability declined progressively during storage irrespective of packaging material and storage condition (Fig 4). Fresh muffins received a sensory score of 8.02, which gradually decreased throughout storage. T₁ retained the highest acceptability, whereas T₆ sample exhibited the fastest decline in sensory quality. The reduction in overall acceptability reflected the cumulative effects of moisture loss, crumb firming, colour changes, progressive lipid oxidation and increasing microbial load during storage, all of which adversely affected the appearance, texture, flavour

and freshness of the muffins. Packaging material markedly influenced the rate of quality deterioration, with the superior oxygen- and moisture-barrier properties of LAFP slowing physicochemical and microbiological changes, whereas the relatively higher permeability of PP and particularly LDPE accelerated quality loss. Similar reductions in sensory acceptability during storage have been reported in different muffins^[9, 15, 30], where progressive deterioration in quality attributes resulted in lower sensory scores with increasing storage duration.

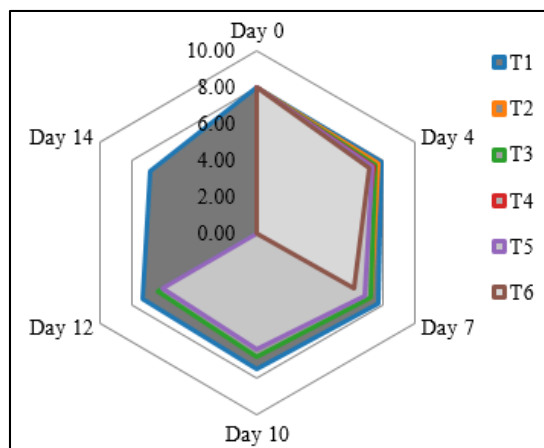


Fig 4: Overall acceptability changes during storage

3.10 Microbiological Analysis

Aerobic plate count (APC) increased progressively

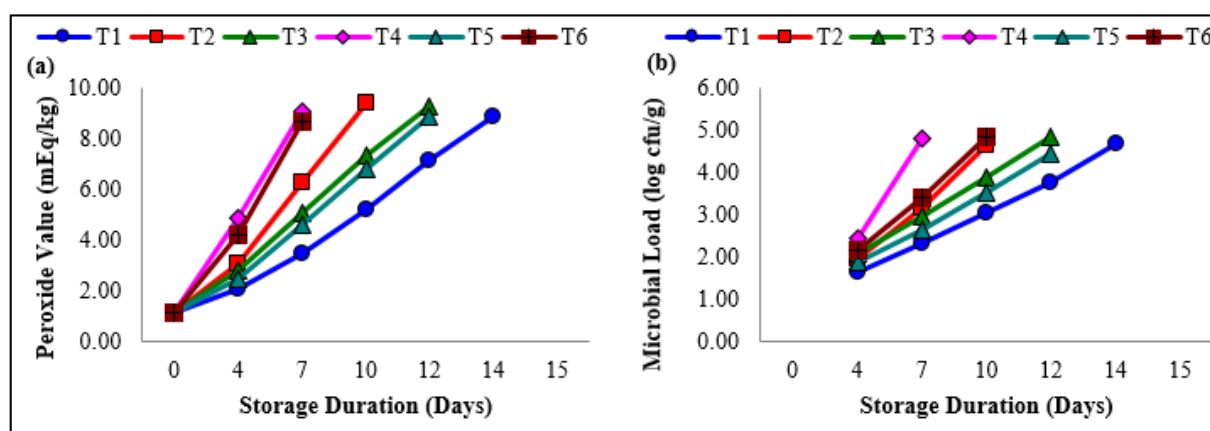


Fig 5: Peroxide value and microbial load during storage

4. Conclusion

This study demonstrated that the shelf-life stability of jackfruit pulp pomace powder (JPPP)-fortified composite millet muffins is governed by the combined effects of packaging material and storage temperature, with refrigerated LAFP packaging (T_1) most effective in preserving overall quality and extending shelf life. Moisture retention, textural firmness and antioxidant degradation emerged as the primary attributes limiting storage life, while crumb colour and protein content remained largely unaffected, identifying them as reliable markers for future shelf-life assessments of similar products. These findings underscore the need to optimize post-production storage conditions alongside product formulation and further confirm that jackfruit pulp pomace can be effectively valorized in millet-based muffins without compromising quality or shelf life. Collectively, the results offer practical guidance for selecting suitable packaging-storage combinations to support the commercial development of nutrient-dense, sustainable bakery products. The findings provide scientific evidence to support the commercial development of sustainable, value-added millet-based functional bakery products.

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throughout storage under all treatments (Fig 5b), reflecting the gradual proliferation of aerobic microorganisms. No colonies were detected immediately after baking, confirming the microbiological safety of the freshly prepared muffins. Thereafter, microbial proliferation depended on the packaging-temperature combination. T_1 exhibited the slowest increase in APC (4.68 log cfu/g after 14 days), whereas T_5 and T_3 reached 4.82 and 4.42 log cfu/g, respectively, by day 12. Under room storage, APC increased more rapidly, reaching 4.62 log cfu/g in T_2 and approximately 4.8 log cfu/g in T_4 and T_6 by the end of their respective storage periods. The reduced microbial growth in LAFP-packaged muffins is attributable to its superior barrier properties, while refrigeration further limited microbial metabolism. In addition, phenolic compounds present in jackfruit pulp pomace powder may have contributed to the delayed microbial proliferation. Similar trends have been reported for jackfruit seed powder-enriched cakes^[2] and functional muffins^[9].

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