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Research Article

Upcycling Citrus Waste into Functional Cookies: Sensory Acceptability, Shelf-Life Evaluation, and Consumer Perspectives

Samandeep Kaur[a,c*], Vikrant Singh[b], Parmjit S. Panesar[c*], Harish K. Chopra[c]

[a]*Thapar Institute of Engineering and Technology, Patiala, Punjab 147004, India*
[b]*Graphic Era (Deemed to be University), Dehradun, Uttarakhand 248002, India*
[c]*Sant Longowal Institute of Engineering and Technology, Longowal, Punjab 148106, India*

*Corresponding authors *E-mail address:* saman95deep@gmail.com (S.K), pspanesarrr@yahoo.com (P.S.P)

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Abstract

With increasing consumer demand for healthier snack options, dietary fiber is gaining prominence in functional food development. This study explores the incorporation of dietary fiber extracted from kinnow (*Citrus reticulata*) by-products i.e., peel powder, pomace powder, dietary fiber from peel, and dietary fiber from pomace into cookies at three substitution levels (5%, 10%, and 15%) in place of refined wheat flour. The resulting high-fiber cookies were evaluated for physicochemical, textural, sensory, and storage characteristics over 90 days. Among all formulations, cookies with 10% dietary fiber substitution demonstrated the best balance of quality parameters, achieving the highest overall acceptability (up to 7.94/9). In contrast, among cookies fortified with native powders, the 5% substitution level of either peel or pomace offered superior sensory scores with minimal textural compromise. While fiber addition increased hardness and influenced spread ratio, moderate levels did not result in significant off-flavors or undesirable mouthfeel. Storage studies revealed that cookies packed in aluminum laminate (AL) pouches exhibited superior oxidative stability, with peroxide and free fatty acid values remaining within permissible FSSAI limits. A consumer survey (n = 444) identified taste as the primary factor influencing acceptability, followed by perceived health benefits and price. These results highlight the potential of citrus by-products as sustainable, fiber-rich ingredients in bakery products, supporting both nutritional enhancement and food waste valorization.

1. Introduction

Dietary fiber is a non-digestible component of plant-based foods, including cellulose, hemicelluloses, pectin, lignin, and gums (Siddiqui et al., 2023). It is known to support gut health, lower cholesterol and blood glucose levels, promote satiety, and aid in weight management. Increased fiber intake is linked to reduced risk of chronic conditions such as cardiovascular disease, obesity, and type 2 diabetes (Soliman, 2019; Alahmari, 2024; Munteanu and Schwartz, 2024). Global health agencies like WHO, FAO, and EFSA recommend 25–38 g/day for adults and 2 g/MJ for children above one year to ensure healthy laxation and disease prevention (Stephen et al., 2017). Fiber, defined as carbohydrate polymers with ≥10 monomeric units, enhances stool bulk and facilitates regular bowel movements (Khalid et al., 2022). With growing consumer demand for healthier foods, incorporating dietary fiber into processed products has become a key strategy in functional food development (Suresh et al., 2024).

Traditionally, fiber enrichment in bakery products has relied on cereal-based sources such as wheat bran and oat fiber. However, the food industry is increasingly exploring non-conventional sources like fruit and vegetable by-products, as well as legumes and pulses, which offer both nutritional benefits and environmental sustainability (Mahmood et al., 2019; Lin, 2022). These agro-industrial residues are rich in bioactive compounds and functional polysaccharides, making them ideal candidates for fiber recovery and value addition. Notably, citrus processing by-products, such as kinnow (*Citrus reticulata*) peel and pomace, are rich in soluble and insoluble fiber, polyphenols, and antioxidants (Kaur et al., 2023 a,b). Despite this, they are often discarded as waste, leading to environmental and economic concerns.

Several studies have demonstrated the feasibility of incorporating fruit-derived dietary fibers, such as those from mango peel, date fiber, and fig seed flour into bakery formulations to enhance their nutritional and functional profiles (Ajila et al., 2008; Bölek, 2021; Asadi et al., 2022). These fibers not only improve the dietary fiber content but also contribute antioxidant and moisture-retention properties. However, limited literature exists on the effect of citrus-derived dietary fiber, particularly from kinnow peel and pomace, on the physical, sensory, and storage properties of cookies.

Cookies, among the most widely consumed bakery products globally, are favored for their palatability, convenience, and extended shelf life due to their low moisture content. However, traditional cookies, primarily made from refined wheat flour, fat, and sugar, are calorie-dense and nutritionally limited, making them less suitable for regular consumption (Asadi et al., 2022). As such, enhancing the nutritional quality of cookies particularly through dietary fiber fortification has gained increasing attention. Cookies also serve as an ideal model for fiber enrichment owing to their formulation flexibility and consumer acceptance. Nevertheless, incorporating dietary fiber presents formulation challenges, often altering dough rheology and final product attributes. Higher fiber levels can reduce the spread ratio, increase hardness, and compromise mouthfeel due to greater water absorption, disrupted gluten development, and the presence of bitter phytoconstituents (Canalis et al., 2019; Yildiz & Gocmen, 2021). Moreover, fiber-enriched cookies are more prone to storage-related quality deterioration such as moisture migration, oxidative rancidity, and textural softening. These changes are closely tied to packaging systems, multilayer aluminum laminates, for instance, offer superior moisture and oxygen barriers compared to single layer LDPE pouches, thereby better preserving product integrity over time (Kandpal et al., 2025).

This study aims to develop high-fiber cookies by incorporating four kinnow by-product sources i.e., peel powder, pomace powder, dietary fiber extracted from peel, and dietary fiber extracted from pomace at three substitution levels (5%, 10%, and 15%). The objective was to evaluate the effect of packaging material and storage duration on physicochemical, textural, sensory, and storage stability of the cookies over a 90-day period. Furthermore, a consumer perception survey was conducted to assess acceptance based on taste, health appeal, and willingness to pay. This study contributes to food waste valorization by utilizing citrus residues in bakery product development while offering insights into optimizing both functionality and consumer appeal.

2. Materials and methods

2.1. Materials and chemicals

Kinnow by-products were procured from a local juice processing unit, dried in a hot air oven (Thermo Scientific) to a moisture content of 8–9% (d.b.), ground into fine powder, and stored in airtight containers for further use. The remaining ingredients used for development for cookies were sourced from local grocery store at SLIET, Longowal, India. All chemicals used were of analytical reagent (AR) grade and obtained from HiMedia, India, and Pooja Science House, India. Enzymes including α-amylase, amyloglucosidase, and protease were sourced from Sigma-Aldrich, India.

2.2. Extraction of dietary fiber

Dietary fiber was extracted separately from kinnow (*Citrus reticulata*) peel and pomace using optimized ultrasound-assisted enzymatic protocols reported in our earlier studies (Kaur et al., 2023 a, b). Briefly, 1 g of kinnow by-product powder was suspended in 40 mL of phosphate buffer (0.08 M, pH 6.0) and subjected to ultrasonic treatment at 38% amplitude, 44 °C for 13 min using an ultrasonic processor (Model: Sinaptech NexTgen Lab 500, France) to enhance fiber yield. After sonication, 50 µL of α-amylase (300 IU/g) was added to the mixture and incubated in a water bath at 98–100 °C for 15 min. Once cooled, the pH was adjusted to 7.5 using 1N HCl, followed by the addition of 100 µL of protease (2.4 IU/g) and incubation at 60 °C for 30 min. After cooling again, the pH was adjusted to 4.5 and 200 µL of amyloglucosidase (300 IU/g) was introduced, with a final incubation step at 60 °C for 30 min. The enzymatically digested mixture was centrifuged at 6000 × g for 15 min (REMI R-8C Laboratory Centrifuge, India). The resulting wet pellet (insoluble residue) was washed with distilled water and oven-dried at 50 °C to obtain insoluble dietary fiber (IDF). The supernatant was mixed with four volumes of preheated ethanol (95%, 60 °C) and left undisturbed for 2 h to precipitate soluble dietary fiber (SDF). The precipitated SDF was washed sequentially: three times with 20 mL of 78% ethanol, twice with 10 mL of 95% ethanol, and twice with 10 mL of acetone. The obtained SDF was oven-dried at 50 °C until constant weight. The total dietary fiber (TDF) content was calculated gravimetrically using the method described by AOAC (2000), using the following equation (Equation 1).

$$TDF\ (\%) = \frac{(W_{SDF} + W_{IDF} - Protein\ Content - Ash\ Content) \times 100}{Weight\ of\ Sample} \quad (1)$$

Here: W_{SDF} = Weight of soluble dietary fiber; W_{IDF}= Weight of insoluble dietary fiber

2.3. Development of cookies using dietary fiber and their shelf life studies

Cookies were prepared using a control formulation adapted from Ekin et al. (2021), consisting of refined wheat flour (100 g), sugar (40 g), shortening (40 g), sodium bicarbonate (0.75 g), ammonium bicarbonate (0.25 g), salt (1 g), and approximately 5 mL of water. In high-fiber formulations, 5%, 10%, or 15% of the wheat flour was substituted with one of four kinnow by-product sources: peel powder, pomace powder, dietary fiber from peel, or dietary fiber from pomace. This resulted in a total of 12 experimental formulations, as detailed in Table 1. The cookie dough was prepared by first creaming sugar and shortening using a planetary mixer (Hobart mixer, Model N50, Canada), followed by gradual incorporation of dry ingredients and water to form a uniform dough. The dough was sheeted to a thickness of 5 mm using a manual dough roller, cut into uniform circular shapes (50 mm diameter), and baked in a preheated oven (Continental, India) at 190 °C for 20 min. After cooling at room temperature for 30 min, the cookies were packaged separately in low-density polyethylene (LDPE) pouches and aluminum laminate (AL) pouches. The aluminum laminate packaging used in this study was a three-ply structure comprising PET/Aluminum/LDPE (12/9/50 µm), while the LDPE pouch was a monolayer film (60 µm). All samples were stored at ambient conditions (~25–30 °C; relative humidity ~65%) for a period of 90 days. To evaluate shelf life, cookies were analyzed at 15-day intervals for the following parameters: moisture content, free fatty acids (FFA), peroxide value (PV), sensory attributes, and microbiological stability (total plate count).

Table 1. Cookie formulations with different kinnow by-product sources and substitution levels.

Ingredient Source	Code	Substitution Level (% of Flour)	Wheat Flour (g)	Kinnow powder/ fiber (g)	Sugar (g)	Shortening (g)
No substitution (Control)	-	0%	100	-	40	40
Peel Powder	Pe	5%	95	5	40	40
Peel Powder	Pe	10%	90	10	40	40
Peel Powder	Pe	15%	85	15	40	40
Pomace Powder	Po	5%	95	5	40	40
Pomace Powder	Po	10%	90	10	40	40
Pomace Powder	Po	15%	85	15	40	40
Dietary Fiber from Peel	Pe_DF	5%	95	5	40	40
Dietary Fiber from Peel	Pe_DF	10%	90	10	40	40
Dietary Fiber from Peel	Pe_DF	15%	85	15	40	40
Dietary Fiber from Pomace	Po_DF	5%	95	5	40	40
Dietary Fiber from Pomace	Po_DF	10%	90	10	40	40
Dietary Fiber from Pomace	Po_DF	15%	85	15	40	40

2.4. Physicochemical characterization of high-fiber cookies

2.4.1. Spread ratio

The cookie spread ratio was determined as the ratio of average diameter to thickness. Diameter was measured by placing six cookies edge-to-edge, rotating them 90°, and recording again. Thickness was measured using a digital vernier caliper (Insize, India; least count= 0.01 mm) by stacking six cookies randomly. The spread ratio was calculated using the equation 2 (AACC, 1995):

$$Spread\ Ratio = \frac{Cookie\ Diameter\ (mm)}{Cookie\ Thickness\ (mm)} \quad (2)$$

2.4.2. Texture analysis

Cookie hardness was measured using a Texture Analyzer (TA.XT2i, Stable Micro Systems, UK) in a three-point bending setup with a 25 g trigger force, 50 kg load cell, and 50 mm support distance. Test settings were: pre-test speed = 1.5 mm/s, test speed = 2.0 mm/s, and post-test speed = 10 mm/s. The maximum force at the breaking point (N) was reported as hardness and fracturability was measured as the distance (in mm) at which the cookie fractured. Each value represents the mean of triplicate readings (Jan et al., 2017).

2.4.3. Moisture content

Moisture content was measured at regular 15-day intervals using AOAC Official Method 925.10 (AOAC, 2000). Approximately 5 g of ground cookie sample was oven-dried at 105 °C to constant weight and expressed as percent moisture.

2.4.4. Color

Color parameters (L*, a*, b*) of cookies were measured using a HunterLab Colorimeter (Model D25 Optical Sensor, Hunter Associates Laboratory Inc., USA). Calibration was done using black and white tiles. L* indicates lightness (0 = black, 100 = white), a* represents red–green axis, and b* corresponds to yellow–blue scale. Values were recorded in triplicate and reported as means (Jan et al., 2017). The color difference (ΔE) was calculated using the equation 3.

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \quad (3)$$

2.5. Storage studies

2.5.1. Sensory evaluation

Sensory properties were evaluated by a panel of 25 members (10 trained, 15 semi-trained) using a 9-point hedonic scale (1 = dislike extremely, 9 = like extremely). Each panelist was trained for descriptive sensory terms before assessing 10 cookie variants per session across two sessions. Attributes assessed included color, texture, mouthfeel, flavor, and overall acceptability (OAA).

2.5.2. Total plate count (TPC)

TPC was determined using AOAC Method 966.23 (AOAC, 2000). Nutrient agar was sterilized (15 psi, 121 °C, 15 min) and poured into Petri plates. Serial dilutions were plated and incubated at 37 °C for 24–48 h. Colonies were counted and expressed as log CFU/g as per equation 4.

$$log_{10}\ CFU\ /\ g\ =\ log_{10}(Colony\ Count)\ +\ log_{10}(Dilution\ Factor) \quad (4)$$

Here CFU= Colony Forming Units

2.5.3. Peroxide value (PV)

The peroxide value (PV) of lipid fractions extracted from cookie samples was determined according to AOAC Method 965.33 (AOAC, 2000), with minor modifications. Briefly, lipids were extracted from ground cookies using chloroform, and 10 mL of the extracted lipid was mixed with 15 mL glacial acetic acid and 1 mL of saturated potassium iodide (KI) solution. The mixture was stirred and kept in the dark for 5 min to allow iodine liberation. After this, 75 mL of distilled water and 1 mL of 1% starch solution were added as an indicator. The liberated iodine was titrated with 0.01 N sodium thiosulfate until the blue-black color disappeared. The PV was calculated as milliequivalents of active oxygen per kilogram of lipid (meq O_2/kg of lipids) using the following equation 5.

$$PV\left(\frac{mEq.}{kg}\right) = \frac{S \times N \times 1000}{Weight\ of\ sample} \quad (5)$$

Here, S = mL of 0.01N $Na_2S_2O_3$ (Blank corrected used) and N = Normality of $Na_2S_2O_3$.

2.5.4. Free fatty acid content (FFA)

FFA was measured using Tarladgis (1960) with modifications from Adelakun and Oyinkansola (2020). Cookies were ground, and lipids were extracted using Soxhlet apparatus. About 3 g of extracted oil was mixed with 30 mL of neutralized ethanol, boiled, and cooled. After adding 1 mL of phenolphthalein, the solution was titrated with 1 N NaOH until a faint pink color persisted. The FFA values were calculated as per Equation 6.

$$Free\ Fatty\ Acid(\%) = \frac{282 \times 0.02\ N\ KOH \times V \times DF \times 100}{W \times 1000} \quad (6)$$

Here, V is titer value of NaOH, W is weight of oil used, DF is the dilution factor.

2.6. Consumer survey

A consumer perception survey was conducted to evaluate acceptance of citrus fiber-enriched cookies and identify factors influencing purchasing decisions. A total of 444 responses were collected using a structured online questionnaire, disseminated via Google Forms to participants across various regions of India. The sample included 286 males, 157 females, and 1 respondent identifying as other. Convenience sampling was employed, with a predominance of students, a key target demographic for functional foods, along with housewives and working professionals. The questionnaire comprised closed-ended, Likert scale, and open-ended questions, designed to assess awareness of dietary fiber, willingness to purchase functional cookies, taste and health-based preferences, and price sensitivity. Cookie acceptance was measured using a five-point Likert scale (1 = strongly disagree to 5 = strongly agree). Data were compiled in Microsoft Excel and analyzed using SPSS software (Version 25, IBM Corp., USA). Descriptive statistics (frequencies and percentages) were used to summarize demographic profiles. Cross-tabulations and Chi-square tests were performed to evaluate associations between variables such as gender, income, product awareness, and willingness to pay.

2.7. Statistical analysis

All experiments were conducted in triplicate, and results are presented as mean ± standard deviation (SD). Data were subjected to one-way analysis of variance (ANOVA), and Tukey's HSD test was employed for post-hoc comparisons to identify statistically significant differences among means at a confidence level of $p < 0.05$. Statistical analysis was performed using SPSS software, Version 25.0 (IBM Corp., Armonk, NY, USA).

3. Results and discussion

3.1. Physico-chemical and textural properties of developed high-fibre cookies

Thirteen cookie formulations were developed by replacing refined wheat flour with 5%, 10%, or 15% of either kinnow peel powder, pomace powder, dietary fiber from peel (Pe_DF), or dietary fiber from pomace (Po_DF), alongside a non-substituted control. This experimental design enabled a detailed comparison between native citrus by-product powders and their corresponding extracted dietary fiber (DF) fractions on cookie structure, texture, and sensory characteristics.

The physical properties of the cookies are summarized in Table 2 (peel-based) and Table 3 (pomace-based). Across all fiber types, a general decline in spread ratio was observed with increasing substitution level, ranging from 8.61 (control) to 7.63 (15% Pe_DF). This reduction is primarily attributed to gluten dilution and the enhanced water-binding capacity (WHC) of the added fibers, which restricted dough spread during baking (Chen et al., 2025; Reddy et al., 2025). Notably, native peel and pomace powders at 5% substitution exhibited higher spread ratios compared to their extracted fiber counterparts, suggesting lower WHC and milder structural interference.

Between the two native powders, pomace powder resulted in slightly higher spread ratios than peel, likely due to its finer particle size and higher residual sugar content, which may promote better dough flow. Conversely, Pe_DF and Po_DF led to significantly lower spread, with Pe_DF showing the most pronounced reduction, possibly due to its higher insoluble fiber and lignin content. These findings are consistent with prior studies indicating that purified or more fibrous ingredients reduce cookie expansion by limiting gluten development and modifying dough rheology (Jurasová & Kukurová, 2011; Bölek, 2021).

The textural properties of cookies, particularly hardness and fracturability, were significantly influenced by the type and level of fiber incorporation. Hardness increased consistently with rising fiber content, ranging from 15.63 N in the control to 28.94 N in 15% Po_DF, indicating increased dough rigidity due to higher water- holding capacity (WHC) and reduced gluten matrix flexibility.

Table 2. Physical, sensory, and textural analysis of high-fiber cookies fortified with kinnow peels and its dietary fiber.

Properties	Sample						
	Control	5% DF	10% DF	15% DF	5% Peel	10% Peel	15% Peel
Physical Characteristics							
D (mm)	48.14±0.04^{a}	47.08±0.02^{e}	46.92±0.03^{f}	46.68±0.05^{g}	47.93±0.04^{b}	47.76±0.05^{c}	47.52±0.02^{d}
T (mm)	5.59±0.02^{d}	5.48±0.01^{f}	5.53±0.02^{e}	6.12±0.01^{b}	5.58±0.02^{d}	5.63±0.01^{c}	6.23±0.01^{a}
Spread ratio	8.61±0.02^{b}	8.59±0.01^{c}	8.48±0.01^{d}	7.63±0.01^{f}	8.74±0.01^{a}	8.63±0.02^{b}	7.77±0.01^{e}
Color Values L*	70.52±1.40^{a}	67.46±1.56^{b}	61.12±0.87^{e}	53.39±1.52^{g}	60.21±0.45^{f}	63.47±0.19^{d}	64.63±0.48^{c}
a*	10.72±0.23^{f}	12.34±0.71^{d}	12.26±0.65^{e}	10.33±0.76^{g}	13.26±0.53^{c}	13.98±0.11^{b}	14.62±0.26^{a}
b*	34.58±0.93^{a}	34.99±1.34^{a}	33.23±1.20^{ab}	27.97±0.93^{c}	26.71±0.06^{d}	25.13±0.09^{e}	24.67±0.09^{f}
ΔE	-	3.48	9.62	18.36	13.22	12.23	12.17
Sensory Characteristics							
Texture	7.94±0.42^{ab}	7.26±0.36^{bc}	7.45±0.52^{b}	6.80±0.25^{cd}	8.22±0.32^{a}	8.13±.22^{a}	6.54±0.21^{de}
Mouthfeel	7.16±0.98^{bc}	7.12±0.46^{c}	7.17±0.81^{bc}	7.04±0.49^{cd}	8.18±0.19^{a}	7.95±0.31^{a}	7.64±0.28^{ab}
Color	7.31±0.34^{c}	7.35±0.51^{c}	7.28±0.48^{d}	7.19±0.28^{de}	8.15±0.21^{ab}	8.22±0.40^{a}	8.06±0.57^{ab}
Flavor	8.04±0.45^{a}	7.51±0.47^{bc}	7.93±0.23^{ab}	7.25±0.36^{d}	8.13±0.19^{a}	7.50±0.29	6.13±0.63^{e}
OAA	8.21±0.63^{a}	7.53±0.45^{b}	7.84±0.53^{ab}	7.15±0.41^{bc}	8.25±0.44^{a}	8.16±0.32^{a}	6.95±0.44^{c}
Texture Analysis							
Hardness (N)	15.63±0.02^{g}	19.96±0.01^{f}	23.65±0.02^{d}	28.55±0.03^{b}	20.48±0.03^{e}	24.27±0.02^{c}	29.29±0.01^{a}
Fracturability (mm)	0.52±0.01^{d}	0.60±0.01^{c}	0.65±0.02^{b}	0.44±0.01^{e}	0.62±0.01^{bc}	0.69±0.02^{a}	0.45±0.01^{e}

#Different superscript values (a, b, c, d, e, f, g) represent significant differences ($p<0.05$) in values across the rows. D= Diameter, T= Thickness, OAA= Overall Acceptability, DF = Dietary Fiber; L* = Lightness; a* = Red-Green axis, b* =Yellow-Blue axis, ΔE= color difference

Table 3. Physical, sensory, and textural analysis of high-fiber cookies fortified with kinnow pomace and its dietary fiber.

Properties	Sample						
	Control	5% DF	10% DF	15% DF	5% Pomace	10% Pomace	15% Pomace
Physical Characteristics							
D (mm)	48.14±0.04^{b}	47.66±0.03^{c}	47.47±0.04^{d}	47.25±0.02^{e}	48.52±0.03^{a}	48.33±0.06^{a}	48.11±0.04^{b}
T (mm)	5.59±0.02^{c}	5.55±0.01^{f}	5.56±0.02^{e}	6.19±0.01^{b}	5.65±0.01^{d}	5.67±0.01^{c}	6.32±0.01^{a}
Spread ratio	8.61±0.02^{c}	8.7±±0.02^{b}.	8.58±0.01^{b}	7.72±0.01^{d}	8.82±0.03^{a}	8.74±0.01^{b}	7.86±0.02^{c}
Color Values L*	70.52±1.40^{a}	68.9±1.54^{b}	65.25±0.86^{c}	61.87±1.50^{e}	65.85±1.56^{c}	63.66±0.87^{d}	62.16±1.52^{d}
a*	10.72±0.23^{b}	11.63±0.71^{a}	11.61±0.64^{a}	9.57±0.75^{bc}	11.97±0.71^{a}	11.95±0.65^{a}	10.05±0.76^{b}
b*	34.58±0.93^{a}	33.65±1.32^{a}	32.03±1.19^{b}	27.04±0.92^{c}	34.19±1.34^{ab}	32.45±1.2^{b}	27.28±0.93^{c}
ΔE	-	2.08	5.92	11.53	4.85	7.29	11.12
Sensory Characteristics							
Texture	7.94±0.42^{b}	7.18±0.08^{c}	7.55±0.22^{b}	6.88±0.13^{d}	8.11±0.17^{a}	8.03±0.12^{a}	6.47±0.11^{e}
Mouthfeel	7.16±0.98^{d}	7.04±0.13^{e}	7.26±0.34^{d}	7.12±0.25^{e}	8.07±0.12^{a}	7.85±0.16^{b}	7.55±0.15^{c}
Color	7.31±0.34^{d}	7.27±0.11^{d}	7.37±0.24^{d}	7.27±0.15^{d}	8.04±0.11^{b}	8.12±0.21^{a}	7.97±0.30^{c}
Flavor	8.04±0.45^{a}	7.42±0.18^{b}	8.03±0.15^{a}	7.33±0.19^{c}	8.02±0.19^{a}	7.41±0.15^{b}	6.06±0.33^{d}
OAA	8.21±0.63^{a}	7.44±0.14^{d}	7.94±0.22^{c}	7.23±0.21^{d}	8.14±0.23^{b}	8.06±0.17^{b}	6.87±0.23^{e}
Texture Analysis							
Hardness (N)	15.63±0.13^{e}	19.72±0.12^{d}	23.94±0.11^{b}	28.87±0.15^{a}	20.24±0.11^{c}	23.96±0.17^{b}	28.94±0.12^{a}
Fracturability (mm)	0.52±0.01^{b}	0.60±0.01^{ab}	0.66±0.02^{a}	0.45±0.01^{c}	0.62±0.02^{a}	0.69±0.03^{a}	0.45±0.01^{c}

#Different superscript values (a, b, c, d, e, f, g) represent significant differences ($p<0.05$) in values across the rows. D= Diameter, T= Thickness, OAA= Overall Acceptability, DF= Dietary Fiber; L* = Lightness; a* = Red-Green axis, b* =Yellow-Blue axis, ΔE= color difference

Cookies enriched with extracted dietary fibers (Pe_DF and Po_DF) exhibited significantly higher hardness than those made with native powders, owing to their concentrated insoluble fiber content and absence of plasticizing components such as sugars and soluble solids. Fracturability, defined as the distance a sample travels before breaking, followed a similar trend. It increased up to 10% substitution, suggesting crisper and more brittle textures, and declined sharply at 15%, where excessive fiber content likely disrupted matrix uniformity, leading to early structural failure. The highest fracturability (0.65–0.69 mm) was observed in 10% Pe_DF and Po_DF cookies, indicating an optimal balance between crispness and structure. In contrast, peel and pomace powders, especially at lower levels, maintained moderate hardness and fracturability, reflecting the plasticizing effects of residual sugars, pectin, and oils, particularly in peel. Among fiber types, Po_DF consistently yielded the firmest textures, followed by Pe_DF, while native pomace powder produced slightly more rigid cookies than peel powder. These differences can be attributed to the fiber composition—with pomace rich in hemicellulose and peel containing more pectin and volatile compounds. Overall, 10% substitution with extracted fiber delivered a favorable textural profile, balancing crispness with structural strength. These findings align with earlier reports on fiber-enriched cookies by Yildiz & Gocmen (2021) and Khalil et al. (2023), where moderate fiber addition enhanced mechanical crispness, while excess loading resulted in undesirable toughness.

Color analysis revealed a consistent reduction in lightness (L)* and increases in a (redness)* and b (yellowness)* with increasing fiber incorporation, particularly in cookies enriched with extracted dietary fibers (Pe_DF and Po_DF). Among the fiber types, cookies formulated with peel-derived dietary fiber (Pe_DF) exhibited the maximum darkening, as reflected by the lowest L* values. This trend reflects a shift toward darker, reddish-yellow hues, primarily due to Maillard and caramelization reactions occurring at surface temperatures above 100 °C. These reactions generate brown-colored compounds such as melanoidins and hydroxymethylfurfural (HMF), which contribute to the characteristic crust color in baked products. Additionally, inherent pigments and polyphenolic compounds in citrus by-products further intensify browning (Ordóñez-Santos et al., 2021; Reddy et al., 2025). In contrast, cookies prepared with native peel or pomace powders especially at 5–10% substitution levels exhibited relatively lighter colors. This is likely due to the presence of residual sugars and lower fiber concentration, which may dilute the browning intensity and buffer the heat-induced pigment transformation. Compared to Pe_DF, Po_DF cookies showed a milder shift in color parameters, suggesting that both the type of fiber and the composition of the matrix significantly influence browning behavior during baking. Similar color trends have been reported in fiber-enriched cookies formulated with kinnow peel flour, date fiber, mango peel, and fig seed flour, where increased fiber levels led to a darker product appearance due to intensified browning and pigment concentration (Bölek, 2021; Khalil et al., 2023; Reddy et al., 2025). These observations emphasize the need to balance functional benefits with visual acceptability in consumer-oriented formulations.

Sensory evaluation showed that cookies with 10% dietary fiber substitution, particularly those containing Pe_DF and Po_DF, achieved the highest overall acceptability (OAA ≈ 7.9–8.0). These formulations offered a favorable balance of texture, flavor, and mouthfeel, closely approximating the sensory profile of control cookies. The improved crispness and mild fiber flavor at this level likely contributed to consumer preference. However, at 15% substitution, OAA scores declined across all fiber types, with panelists noting increased hardness and slight bitterness, particularly in Pe_DF formulations. This sensory decline is attributed to high polyphenol content and reduced sugar dilution, which may have intensified astringency and masked sweetness. Among the native powders, cookies with 5% peel or pomace powder achieved the best flavor and texture ratings, benefiting from the presence of residual citrus oils and natural sugars, which enhanced palatability. In contrast, 10–15% levels of native powders led to a drier mouthfeel and grittier texture, particularly with pomace, possibly due to its coarser fiber structure and lower pectin content.

Notably, while Po_DF cookies were slightly more acceptable than Pe_DF at higher concentrations likely due to less bitterness and milder aroma both remained sensorially acceptable at the 10% level. Across all formulations, OAA scores remained above 7, indicating general consumer acceptance. These results are consistent with previous studies showing that 8–10% fiber fortification is optimal for maintaining desirable sensory properties in bakery products (Ajila et al., 2008; Canalis et al., 2019). The findings also highlight the importance of fiber source and composition in influencing flavor, texture, and overall consumer appeal.

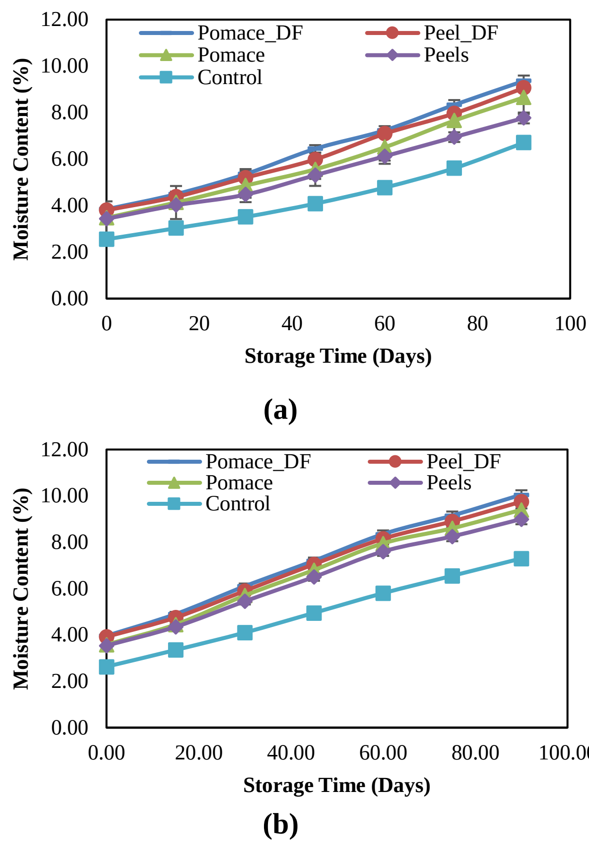


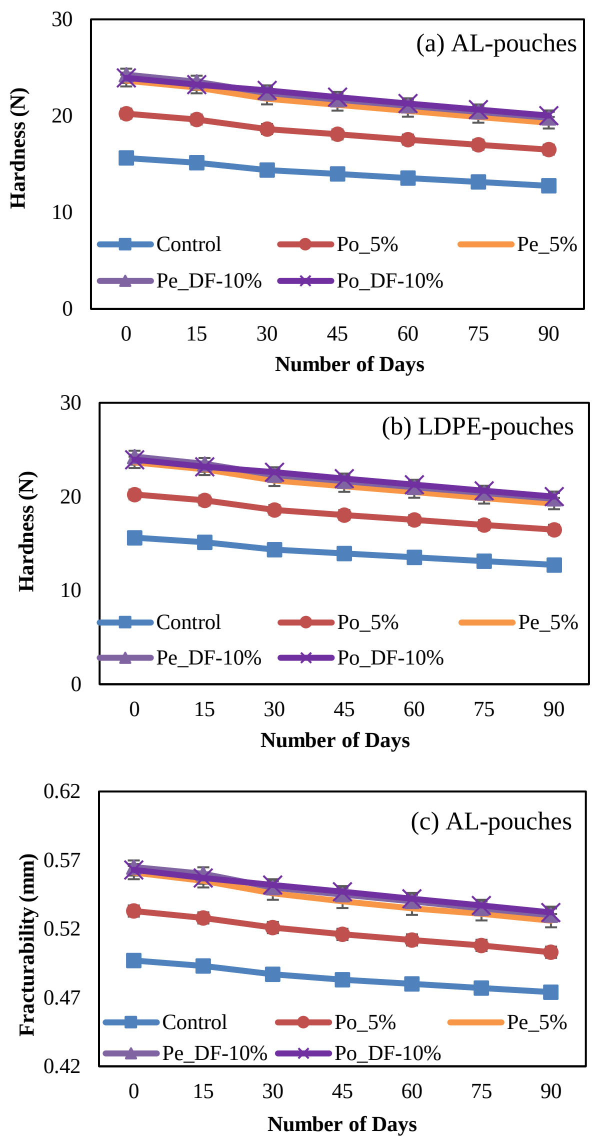
Figure 1. Effect of storage on the moisture content of cookies containing kinnow by-products (at 5% substitution level) and their dietary fiber (at 10% substitution level) stored in (a) Laminate pouches, (b) LDPE pouches (Values have been presented in mean ±S.D.; DF= dietary fiber).

A clear distinction was observed between cookies made with native by-product powders and those formulated using extracted dietary fibers. While both contributed to fiber enrichment, DF-based formulations caused more pronounced changes in texture (increased hardness) and color (lower L* values), due to their higher insoluble fiber concentration and stronger water-binding capacity. In contrast, native powders, especially at lower inclusion levels, retained more soluble sugars and volatile compounds, resulting in milder textural and sensory impacts.

Beyond sensory and structural aspects, the incorporation of citrus-derived dietary fibers holds nutritional relevance, offering health benefits such as improved glycemic control, enhanced satiety, and cholesterol reduction (Jovanovski et al., 2019). According to the National Research Council (1989), a daily increase of 6 g in dietary fiber can reduce ischemic heart disease mortality by 25%, emphasizing the importance of such functional bakery innovations. Based on the results obtained, cookies prepared with 10% dietary fiber (from peel and pomace) and those with 5% native by-product powders were selected for extended storage studies. These variants offered the most favorable combination of nutritional enhancement, textural integrity, and consumer acceptability, making them appropriate candidates for shelf-life and packaging evaluation under ambient conditions.

3.2. Storage studies of high-fiber cookies

Storage studies of cookies play a vital role in assessing the quality, safety, and shelf life of these baked goods. These studies involve evaluating various parameters such as moisture content, FFA levels, microbial counts, and sensory attributes over time to understand how cookies change during storage. The storage of cookies in different packaging materials can significantly impact their quality and shelf life. In the present study, the storage of high-fiber cookies was done in metalized pouches (aluminum) and low-density polyethylene (LDPE). The cookies are hygroscopic in nature and easily gain moisture when subjected to environment. The PV measures the amount of peroxides present in the cookies, which can indicate the level of oxidation and rancidity. The FFA content measures the amount of fatty acids that have been liberated from the triglycerides in the cookies. Both parameters can affect the flavor, texture, and nutritional value of the cookies. By conducting storage studies, researchers and food manufacturers can determine the optimal storage conditions, packaging materials, and shelf life of cookies.



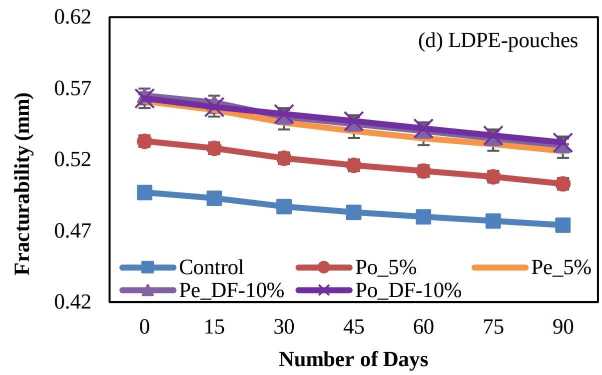


Figure 2. Effect of storage on texture analysis of cookies (a, b) hardness, (c, d) fracturability values for cookies stored in different packaging materials
(Here Pe= peels, Po= pomace, DF= dietary fiber; values have been presented in mean ± S.D.)

3.2.1. Effect on moisture content

Moisture content was monitored throughout the 90-day storage period as it critically influences texture, microbial stability, and the onset of oxidative rancidity in cookies. As shown in Fig.1, all formulations exhibited a steady moisture increase over time, with significantly higher values in LDPE-stored cookies compared to those in aluminum laminate (AL) pouches, owing to the higher water vapor transmission rate (WVTR) of LDPE. By day 90, moisture levels in LDPE-packaged cookies ranged from 6.70% (control) to 9.36% (10% Po_DF), while in AL packaging, the corresponding values ranged from 7.30% to 10.05%, confirming the superior moisture barrier of laminate films. Among formulations, cookies with 10% dietary fiber (Pe_DF and Po_DF) absorbed more moisture than those with 5% native powders (Pe and Po), due to their greater water-holding capacity (WHC) and finer particle size, which promote moisture migration and binding.

Even at lower substitution levels, native peel and pomace powders also contributed to substantial moisture gain. For instance, 5% Po cookies reached 8.65% (LDPE) and 9.40% (AL), while 5% Pe cookies reached 7.77% (LDPE) and 9.00% (AL) at day 90. This suggests that even small additions of citrus by-products—rich in pectin, soluble sugars, and dietary fibers—can affect hygroscopicity. Notably, Po_DF showed the highest moisture uptake, likely due to its higher porosity and insoluble fiber content, while peel-based cookies exhibited slightly less gain, possibly due to the presence of essential oils and polyphenols which may offer limited moisture resistance.

The increase in moisture corresponded with a decline in cookie hardness, especially in LDPE packaging. For example, the texture score of Pe_DF cookies in LDPE dropped from 7.14 (day 30) to 6.65 (day 90). The resulting softening and sogginess negatively impacted sensory acceptability, as also reflected in the OAA scores discussed in Section 3.2.6. Furthermore, high moisture levels may accelerate lipid hydrolysis, contributing to elevated free fatty acid (FFA) content (discussed in Section 3.2.3). These observations align with previous reports such as Sahni, & Shere, (2017) and Nagi et al. (2012) who reported higher moisture gain in biscuits stored in LDPE and HDPE than in metalized AL pouches. Similarly, Rahman et al. (2019) reported that biscuits stored at 30°C in aluminum foil showed moisture gain from 4.89% to 6.63%, while those in metallized packaging ranged from 4.89% to 5.90%. These findings validate that cookies, as hygroscopic food products, are prone to moisture uptake from ambient air, and this is exacerbated in high-fiber variants due to their inherent WHC and microstructure (He et al., 2023). In conclusion, both fiber type and packaging material significantly influenced moisture retention. Aluminum laminates proved more effective in controlling moisture ingress, thereby preserving textural quality and oxidative stability, reinforcing their suitability for the packaging of fiber-enriched bakery products.

3.2.2. Effect on texture

The textural attributes of cookies were significantly influenced by the incorporation of kinnow by-products and their dietary fibers. As shown in Fig. 2, the addition of fiber whether in the form of native powders or extracted dietary fiber increased cookie hardness compared to the control (15.63 N). The highest initial hardness values were recorded for cookies containing 10% dietary fiber, with Pe_DF and Po_DF reaching 24.27 N and 23.94 N, respectively. Native powders (5% Pe and 5% Po) showed intermediate hardness (20.23–23.65 N), while the control remained the softest. The observed increase in cookie hardness can be attributed to the high content of insoluble dietary fibers, which reduce dough plasticity and enhance matrix rigidity. Insoluble fibers possess a porous, hydrophilic structure that enables them to bind significant amounts of water within the dough. This water binding limits the availability of free moisture necessary for optimal gluten development and starch gelatinization, ultimately leading to reduced dough extensibility. As a result, the baked cookies exhibit a denser and firmer texture (Aydogdu, et al., 2018). Similar trends have been reported in previous studies involving fiber-rich ingredients such as almond flour (de Oliveira et al., 2015) and mango peel powder (Ajila et al., 2008), where increased fiber content corresponded with heightened hardness due to changes in dough hydration and structural properties.

Throughout storage, all samples exhibited a gradual reduction in hardness, with laminate-packaged cookies maintaining better structural integrity than LDPE-packed counterparts. By day 90, the hardness of Pe_DF cookies had declined to 19.80 N (laminate) and 19.77 N (LDPE), while that of 5% Po dropped to 16.5 N (laminate) and 16.48 N (LDPE). This decline is consistent with moisture uptake over time (see Section 3.2.1), which likely plasticized the cookie matrix and softened the crumb structure. The softening was more pronounced in LDPE-packaged samples, where higher water vapor permeability facilitated greater moisture ingress. Alongside hardness, fracturability, the distance a sample bends before breaking, also decreased slightly during storage. Initial fracturability was highest in Pe_DF and Po_DF cookies (≈0.565 mm), indicating a crisp and brittle structure desirable in cookies. Over time, values declined to ≈0.530 mm (day 90), particularly in LDPE-packed samples. This trend confirms that fiber content contributes not only to increased hardness but also to enhanced crispness, although this benefit diminishes over time due to water migration and structural relaxation.

Among formulations, Po_DF maintained the highest texture stability, while cookies made with native peel powder softened more rapidly. The structural robustness of pomace-based cookies may be due to a coarser fiber matrix and lower polyphenolic interference, whereas peel-based formulations may have been affected by volatile oils and higher pectin content, which promote moisture binding and subsequent softening.

3.2.3. Effect on free fatty acid content

Free fatty acid (FFA) content was assessed to evaluate lipid hydrolysis during storage—a critical factor influencing cookie shelf life, oxidative stability, and sensory quality. As shown in Fig. 3, a steady rise in FFA was observed across all formulations over 90 days, attributed to the breakdown of triglycerides into free fatty acids under ambient storage conditions. Despite the increase, FFA levels remained well below the FSSAI threshold of 1.5%, indicating no onset of hydrolytic rancidity. At day 90, control cookies stored in LDPE pouches reached the highest FFA level (0.54%), while those packed in laminate pouches recorded 0.48%, emphasizing the superior oxygen and moisture barrier of aluminum laminate compared to LDPE. This is consistent with findings by Nagi et al. (2012), who reported that metalized polyester, with its aluminum layer, provides an effective barrier against light and oxygen, thereby limiting lipid oxidation and subsequent free fatty acid (FFA) formation in biscuits.

Dietary fiber-enriched cookies, particularly those containing 10% Po_DF and Pe_DF, showed slower FFA accumulation than the control, despite higher moisture levels (as reported in Section 3.2.1). At day 90, Pe_DF reached 0.48% (LDPE) and 0.43% (laminate), while Po_DF recorded 0.46% and 0.41%, respectively. This may be attributed to the presence of bioactive compounds, notably phenolics and flavonoids, in kinnow by-products, which exert antioxidant effects, mitigating oxidative fat degradation. The role of dietary fiber in modulating fat-water interactions may also contribute to this protective effect (Kaur et al., 2023).

Among native powder samples, 5% Po and Pe cookies exhibited moderate FFA levels, ranging between the control and DF formulations. These samples reached 0.46–0.45% (LDPE) and 0.41–0.40% (laminate) by day 90, suggesting that while native powders offer some functional benefit, their lower concentration of antioxidants and higher residual sugar content may limit lipid protection.

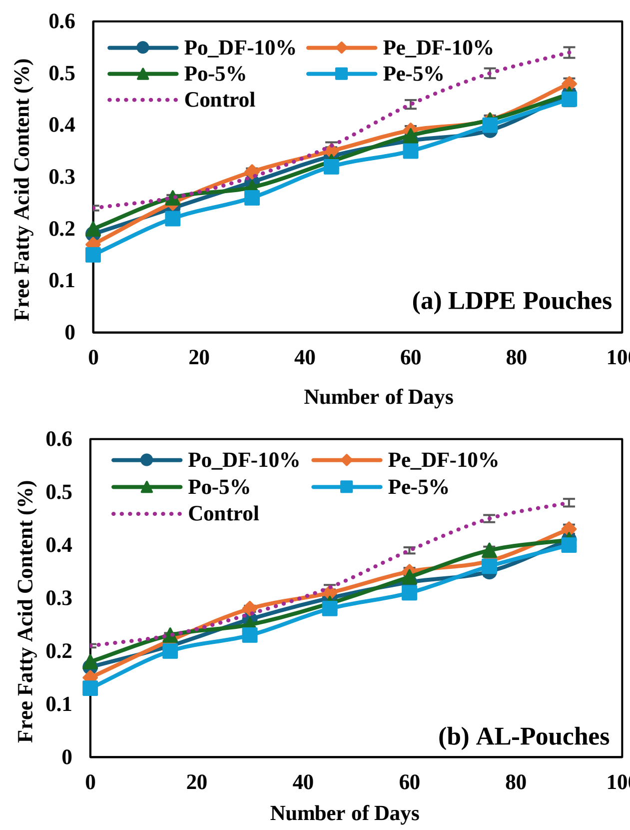


Figure 3. Effect of storage on free fatty acid content of cookies containing kinnow by-products and their dietary fiber stored in (a) LDPE pouches, (b) AL pouches.

(Values have been presented in mean ±S.D. Here DF= dietary fiber, Pe= Peel, and Po= pomace)

The observed FFA trends reflect a strong interaction between ingredient composition, packaging material, and storage time. Cookies in LDPE pouches, due to higher WVTR and oxygen permeability, absorbed more moisture, which likely accelerated lipase-mediated fat breakdown (Duta et al., 2019). In contrast, aluminum laminate films helped retain oxidative stability, as also corroborated by texture and moisture data (Jan et al., 2017). Additionally, the use of fresh shortening, optimized baking parameters, and inclusion of antioxidant-rich ingredients ensured that lipid quality remained within acceptable limits throughout storage.

3.2.4. Effect on peroxide values

Peroxide value (PV) serves as a sensitive indicator of primary lipid oxidation, offering insight into the onset of rancidity during cookie storage. As shown in Fig. 4, PV values gradually increased in all formulations throughout the 90-day storage period, consistent with the accumulation of hydroperoxides from fat oxidation. Importantly, all samples remained well below the FSSAI threshold of 10 mEq/kg, confirming acceptable oxidative stability and absence of rancid off-flavors.

At day 0, PV values ranged from 0.20 mEq/kg (Pe-5%, laminate) to 0.39 mEq/kg (Control, LDPE), reflecting the inherent oxidative susceptibility of the cookie matrix. Over time, a progressive rise was observed in both packaging conditions. After 90 days, LDPE-packaged cookies showed the highest PVs, peaking at 0.97 mEq/kg for the control, followed by 0.80 (Pe_DF) and 0.76 (Po_DF and Po-5%). In contrast, laminate-packaged counterparts exhibited lower PVs: 0.806 mEq/kg (control), 0.663 (Pe_DF), 0.636 (Po_DF), and ~0.63–0.66 for native powders.

These results clearly demonstrate the protective role of aluminum laminate packaging, which provided a more effective barrier against oxygen ingress compared to LDPE. The higher permeability of LDPE led to more rapid oxidation of fats, consistent with prior reports where PVs of cookies stored in low-barrier films exceeded stability limits faster (Manzocco et al., 2020; Kumari et al., 2021). These observations also align with earlier studies in biscuits and crackers, which reported PV thresholds of 3–6 mEq/kg as critical for acceptable flavor and aroma retention (Duta et al., 2019).

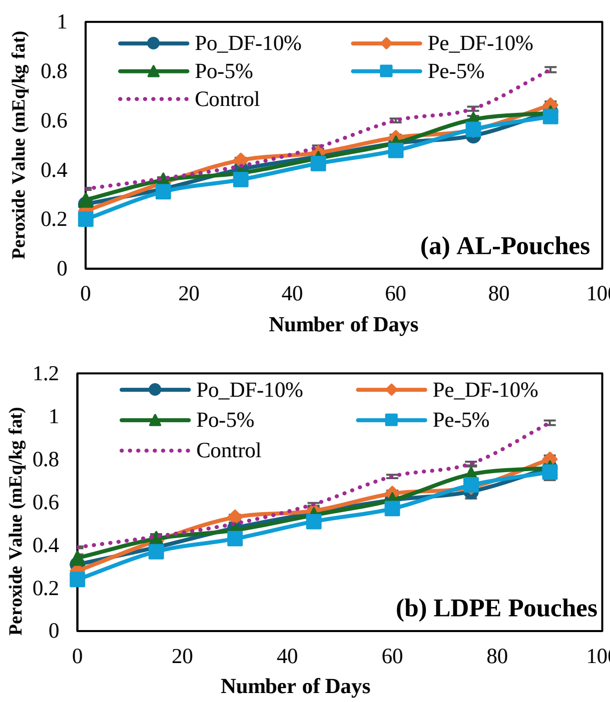


Figure 4. Effect of storage on peroxide value of cookies containing kinnow by-products and their dietary fiber stored in (a) AL Pouches (b) LDPE pouches. (Values have been presented in mean ±S.D. Here DF= dietary fiber, Pe= Peel, and Po= pomace)

Among the formulations, fiber-enriched cookies (especially those with 10% Pe_DF and Po_DF) consistently exhibited lower PVs than the control across both packaging types. This enhanced oxidative stability is likely attributed to the presence of polyphenols and flavonoids in kinnow-derived fibers, which exhibit natural antioxidant activity. In particular, Po_DF (laminate) maintained a PV of just 0.636 mEq/kg by day 90, significantly lower than the control in LDPE. This supports findings that citrus by-products contain bioactives that inhibit peroxide formation and delay oxidative chain reactions (Kaur P. et al., 2023).

Interestingly, even at a lower substitution level (5%), native powders (Pe and Po) showed better oxidative stability than the control, but slightly poorer performance than extracted DF. For example, Po-5% reached 0.76 mEq/kg in LDPE and 0.631 mEq/kg in laminate, compared to 0.97 and 0.806 for the respective control samples. This suggests that although native powders retain some antioxidant potential, their lower fiber purity and higher residual sugars may reduce their ability to effectively scavenge reactive oxygen species. Overall, no rancid odor or flavor was detected by sensory panelists in any sample during the study period, reinforcing the acceptability of PV trends. The primary cause of sensory rejection after 90 days, especially in LDPE-packaged cookies, was attributed to loss of crispness and changes in taste, not oxidation. These results confirm that cookies enriched with kinnow peel or pomace fiber, particularly when packed in aluminum laminates, can maintain good oxidative stability and sensory quality for up to 90 days. The combined use of functional ingredients and high-barrier packaging thus presents a scalable solution for developing shelf-stable, high-fiber bakery products.

3.2.5. Effect on total plate count

Microbiological quality was monitored through total plate count (TPC) over the 90-day storage period (as presented in Fig. 5), as it reflects microbial proliferation and shelf-life stability of cookies. Across all formulations, TPC increased steadily with storage duration, consistent with moisture gain and nutrient availability. However, values remained below the critical limit of 5 log CFU/g, confirming the microbiological safety of the product throughout storage. At day 90, LDPE-packaged samples exhibited higher microbial loads, with TPCs ranging from 3.88 log CFU/g (5% Pe) to 4.32 log CFU/g (control).

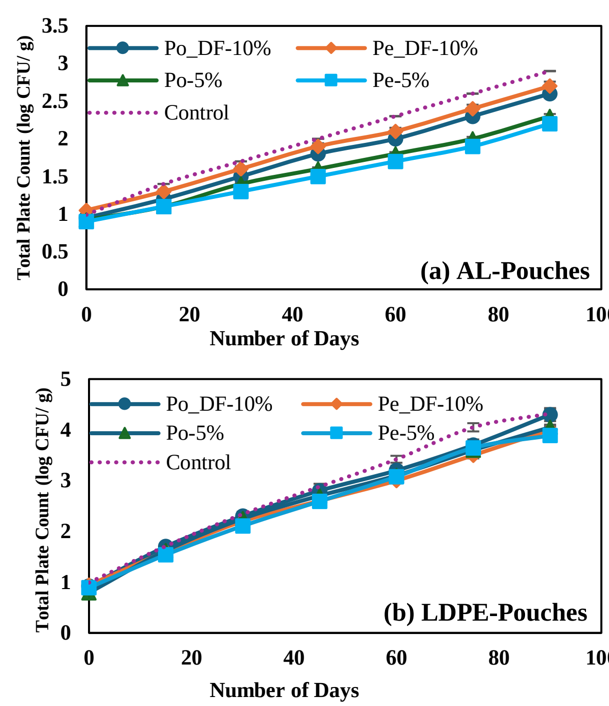


Figure 5. Effect of storage on microbial stability of high-fiber cookies stored in (a) AL-pouches, (b) LDPE pouches. (Here DF= dietary fiber, Pe= Peel, and Po= pomace; values are presented as mean±S.D)

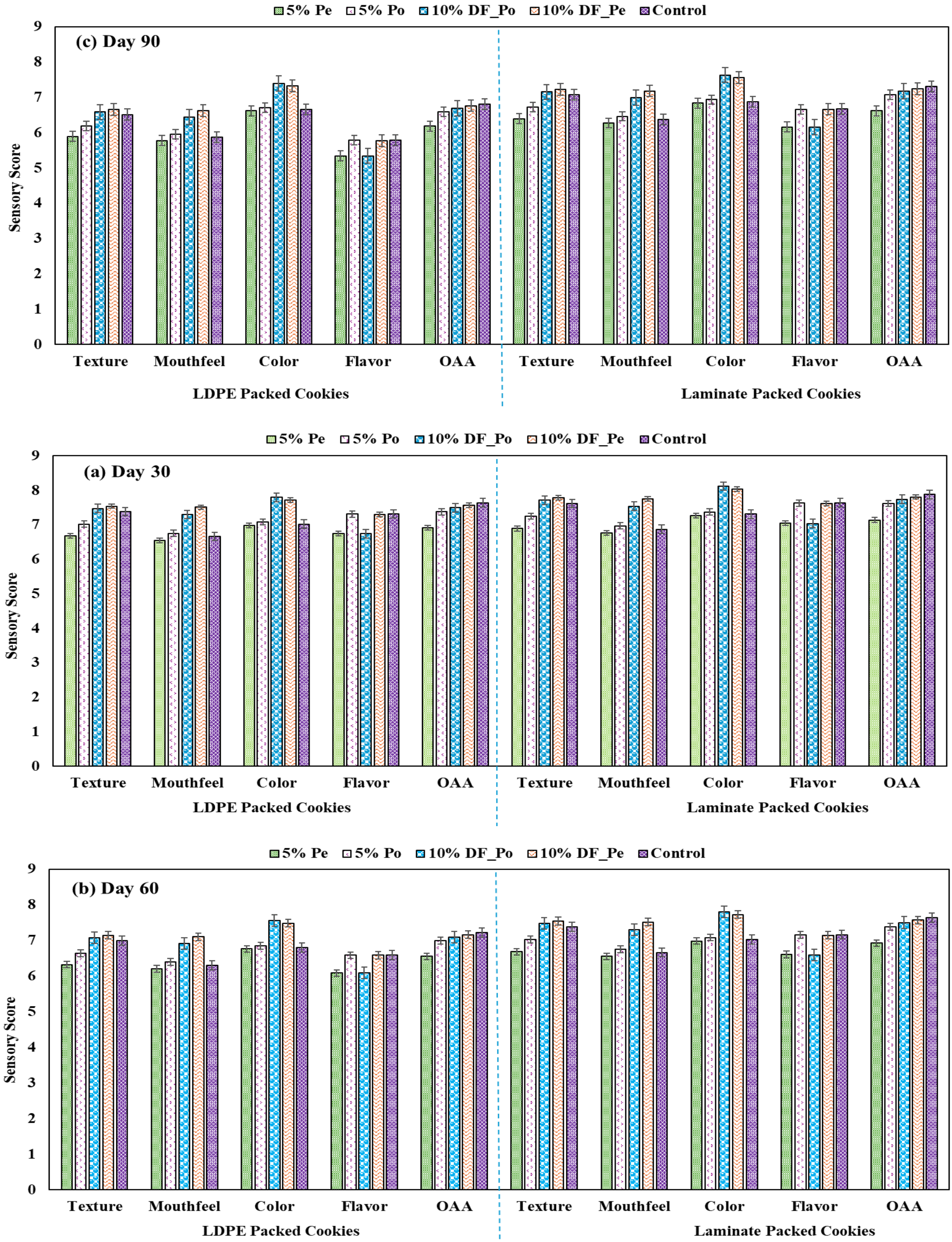


Figure 6. Effect of storage and packaging material on sensory characteristics of high-fiber cookies (a) 30 days, (b) 60 days, (c) 90 days
(Here DF= dietary fiber, Pe= peel, and Po= pomace; Values have been presented in mean±S.D,)

This corresponded to higher moisture levels recorded in LDPE-packed cookies (e.g., 9.36% in 10% Po_DF vs. 6.70% in control), which likely promoted microbial activity. In contrast, laminate-packaged samples maintained significantly lower TPCs, ranging from 2.2 log CFU/g (10% Pe_DF) to 2.9 log CFU/g (control) at day 90, reinforcing the superior barrier performance of aluminum laminate in limiting moisture ingress and oxygen exposure.

Among the formulations, cookies fortified with 10% dietary fiber (both Pe_DF and Po_DF) and 5% native powders (Pe and Po) demonstrated better microbial resistance compared to the control. For instance, at day 90, 10% Pe_DF cookies stored in laminate had a TPC of 2.2 log CFU/g, whereas the control recorded 2.9 log CFU/g under identical conditions. This could be attributed to the antimicrobial activity of phytochemicals, particularly phenolics and essential oils, retained in citrus by-products, which have been documented to suppress microbial growth (Ajila et al., 2008).

Furthermore, the lower TPC in 10% Pe_DF and Po_DF cookies suggests that not only the presence of bioactives but also higher fiber concentration may inhibit microbial colonization by reducing water activity and limiting free water availability. Thus, both ingredient type and packaging material significantly influenced microbial stability. These results emphasize the effectiveness of laminate packaging in prolonging shelf life and the added value of citrus by-products in enhancing microbiological safety of functional cookies.

3.2.6. Effect on sensory properties

The sensory performance of the selected cookie formulations i.e., 5% peel (Pe), 5% pomace (Po), 10% dietary fiber from peel (Pe_DF), and 10% dietary fiber from pomace (Po_DF)—was evaluated over a 90-day period under two packaging systems: LDPE and aluminum laminate (See Fig. 6). At day 30, cookies packed in aluminum laminate demonstrated higher overall acceptability (OAA) scores across all samples compared to LDPE. For example, 10% Pe_DF and 10% Po_DF registered OAA scores of 7.81 and 7.74, respectively, in laminate packaging, versus 7.57 and 7.50 in LDPE. This trend indicates superior sensory retention in laminate, likely due to its lower oxygen and moisture permeability.

Between formulations, pomace-based cookies consistently outperformed peel-based variants, both in native and DF forms. At day 60, 10% Po_DF cookies scored an OAA of 7.50 in laminate, compared to 7.16 for Pe_DF and only 6.92 for 5% Pe, reflecting a more favorable flavor profile and lower bitterness in pomace. Flavor scores followed a similar trend, with Pe_DF showing a decline to 6.58 in LDPE by day 60, while Po_DF maintained 6.59–6.59 across packaging types. Peel samples tended to develop off-flavors more rapidly, likely due to their higher polyphenol and essential oil content, which are more prone to oxidation. Mouthfeel and texture were also better preserved in laminate packaging. At day 90, 10% Pe_DF maintained a texture score of 7.22 and mouthfeel of 7.18 in laminate, while dropping to 6.65 and 6.62, respectively, in LDPE. Conversely, native powders (5% Pe, 5% Po) showed a sharper decline across all sensory attributes over time, likely due to higher moisture migration and matrix degradation under less protective LDPE conditions.

Overall, laminate packaging was superior in retaining sensory quality, and fiber source significantly influenced product perception. While dietary fibers offered enhanced structural and nutritional benefits, pomace-based fibers demonstrated better sensory stability, possibly due to their lower bitterness, higher carbohydrate content, and less volatile flavor compounds compared to citrus peel. These findings affirm that while fiber enrichment can improve functional value, consumer acceptance remains closely tied to sensory experience particularly texture, mouthfeel, and flavor (Mirzaei-Fard et al., 2025). Optimizing formulation and packaging together is essential for maximizing shelf-life and marketability of functional baked goods. Strategies such as ingredient pairing (e.g., nut flours or sugar replacers) and advanced barrier films may further enhance acceptability and extend sensory integrity during storage (Yildiz & Gocmen, 2021; Khalil et al., 2023).

3.2.7. Survey on consumer perception of high-fiber cookies

To complement the sensory evaluation, a structured survey (n = 444) was conducted to assess consumer perception and purchase behavior regarding high-fiber cookies developed from citrus by-products. The survey examined the influence of demographic factors such as gender, age, education, and income on preferences related to taste, health benefits, price sensitivity, and product quality.

Results showed that 60.3% of respondents valued functional foods only when taste expectations were met, while 20.2% were willing to compromise on taste for health benefits. Notably, 73.3% considered health benefits a key purchase driver, indicating that although taste remains the top priority, nutritional value significantly influences consumer choices. This aligns with previous findings highlighting taste and perceived health benefits as primary determinants of functional food acceptance (Topolska et al., 2021; Pahwa et al., 2023).

Price sensitivity analysis revealed that 33% of consumers were willing to pay up to 5% more, and 24.6% up to 10% more, for healthier cookies, suggesting moderate elasticity for premium-priced functional products. Product quality and personal suitability were prioritized over price, indicating a quality-driven market. Chi-square analysis found no significant association between gender or income and perception of taste or health benefits. However, education level significantly influenced perceived quality ($p < 0.05$), with higher-educated respondents more likely to associate functional foods with superior attributes, supporting literature linking education to improved food literacy (Ivkov et al., 2018; Daniele et al., 2024).

The survey also explored adoption barriers: 49.5% cited lack of awareness, while 18% pointed to price as limiting factors. These findings reflect global trends showing that limited awareness, high cost, and insufficient sensory appeal hinder functional food acceptance (Alongi & Anese, 2021; Baker et al., 2022). Younger respondents prioritized taste, whereas older participants, especially those with health concerns, were more health-focused (Pahwa et al., 2023). Trust in taste and product safety also emerged as strong purchase influencers (Çakıroğlu, 2018). In summary, the survey confirmed the dual importance of taste and health benefits in shaping consumer acceptance of fiber-rich cookies. It highlighted the need for targeted education, clear labeling, and strategic marketing to enhance awareness and encourage broader adoption of functional bakery products, particularly in emerging markets where such innovations are still gaining traction.

4. Conclusion and future prospects

The present study demonstrated the successful development of high-fiber cookies enriched with dietary fiber extracted from kinnow peel and pomace. Up to 10% substitution was found optimal for balancing nutritional improvement and sensory acceptability, whereas higher levels increased hardness and imparted off-flavors. Among fiber types, pomace-based formulations exhibited better textural and flavor stability than peel-based counterparts, attributed to compositional differences. Cookies with native by-product powders at 5% also showed favorable performance, providing a simpler, cost-effective option for moderate fiber fortification. During storage, cookies packed in aluminum laminate pouches retained superior oxidative and microbial stability compared to LDPE, reinforcing the importance of high-barrier packaging for fiber-enriched bakery products. Quality indicators such as moisture content, peroxide value, free fatty acids, and total plate count remained within acceptable limits over 90 days, confirming good shelf-life. Consumer survey insights revealed that taste, followed by health benefits, were the most influential factors driving purchase intent. Willingness to pay a premium for fiber-rich cookies suggests market potential, particularly among health-conscious demographics.

Future work should focus on improving textural properties at higher fiber levels through enzymatic modification or ingredient synergies and validating shelf-life under real-world storage conditions. Market segmentation studies and awareness campaigns could further support the commercialization of such functional products, contributing to both nutrition enhancement and citrus by-product valorization.

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Credit authorship contribution statement

Samandeep Kaur: Conceptualization, writing original draft, writing-reviewing and editing, software.

Vikrant Singh: Writing-reviewing and editing, software.

Parmjit S. Panesar: Conceptualization, supervision.

Harish K. Chopra: Supervision.

Ethics statement/ Ethical Approvals

This study was conducted in accordance with all applicable ethical guidelines, regulations, and institutional standards. Informed consent was obtained from all participants involved in the sensory evaluation and consumer survey. No studies involving animals or clinical trials on humans were conducted as part of this research.

Data availability statement

All data generated or analyzed during this study are included in this published article. Additional information is available from the corresponding author upon reasonable request.

Conflicts of interest

Authors declare no known conflict of interest.

Funding

No funding was received for carrying out this research.

Declaration of AI involvement

The research design, data analysis, interpretation of results, and all intellectual content presented in this manuscript are entirely the work of the authors. Grammarly, an AI-based language tool, was used only for grammar correction and language refinement during manuscript preparation.

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