Future Foods 12 (2025) 100768

Contents lists available at ScienceDirect

Future Foods

journal homepage: www.elsevier.com/locate/fufo

Valorization of red dragon fruit peel (Hylocereus polyrhizus) as a functional ingredient for fortified biscuits: physicochemical, nutritional, and sensory implications

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ARTICLE INFO

Keywords:
Antioxidant activity
Bioactive compounds
Food waste utilization
Food fortification
Shelf-life

ABSTRACT

This study valorizes red dragon fruit peel (an agro-industrial byproduct) as a useful ingredient in biscuits. Proximate analysis of the Red dragon fruit peel powder (RDFPP) revealed a high crude fiber (23.68 %), ash (10.60 %), and carbohydrates (43.32 %), along with bioactive components such as total phenolic content (0.34 mg GAE/g), flavonoids (53.32 mg QE/g) and antioxidant activity: 43.22 %). Fourier transform infrared spectroscopy identified functional groups associated with polysaccharides, phenolic content, flavonoids, and lipids in both peel and biscuits. Biscuits containing 0–9 % RDFPP were evaluated for physicochemical, bioactive, sensory, and microbiological qualities. Increasing RDFPP substitution increased ash (0.71 % to 2.27 %) and fiber (0.08 % to 0.74 %), while decreasing moisture (5.58 % to 4.21 %) and pH (5.34 to 5.03), enhancing shelf stability. Antioxidant activity and bioactive compounds increased proportionally, with 9 % RDFPP showing the highest values (total phenolic content: 0.50 mg GAE/g; total flavonoids: 1.99 ± 0.02 mg QE/g; DPPH: 38.79 %). Sensory evaluation indicated that 6 % RDFPP was the ideal acceptability level, after which color (darker, L*: 36.61) and taste declined due to betacyanin pigments and acidic significance. Scanning electron microscopy analysis revealed structural porosity at higher RDFPP levels, correlating with texture changes. Microbial shelf-life studies showed that RDFPP has antimicrobial properties, reducing bacterial growth in 9 % RDFPP biscuits (8.09 $\log_{10}$ CFU/g) compared to the control (8.45 $\log_{10}$ CFU/g) after 15 days. These findings highlighted the ability of RDFPP to enhance nutritional and functional properties of baked products. A 6 % RDFPP substitution optimized antioxidant enrichment, fiber fortification, and consumer acceptance, providing a sustainable solution for repurposing agricultural waste into value-added foods.

1. Introduction

Food processing industries produce a large amount of byproducts, many of which contain valuable bioactive substances with potential functional food applications (Sagar et al., 2018). Waste management can be minimized by recovering bioactive substances from fruit waste, which can be utilized in developing nutritious plant-based products for both food and feed applications (Haryati et al., 2025; Moseri et al., 2025; Agustin et al., 2024; Albaayit et al., 2024). Tannins, flavonoids, phenolics, and limonoids, which are relatively rare in many plants, are found in abundance in the peels of numerous fruits, a byproduct of underutilized fruit processing (Tahir et al., 2024). Dragon fruit peels contain 22–44 % of the fruit's weight and are typically disposed of as waste after being processed, particularly in the beverage industry (Liaotrakoon et al., 2012). The extraction of bioactive substances from dragon fruit peels, such as phenolics, betalains, and dietary fibers, contributes to waste reduction and provides health advantages like antibacterial, anti-inflammatory, and antioxidant qualities that can assist with preventing chronic diseases (Le et al., 2022).

Hylocereus polyrhizus (red dragon fruit with red peel and pulp), a *Cactaceae* plant from America and South Asia, is valued for its diverse bioactive components, making it both nutritionally and therapeutically

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https://doi.org/10.1016/j.fufo.2025.100768
Received 3 June 2025; Received in revised form 16 September 2025; Accepted 22 September 2025
Available online 23 September 2025

important (Chowdhury et al., 2024). Plant genotype, harvest timing, extraction techniques, and pedoclimatic conditions are some of the environmental elements that affect the chemical composition and biological activity of plant essential oils and extracts (Gorzin et al., 2024). Management techniques like fertilization and the use of biofertilizer can affect the chemical composition and biological activity of plant tissues in addition to environmental influences (Tiwari et al., 2025). Chlorophyll levels and photosynthetic efficiency affect the formation of carbohydrates and secondary metabolites in plant tissues (Ashar et al., 2024). This indicates that the bioactive substances found in the peel of dragon fruit are both species-specific and the result of basic physiological mechanisms. Among the various dragon fruit varieties *H. polyrhizus* is widely cultivated in Bangladesh as an important nutrients source for the population (Nur et al., 2023). The peel, which typically counts as waste, of *H. polyrhizus* was found to have phytochemical qualities, total phenols, antioxidant capacity, and antibacterial activity (Manihuruk et al., 2017). Large quantities of betacyanins were also present in the peel, which might be used to make natural coloring (Roriz et al., 2022). Because of the increased consumer demand for natural health-promoting bioactive substances, these wastes have prompted intense research. The value of dragon fruit could be increased in biscuit production by using the powder made from the peel.

Bakery products, especially biscuits, are popular worldwide for their accessibility and taste, representing the largest category of chemically leavened snack items. The name "biscuit" comes from the Latin word "danis biscoctus," which means "double-cooked bread," and alludes to bread rusks that were manufactured for sailors as early as the Middle Ages (Srivastava et al., 2015). The three main ingredients used to make biscuits are refined flour, sugar, and hydrogenated fats, along with a few additional minor ingredients like emulsifiers and additives (Wani et al., 2015). The food industry is continuously searching for methods to increase the nutritious content of bakery products while decreasing waste because these goods are a common food item worldwide (Tahir et al., 2023). The effect of addition red dragon fruit peel powder to biscuits at different percentages on their physicochemical characteristics, antioxidant activity, sensory acceptance, and microbiological shelf life were assessed in this study. In addition to its pigment content, red dragon fruit peel powder contains various phytochemicals and fibers that may influence functional properties of the final product, similar to the way bioactive peptides from *Scenedesmus obliquus* have been reported to exhibit antioxidant, emulsifying, fat-binding, and foaming properties, supporting their use in functional food development (Amiri et al., 2025). The objective of the present study was to investigate the possibility of using dragon fruit peels as a functional food ingredient while addressing food waste challenges. Functional foods can be used in a more comprehensive strategy that targets several aspects of lifestyle to help people achieve better overall health (Abedinia et al., 2025). The findings from this study could provide valuable insights for the food sector in developing healthier, more sustainable, and nutritionally improved baked products.

2. Materials and methods

2.1. Collection and preparation of raw material

Freshly red-skinned dragon fruit with red flesh (*H. polyrhizus*) were collected from Purapara Bazar in Chowgacha Upazilla, Jashore, Bangladesh (Fig. 1).

After collecting, the fruits were cleaned several times with deionized water to eliminate dirt and dust, and then the peels were separated from the pulp. The peels were cut into 0.5 cm in width and 5 cm in length. The pieces of peel were spread on a foil paper separately and they were kept in a hot air dryer at 55.0 ± 2 °C for 48 h. After drying, the dried peels were grounded into fine powder using a grinder, sieved, packed, and

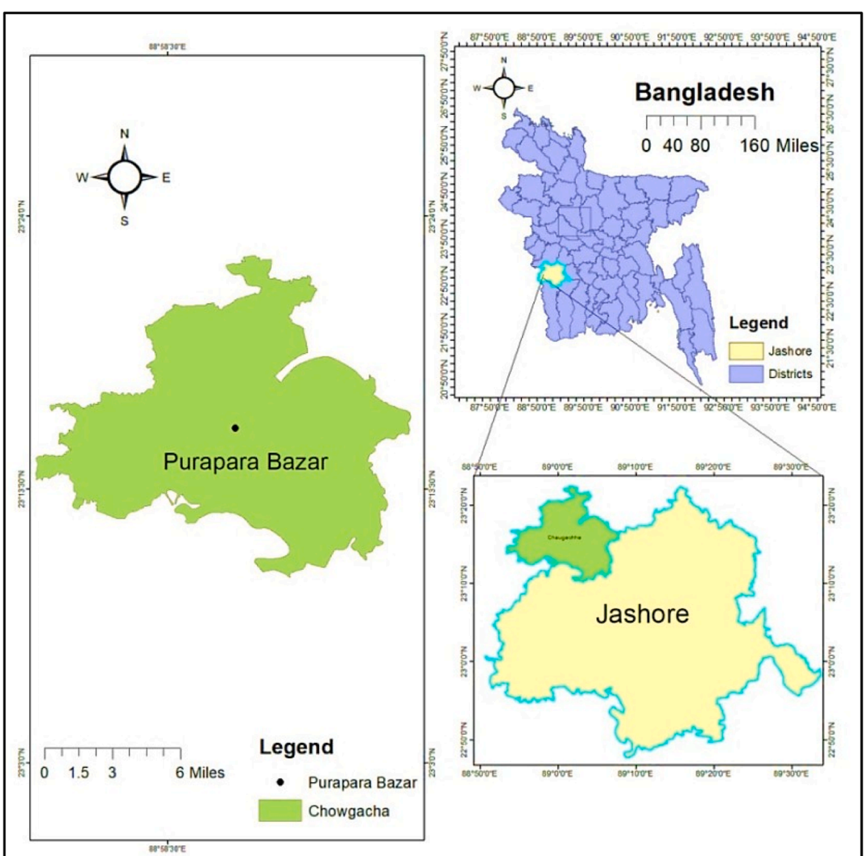

Fig. 1. Schematic map of the experimental area representing Purapara Bazar in Chowgacha Upazila, Jashore, Bangladesh.

sealed in polythene before being kept in an airtight container.

2.2. Sources of materials

The necessary chemicals and reagents were analytical grade with maximum purity (Sigma-Aldrich, USA and Merck, Germany), and all the analytical work was conducted at the laboratory of the Department of Food Engineering at Jashore University of Science and Technology. In this study, the development of composite biscuits was performed in the Department of Food Engineering Laboratory. Wheat flour (Brand: Teer Atta, City Group Bangladesh Ltd.), sugar (Brand: Fresh Sugar, Fresh Group Bangladesh Ltd.), salt (Brand: Fresh Salt, Fresh Group Bangladesh Ltd.), milk powder (Brand: Dano, Arla Foods Bangladesh Ltd.), baking powder (Brand: Foster Clark, Foster Clark Products Ltd.), vegetable oil (Brand: Rupchanda, Gon shing edible oil Ltd.) were purchased from the outlet shwapno super shop, Jashore Sadar, Jashore, Bangladesh.

2.3. Preparation of red dragon fruit peel powder (RDFPP) fortified biscuits

The dry ingredients and liquid ingredients (the ingredient proportions for the 0 % (Control), 3 %, 6 %, and 9 % RDFPP) formulations are given in Table 1 were combined separately and put together to form a dough, which was then stored in an airtight container and left to rest at room temperature for half an hour. This procedure was based on the formulation described by Mir et al. (2017) with some modifications (Fig. 2). Following the resting period, the dough was physically rolled into a consistent thickness before being sliced and shaped into the round shapes. The biscuits were baked for 10.0 min at 170.0 ± 1.0 °C in a preheated oven. The biscuits were allowed to cool for 5 min at room temperature before being wrapped in an aluminum-coated bag, sealed, and kept in an airtight container at room temperature for further analysis.

2.4. Determination of physicochemical properties

2.4.1. Proximate analysis

To determine the moisture content, crude fat, crude protein, crude fiber and total ash of RDFPP and RDFPP fortified biscuits, AOAC (2000) method was used, whereas by subtracting the sums of other nutrients carbohydrate was determined.

2.4.2. pH

The pH of RDFPP and the fortified biscuits with RDFPP was measured by the method of Jamilah et al. (2011) with slight modifications. First, 100 mL of deionized water were used to homogenize 10 g of the sample. Following that, the slurry was left to settle at room temperature. After that, pH 7.00, 4.01, and 9.21 buffer solutions were used to calibrate the pH meter (HI2211, HANNA, Romania) and electrode probe (HI1131, HANNA, Romania).

2.4.3. Color

The color of RDFPP and RDFPP-fortified biscuits was analyzed using a colorimeter (CR-400/410, KONICA MINOLTA, Japan). The color parameters L* (0 = black and 100 = white), a* (negative = green and positive = red), b* (negative = blue and positive = yellow) were measured, and the hue angle (h°) was calculated according to Eq. (1) (Khajeh et al., 2025). The colorimeter was calibrated on a reference white and black plate prior to measurement the color parameters.

$$h = tan^{-1}\left(\frac{b^*}{a^*}\right) \tag{1}$$

Table 1
Formulation of RDFPP fortified biscuit.

Raw Ingredients	Control (0 %)	3 % RDFPP	6 % RDFPP	9 % RDFPP
Wheat Flour	100	97	94	91
RDFPP	0	3	6	9
Sugar	25	25	25	25
Salt	0.5	0.5	0.5	0.5
Milk Powder	12	12	12	12
Edible Oil	30	30	30	30
Water	25	25	25	25
Baking Powder	1	1	1	1

2.4.4. Weight, diameter, thickness, density and spread ratio of RDFPP fortified biscuits

For physical analysis (weight, diameter, thickness, density and spread ratio), 3 biscuits were chosen at random. The weight of biscuits was taken after they were baked. The evaluation of diameter and thickness was done according to the method described by Ho and Abdul Latif (2016). The weight of the biscuit divided by its volume provides the density. By dividing the diameter of biscuits by their thickness, the spread ratio was determined (Zoulias et al., 2000).

2.4.5. Hardness of RDFPP fortified biscuits

Hardness of biscuits was determined using a texture analyzer (TA.XT plus, Stable Microsystems, USA). Biscuits were measured within 24 h after baking using sharp cutting bladed probe type HDP/BS blade. The maximum force used was 50 kg, the speed was 0.01–40 mm/s, the maximum aperture was 370 mm or 590 mm, the distance resolution was 0.001 mm and the data acquisition rate was 2000 pps.

2.5. Determination of functional properties of peel

2.5.1. Water and oil absorption capacity

The water absorption capacity (WAC) and oil absorption capacity (OAC) were determined with slight modifications according to López-Vargas et al. (2013). To measure WHC or OHC, 250 ± 0.02 mg of dragon fruit peel powder was mixed with 25 mL of distilled water or commercial rice bran oil, then vortexed for 1 min and left at room temperature for 1 hour. The sample was centrifuged at 1450.0 ± 10.0 × *g* using a centrifuge (DSC-200T, Digisystem, Taiwan) for 5 min before discarding the supernatant. The sediment was weighed. The weight difference between the sediment and the sample was used to determine WAC and OAC, which were presented as grams of water absorbed per gram of sample and grams of oil absorbed per gram of sample, respectively.

2.5.2. Swelling capacity

Swelling capacity was determined by using the method of López-Vargas et al. (2013). A calibrated cylinder was filled with 2 g of sample, and the initial loaded bed volume (V_1) was measured. The powder was hydrated with 100 mL of distilled water at room temperature for 20 h until swelling was finished. After recording the bed volume (V_2), SWC was computed by Eq. (2), and it was then expressed as mL/g of sample.

$$Swelling\ capacity\ (mL/g) = \frac{V_2 - V_1}{mass\ of\ sample} \tag{2}$$

2.6. Determination of bioactive compounds and antioxidant activity of peel and fortified biscuits

2.6.1. Total phenolic content

A modified Folin-Ciocalteu technique was used to determine the total phenolic content in RDFPP and RDFPP fortified biscuits with slight modifications (Park et al., 2014). In short, 1 mL of each extract (1 g/mL) was combined with 5 mL of Folin-Ciocalteu reagent (1:10 v/v in distilled water) and 4 mL of 7.5 % (w/v) sodium carbonate solution. After 15 s of vortexing to intensify the color, the mixture was left to stand at 40 °C for 30 min. The absorbance at 765 nm was measured using a Thermo

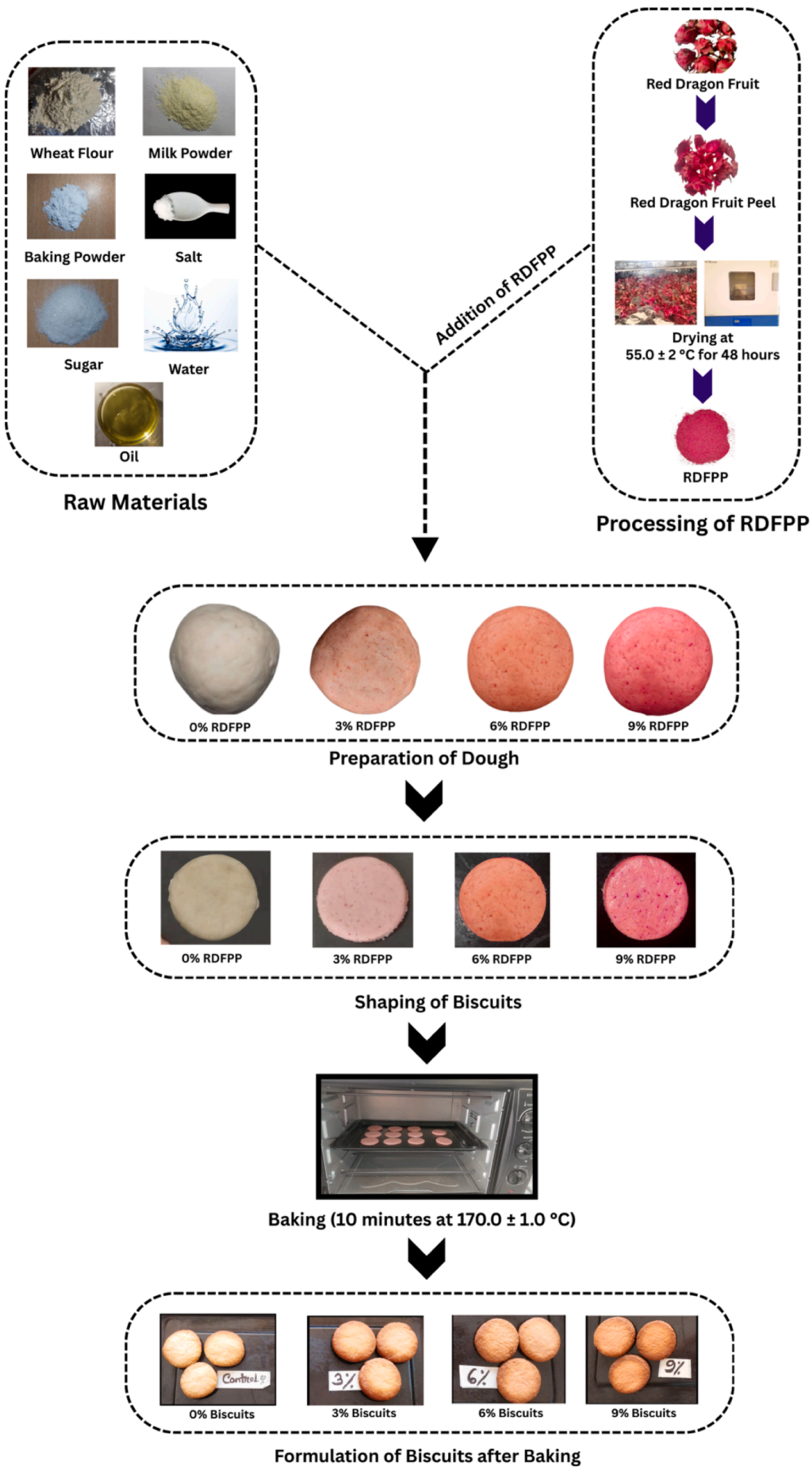

Fig. 2. Processing steps of RDFPP fortified biscuits.

Scientific double beam UV–Vis spectrophotometer (T60, UV–Vis Spectrophotometer, UK). The blank was prepared using ethanol instead of the sample. A blank was also compared to a set of reference solutions for gallic acid. The linear equation from the gallic acid standard curve was then used to calculate the TPC. Using the linear equation $y = 0.0074\,x + 0.4075$, $R^2 = 0.9982$, which was developed through examination of a calibration graph concentration spanning from 100 to 600 ppm generated using standard Gallic acid, the total phenolic content was measured in milligrams of gallic acid equivalents.

2.6.2. *Total flavonoids*

The method described by Chang et al. (2002) was used with slight modifications for determining the flavonoid content in RDFPP and RDFPP fortified biscuits. 5 mL of methanolic extract were combined with 2.5 mL of $AlCl_3$ solution. After 15 min of incubation at room temperature, absorbance was measured at 430 nm using a double beam Scientific UV–Vis Spectrophotometer (T60, UV–Vis Spectrophotometer, UK). To create the $AlCl_3$ reagent solution, 100 mL of de-ionized water was mixed with 133 mg of crystalline $AlCl_3$ and 400 mg of crystalline sodium acetate. Quercetin standards were used to create a linear standard calibration curve with $y = 0.0154\,x + 0.0301$, $R^2 = 0.9991$.

2.6.3. DPPH (1, 1-diphenyl-2-picrylhydrazyl) free radical scavenging activity assay

The stable DPPH radical-scavenging activity of RDFPP and RDFPP fortified biscuits was calculated following the method given by Alam et al. (2023). This test was carried out by adding 2 mL of extract solutions in various concentrations to 2 mL of 0.1 mM DPPH solutions. After that, the liquid was rapidly stirred for 15 s. For a reaction to occur, the solutions were left to stand at room temperature in a dark environment for 30 ± 0.5 min. After 30 min, absorbance was measured against a blank using a twin-beam Scientific UV–Vis Spectrophotometer set to 517 nm (T60, UV–Vis Spectrophotometer, UK). The DPPH Free Radical Scavenging Activity (%) was calculated according to Eq. (3):

$$\textit{DPPH Free Radical Scavenging Activity}\ (\%) = \frac{A_s\ (blank) - A_b\ (sample)}{A_b\ (blank)} \times 100 \tag{3}$$

2.7. Fourier transform infrared spectroscopy (FTIR) analysis of functional groups

The FTIR analysis of peel and fortified biscuits was carried out in the 'Nano-bio and Advanced Materials Engineering (NAME)' Laboratory at Jashore University of Science and Technology using Lubis et al. (2017) modified methodologies. The functional groups of the sample were identified using a Spectrum Two FT-IR Spectrometer (L160000A, PerkinElmer, UK). The spectra were analyzed in the wavelength of 4000 cm^{-1} to 400 cm^{-1}.

2.8. Scanning electron microscopy (SEM) analysis of RDFPP fortified biscuits

A scanning electron microscope (SEM) was used to analyze the microstructures of the control and RDFPP-fortified (0 %, 3 %, 6 % and 9 %) biscuits at the genome center of Jashore University of Science and Technology in Jashore, Bangladesh. A ZEISS 1550VP Field Emission Scanning Electron Microscope (SEM) with Oxford Energy Dispersive Spectroscopy (EDS) and HKL Electron Backscatter Diffraction (EBSD) was the particular SEM utilized (Schädler et al. 2008). An energy-dispersive X-ray machine and a computer-controlled field emission scanning microscope were used in the SEM analysis. Each proportion of biscuit granules was placed on the metal rod and then deposited into the specimen container. The granules' surface was coated with a thin layer of gold using N_2 gas to improve electrical conductivity. With an electron high tension (EHT) voltage of 5.00 KV, the coated samples were analyzed using SEM-EDX. The apparatus included an energy dispersive X-ray spectrometer. The 5.00 KX, 10.00 KX, and 20.00 KX magnification images that were taken for the 0 %, 3 %, 6 %, and 9 % RDFPP fortified biscuits separately have made the detailed microstructure clearly visible.

2.9. Determination of microbial shelf-life (0–15 days) of RDFPP biscuits

Complete bacteria, molds, and yeasts were counted in biscuit samples using the plate count method following 0, 3, 6, 9, 12, and 15 days of room temperature storage; all studies were carried out in triplicate. The plate counts technique on nutrient agar medium, as described in (American Society for Microbiology, 1957) with few adjustments, was used to determine the total plate bacterial counts. The biscuit sample, weighing 20 g, was safely moved to a sterile stomacher bag and homogenized in 180 mL of sterile saline for 2 min in a stomacher (BagMixer 400 W, Interscience, France). After the 1:10 dilutions were finished, 1 mL of the suspension from each serial dilution was injected onto the plate count. The next step is to further dilute the mixture until it reaches 10^7. To count the microorganisms under investigation, the final diluted samples (0.1 mL) were dipped in specific culture media. The total viable count was carried out during 24 h at 37 °C. Each plate underwent yeast and mold count incubation according to the method of Murray et al. (2007) with few adjustments.

2.10. Sensory evaluation of RDFPP fortified biscuits

The sensory evaluation of the biscuit samples were assessed using the method of Chopra et al. (2018). Ten semi-trained panelists judged the prepared biscuits' quality as part of the sensory evaluation process. Analyzing overall sensory quality of biscuits as experienced by the senses of taste, touch, and appearance is the focus of the evaluation. On a scale of 9 points from "like extremely" to "dislike extremely," the degree of a biscuit's pleasant and unpleasant experience was assessed using a hedonic scale rating test. An assessment form with multiple sensory parameters and score alternatives with numerical rankings was distributed to the panelists. After every assessment form was filled out, the data were collected for statistical analysis. The sensory qualities of the biscuits, including appearance, taste, color, aroma, texture and overall acceptability were evaluated.

2.11. Statistical analysis

All values were expressed as mean ± standard deviation (SD) of triplicate analyses. One-way analysis of variance (ANOVA) was performed to assess significant differences among groups, followed by the least significant difference (LSD) test and Tukey's post-hoc test at a 95 % confidence interval. Statistical analysis was conducted using IBM SPSS Statistics version 27.0 (IBM Corp., Armonk, NY, USA).

3. Results and discussion

3.1. Quality characteristics of red dragon fruit peel powder

3.1.1. Physicochemical properties

Proximate analysis plays a crucial role in determining the basic nutritional composition of food materials, including moisture, ash, crude fat, crude protein, crude fiber, and carbohydrate contents (Table 2). This analysis provides essential data for evaluating the potential of agro-industrial by-products like red dragon fruit peel as functional food ingredients or additives in product development. The proximate composition of RDFPP revealed moisture (10.29 ± 0.07 %), ash (10.60 ± 0.11 %), crude fat (6.14 ± 0.09 %), crude protein (5.96 ± 0.07 %), crude fiber (23.68 ± 0.10 %), and carbohydrate (43.32 ± 0.13 %). These results are closely similar to those reported by Chia and Chong (2015), except for moisture and carbohydrate contents. The processing method can significantly affect the moisture and carbohydrate content. For example, the preparation of fruit leather with varying sugar proportions and drying times resulted in different moisture and carbohydrate levels (Kc et al., 2022). The pH of red dragon fruit peel was 5.08 ± 0.02, which is slightly acidic and consistent with the findings of Jamilah et al. (2011). Color is an essential factor when adding byproducts into new food formulations, as noticeable changes in this attribute within the food matrix can lead to consumer rejection. L* values ranged from 0 (black) to 100 (white). A negative a* value represented the color green, whereas a positive value indicated the color red-purple. A positive number for b* indicated yellow, and a negative value denoted blue.

The L*, a*, b* values were found to be 37.35±0.32, 13.55±0.29, 0.94±0.19, respectively. The L* value shows that the sample is quite dark, which is typical for dried or concentrated fruit materials like red

Table 2
Quality characteristics of red dragon fruit peel powder.

	Quality Parameters		Values
Physicochemical Properties	Moisture (%)		10.29±0.07
	Ash (%)		10.60±0.11
	Crude fat (%)		6.14±0.09
	Crude Protein (%)		5.96±0.07
	Crude Fiber (%)		23.68±0.10
	Carbohydrate (%)		43.32±0.13
	pH		5.08±0.02
	Color	L*	37.35±0.32
		a*	13.55±0.29
		b*	0.94±0.19
		h°	3.97±0.71
Functional Properties	Water Absorption Capacity (g/g)		2.54±0.11
	Oil Absorption Capacity (g/g)		3.53±0.05
	Swelling Capacity (mL/g)		6.28±0.07
Bioactive Compounds and Antioxidant Activity	Total Phenolic Content (mg GAE/g)		0.34±0.30
	Total Flavonoids (mg QE/g))		53.32±2.18
	DPPH Activity (%)		43.22±1.82

Values are expected as mean ±SD for 3 determinations. L*: black to white; a*: Green to red-purple; b*: yellow to blue; h°: hue angle.

dragon fruit peel. The a* value rose while the b* value decreased indicating increased redness and declined yellowness. The positive and fairly high a* value indicates a strong red to red-purple hue, which aligns with the natural pigmentation of dragon fruit peel due to the presence of betacyanins that give it a reddish-purple color. The slightly positive b* value suggests a very mild yellow tone that is close to neutral, indicating the sample appears more red than yellow overall. The color values obtained in this work for red dragon fruit (*Hylocereus costaricensis*) peel powder were closely similar to the finding obtained by Chia and Chong (2015). The hue angle (h°) of dragon fruit peel was 3.97 ± 0.71, indicating a strong shift toward the red region of the color space. Such a low hue angle suggests that dragon fruit peel exhibits an intense reddish coloration, which is consistent with the high betacyanin pigment content.

3.1.2. Functional properties

Results presented in Table 2 showed that water absorption capacity, oil absorption capacity, and swelling capacity of red dragon fruit peel were 2.54 ± 0.11 g/g, 3.53 ± 0.05 g/g, and 6.28 ± 0.07 mL/g, respectively. The results also showed similarity with the values reported by Chia and Chong (2015) that highlighted its potential to enhance food viscosity, modify product texture, and act as an emulsifying agent.

3.1.3. Bioactive compound composition and antioxidant activity

Phenolic compounds are essential for inhibiting lipid oxidation and scavenging free radicals due to their antioxidant activities (Khajeh et al., 2025). RDFPP contained total phenolic content of 0.34 ± 0.30 mg GAE/g, total flavonoids of 53.32 ± 2.18 mg QE/g, and DPPH radical scavenging activity of 43.22 ± 1.82 %. These results indicated that RDFPP is a rich source of natural antioxidants, largely attributed to its high flavonoid concentration. Flavonoids showed potential antioxidant properties through mechanisms such as hydrogen donation, metal ion chelation, single oxygen transfer, and the quenching of singlet oxygen (Amic et al., 2007). These results were aligned with Quan et al. (2024), who found similar bioactive properties in dragon fruit peel powder dried in hot air dryer at 55 °C (Table 2).

3.1.4. FTIR analysis of functional groups

The peel of red dragon fruit (*Hylocereus* spp.) was analyzed FTIR (Fig. 3C), which showed the presence of several functional groups linked to bioactive substances. The presence of phenolic acids, flavonoids, and polysaccharides, which support the peel's antibacterial and antioxidant qualities, is shown by the large peak seen at 3305 cm^{-1}, which correlates to hydroxyl (-OH) stretching vibrations (Resende et al., 2020). The presence of flavonoids and tannins is further confirmed by the peak at 1620 cm^{-1}, which is associated with C=O (carbonyl) and C=C (aromatic) stretching (Resende et al., 2020). Furthermore, the presence of phenolic acids and flavonoid glycosides is suggested by C–O stretching vibrations at 1322 cm^{-1}, whereas the presence of polysaccharides like cellulose and pectin is indicated by the absorption band at 1013 cm^{-1}, which corresponds to C–O–C stretching (Silverstein et al., 2005). Long-chain fatty acids, lipids, and waxes are present because the absorption peak at 2921 cm^{-1} correlates to the C–H stretching vibrations of aliphatic chains. This peak indicates lipid-based substances that support the protective properties of plant peels, such as cutin and suberin (Pavia et al., 2015). Flavonoids, tannins, or polyphenolic chemicals are indicated by the peak at 610 cm^{-1}, which is linked to aromatic C–H out-of-plane bending vibrations (Pavia et al., 2015). Furthermore, C–X (halogen) stretching vibrations have been identified by absorption in the 500–700 cm^{-1} area, which may indicate halogenated organic molecules (Pavia et al., 2015). These spectral findings confirm that red dragon fruit peel is rich in bioactive compounds, polysaccharides, and lipids, supporting its potential application as a functional food ingredient.

3.2. Physicochemical properties of RDFPP fortified biscuits

The proximate compositions of biscuits (0 % RDFPP, 3 % RDFPP, 6 % RDFPP, and 9 % RDFPP) are shown in Table 3. The ash content of biscuits increased from 3.32 % to 5.58 %. The highest value of moisture content (5.58 %) in 0 % RDFPP biscuits and the lowest value of moisture content (5.58 %) in 9 % RDFPP were observed. The substitution of RDFPP for refined flour beyond the 5 % level significantly ($p < 0.05$) lowered the moisture content of biscuits. Similar findings from Ho and Abdul Latif (2016) were found in the results of the current investigation. Bertagnolli et al. (2014) contended that cookies with low moisture content will last longer if they are kept in controlled conditions, such as dry, cool storage and suitable packaging that is resistant to moisture, gases, and ideally a light barrier. As a result, using RDFPP instead of refined flour while making biscuits will result in a product that is more shelf-stable because it contains less moisture. For every sample, there was a significant difference ($p < 0.05$) in the amount of ash (Table 3). The biscuits' ash content increased from 0.71 % to 2.27 % to 2.27 %. The biscuits made with 9 % RDFPP had the highest ash content (2.27 %), followed by those made with 6 % RDFPP (1.69 %) and 3 % RDFPP (1.02 %). The biscuits made with 0 % RDFPP (control) had the lowest ash content (0.71 %). These findings are consistent with Wani et al. (2015), who found that adding whey protein to cookies increased their ash level proportionately. The fat content of biscuits was unaffected when RDFPP was substituted for refined flour at amounts of 3–9 % (Table 3). This could be explained by the fact that refined and dragon peel flour particles are similar in size, making it easier to extract a comparable amount of oil from food products (Chia and Chong, 2015). The protein content of the composite biscuits was found to be significantly lower than that of the control (9.19 %), with values of 9.17 %, 8.94 %, and 8.80 % for 3 % RDFPP, 6 % RDFPP, and 9 % RDFPP, respectively. The carbohydrate of the composite biscuits (64.99 %, 65.09 %, and 65.13 % for 3 % RDFPP, 6 % RDFPP, and 9 % RDFPP, respectively) was revealed to be significantly higher than in the control (63.91 %). The current study's findings were consistent with those of Ho and Abdul Latif (2016), who found that cookies made with powdered peel from red-skinned dragon fruit with white flesh (*Hylocereus undatus*) had lower protein value and higher carbohydrate value than cookies made using composite flour. The fiber content of the composite biscuits was found to be significantly higher

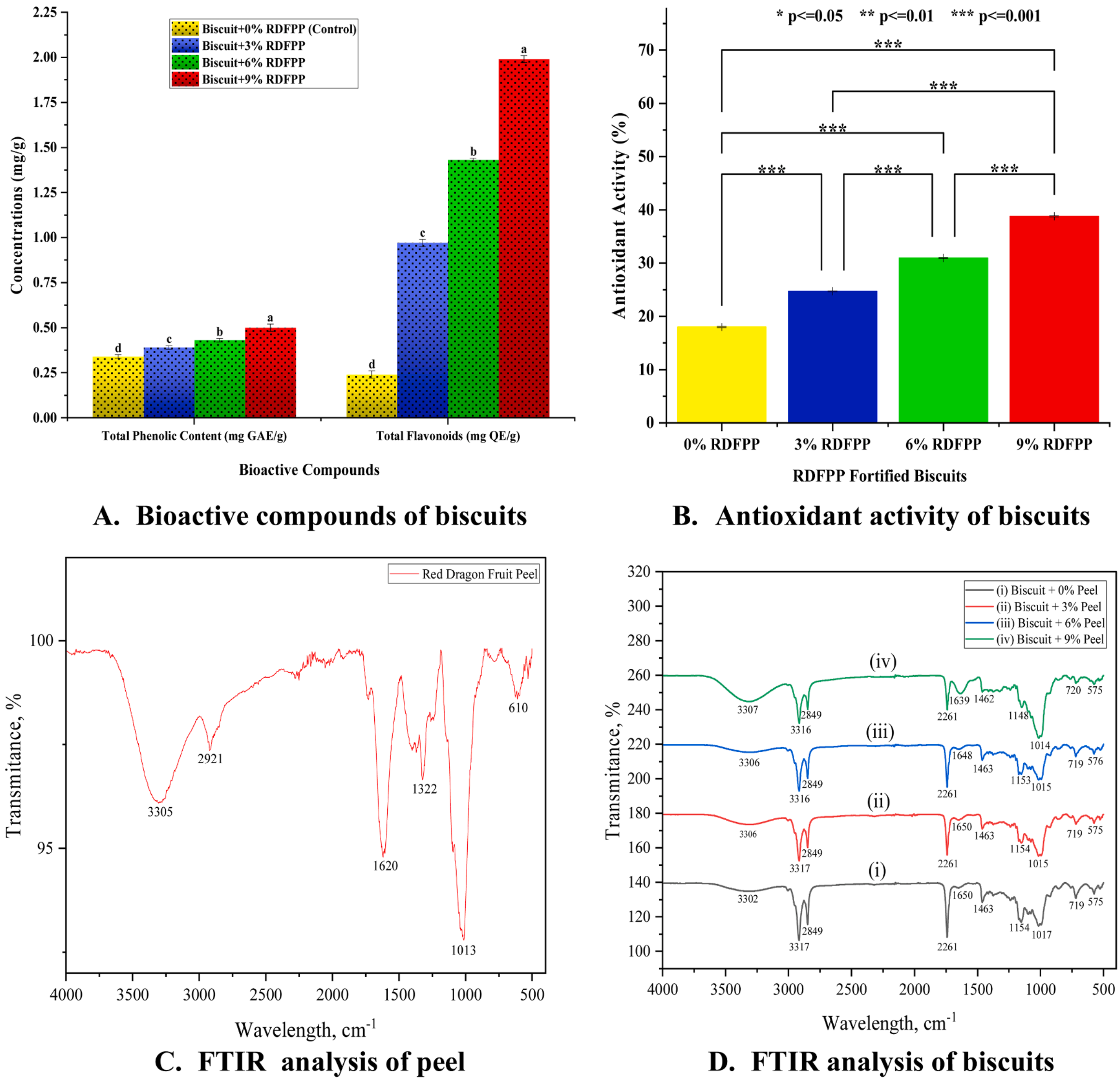

Fig. 3. Bioactive compounds, Antioxidant activity and FTIR analysis (A. Bioactive compounds of RDFPP fortified biscuits, B. Antioxidant activity of RDFPP fortified biscuits, C. FTIR of *H. polyrhizus* peel and D. FTIR of RDFPP fortified biscuits).

than that of the control (0.08 %) at 0.25 %, 0.49 %, and 0.74 % for 3 % RDFPP, 6 % RDFPP, and 9 % RDFPP, respectively. This was explained by the fact that red dragon peel powder has more fiber than refined flour. According to reports, powdered dried dragon fruit peel has 44 times more crude fiber than refined flour (Bala et al., 2015). The substitution of RDFPP for refined flour beyond 5 % level significantly ($p < 0.05$) lowered the pH value of biscuits. The pH of the composite biscuits (5.23, 5.17, and 5.03 for 3 % RDFPP, 6 % RDFPP and 9 % RDFPP, respectively) was revealed significantly lower than in the control (5.34 %). Increase in pH value with increasing RDFPP indicated the biscuits became more acidic, it may be because of the existence of several organic acids in peel which contribute to lowering the pH when they are incorporated into food products. The result is similar to the findings of Raiyan et al. (2024) used seaweed incorporated biscuits and got lower pH in treatments than in control. The molecular properties of proteins depend on factors such as pH, ionic strength, and the presence of polysaccharides (Amiri et al., 2024), suggesting that this acidity shift may also influence protein interactions and textural characteristics during baking.

The color characteristics of the biscuits (3 % RDFPP, 6 % RDFPP, and 9 % RDFPP) are displayed in Table 3. The brightness (L*), redness (a*), and yellowness (b*) of the biscuits' color were evaluated. L* values were significantly lower in the RDFPP-containing cookies (36.61 % to 57.81 %) compared to the control (66.95 %). The biscuits with 9 % RDFPP blended had the lowest L* value, 36.61 %. According to Chia and Chong (2015), this was explained by either the caramelization of the sugar in dragon fruit peel or a Maillard process that results in browning when baked at a high temperature. The findings showed a similar result with Ho and Abdul Latif (2016). The hue angle (h°) of biscuits decreased significantly ($p < 0.05$) with increasing levels of RDFPP, ranging from 83.69 ± 0.93 (control, 0 %) to 47.53 ± 0.52 (9 % RDFPP). This decreasing trend in h° indicated a shift in biscuit color from yellowish (higher h°) toward reddish/brownish tones (lower h°) as the level of RDFPP increased. This result is consistent with the findings of Ramashia et al. (2024), who reported that the addition of malted pearl millet (MPM) and orange peel flour (OPF) reduced the hue angle of biscuits. The presence of betacyanin pigments in the red peels of the RDFPP is responsible for the considerable decrease in yellowness (b*) and significant increase in redness (a*) of the biscuits ($p < 0.05$), which is similar to the findings Chumroenvidhayakul et al. (2023). The effects of adding RDFPP at different levels (0 %, 3 %, 6 %, and 9 %) on biscuit physical properties are shown in Table 3. The weights of all samples ranged from 14.99 ± 0.01 g to 15.01 ± 0.01 g, with no significant differences ($p > 0.05$). Ho and Abdul Latif et al. (2016) reported similar results, noting that substituting pitaya (*Hylocereus undatus*) peel flour

Table 3
Physicochemical properties of RDFPP fortified biscuits.

Parameters		Control Biscuit (0 % RDFPP)	Biscuit with 3 % RDFPP	Biscuit with 6 % RDFPP	Biscuit with 9 % RDFPP
Moisture (%)		5.58±0.02[a]	4.24±0.02[b]	3.72±0.02[c]	3.32±0.02[d]
Ash (%)		0.71±0.01[d]	1.02±0.01[c]	1.69±0.01[b]	2.27±0.01[a]
Crude fat (%)		20.61±0.03[a]	20.58±0.03[a]	20.56±0.03[a]	20.48±0.01[b]
Crude Protein (%)		9.19±0.01[a]	9.17±0.01[b]	8.94±0.01[c]	8.80±0.01[d]
Carbohydrate (%)		63.91±0.03[d]	64.99±0.02[c]	65.09±0.02[b]	65.13±0.01[a]
Crude Fiber (%)		0.08±0.02[d]	0.25±0.01[c]	0.49±0.01[b]	0.74±0.02[a]
pH		5.34±0.01[a]	5.23±0.01[b]	5.17±0.01[c]	5.03±0.01[d]
Color	**L***	66.95±1.20[a]	57.81±1.16[b]	42.57±1.35[c]	36.61±1.24[d]
	a*	3.54±0.54[d]	8.81±0.64[c]	13.19±0.53[b]	17.77±0.49[a]
	b*	32.03±0.12[a]	27.07±0.14[b]	22.52±0.16[c]	19.45±0.12[d]
	h°	83.69±0.93[a]	71.98±1.13[b]	59.65±0.82[c]	47.53±0.52[d]
Weight (g)		14.99±0.01[a]	15.00±0.01[a]	15.01±0.01[a]	15.01±0.01[a]
Thickness (cm)		0.67±0.02[a]	0.66±0.02[a]	0.59±0.02[b]	0.61±0.01[b]
Diameter (cm)		5.20±0.01[b]	5.16±0.02[c]	5.27±0.02[a]	5.29±0.03[a]
Spread Ratio		7.77±0.24[b]	7.83±0.23[b]	8.93±0.29[a]	8.67±0.19[a]
Hardness (kg)		3.33±0.59[a]	3.39±0.58[a]	3.50±0.57[a]	3.59±0.54[a]

Values are expected as mean ±SD for 3 determinations. L*: black to white; a*: Green to red-purple; b*: yellow to blue; h°: hue angle.

had no influence on cookie weight. The lowest values were found at 6 % and 9 % RDFPP, with thickness decreasing significantly ($p < 0.05$) at increasing RDFPP levels. The thickness of the control and 3 % RDFPP biscuits was higher (0.67 ± 0.02 cm and 0.66 ± 0.02 cm, respectively), while the thickness of the 6 % (0.59 ± 0.02 cm) and 9 % RDFPP (0.61 ± 0.01 cm) biscuits was significantly smaller. This is likely due to gluten dilution, as also noted by Aslam et al. (2014). The diameter of the biscuits increased with the addition of RDFPP, with values ranging from 5.16 ± 0.02 cm in control to 5.29 ± 0.03 cm in the 9 % RDFPP sample. The diameter increased as RDFPP was added, indicating more spread, which is similar to the results of Ho and Abdul Latif et al. (2016). The weaker gluten network and reduced dough viscosity allowed more expansion during baking. Adding RDFPP resulted in a significant increase in the spread ratio ($p < 0.05$). The control had a spread ratio of 7.77 ± 0.24, which increased to 8.93 ± 0.29 at 6 % RDFPP and 8.67 ± 0.19 at 9 % RDFPP. This increase in spread ratio may be attributed to a reduction in dough viscosity due to water absorption and sugar dissolution in the dough, which allows cookies to spread more during baking (Noor Aziah et al., 2012). The hardness values (3.33 ± 0.59 kg to 3.59 ± 0.54 kg) indicated no significant differences ($p > 0.05$), which is consistent with Ho and Abdul Latif (2016) and Mridula et al. (2007), who observed that fiber or sorghum substitution did not affect cookie hardness significantly. Addition of peel significantly affected biscuit thickness, diameter, and spread ratio but did not affect the weight or hardness. These effects are linked to reduced gluten content and increased water absorption due to fiber, supporting RDFPP's potential as a functional ingredient in biscuit formulation.

3.3. Analysis of bioactive compounds and antioxidant activity of RDFPP fortified biscuits

The addition of RDFPP into biscuits resulted in a significant improvement ($p < 0.05$) in total phenolic content, total flavonoids and DPPH radical scavenging activity (Fig. 3A and 3B). The total phenolic content increased from 0.34 ± 0.01 mg GAE/g in the control biscuits to 0.39 ± 0.01 mg GAE/g, 0.43 ± 0.01 mg GAE/g, and 0.50 ± 0.02 mg GAE/g in the 3 %, 6 %, and 9 % RDFPP biscuits, respectively. Total flavonoids also increased from 0.24 ± 0.02 mg QE/g in the control to 0.97 ± 0.02 mg QE/g, 1.43 ± 0.01 mg QE/g, and 1.99 ± 0.02 mg QE/g in the 3 %, 6 %, and 9 % RDFPP biscuits, respectively. Similarly, the DPPH free radical scavenging activity increased from 17.98 ± 0.11 % in the control to 24.69 ± 0.09 %, 30.98 ± 0.10 %, and 38.79 ± 0.12 % in the 3 %, 6 %, and 9 % RDFPP biscuits, respectively. These findings showed that adding the RDFPP percentage improved the antioxidant properties, total phenolic content, and flavonoids of the biscuits, with the 9 % RDFPP formulation having the highest results. These findings were similar to Raiyan et al. (2024), who observed that increasing the percentage of *Gracilaria tenuistipitata* in crackers increased total phenolic content and DPPH radical scavenging activity. Furthermore, Nolla et al. (2025) found that fortifying biscuits with incorporated powders of *Carica papaya, Ananas comosus*, and *Beta vulgaris* significantly increased total phenolic content, total flavonoids, and antioxidant activity, which supported our findings.

3.4. FTIR analysis of functional groups in RDFPP fortified biscuits

Functional groups in biscuits fortified with 0 %, 3 %, 6 %, and 9 % red dragon fruit peel were analyzed using FTIR spectroscopy. The presence of bioactive chemicals provided by the peel of the red dragon fruit is indicated by the spectra (Fig. 3C and 3D), which show separated peaks that relate to different chemical bonds.

O—H stretching vibrations are represented by the broad peak at 3300–3317 cm^{-1}, which suggests the presence of hydroxyl groups, most likely from water, polysaccharides, and phenolic chemicals (Resende et al., 2020). The presence of lipids and long-chain fatty acids in the biscuit formulation is related to the peaks at 2849 cm^{-1}, which represent C–H stretching from aliphatic chains (Pavia et al., 2015). Carbonyl groups from proteins, flavonoids, and tannins are known for having $C = O$ stretching vibrations, which are detected at 1650–1639 cm^{-1} (Silverstein et al., 2005). According to Pavia et al. (2015), the peaks at 1462–1463 cm^{-1} indicate C–H bending vibrations, which are indicative of lipids and aliphatic chemicals in the biscuit matrix. The presence of carbohydrates like pectin and cellulose, which are available in the peel of red dragon fruit, is probably indicated by a notable absorption band at 1014–1017 cm^{-1} that matches the C–O–C stretching (Silverstein et al., 2005). As peel content increases, the peaks at 719–720 cm^{-1} and 575–576 cm^{-1} indicate C–H out-of-plane bending vibrations, which are indicative of aromatic chemicals, maybe flavonoids and other polyphenolics (Pavia et al., 2015). Significantly, a higher proportion of red dragon fruit peel results in higher intensities of the hydroxyl (O–H), carbonyl (C=O), and carbohydrate-related (C–O–C) peaks. The absence of any new absorption bands showed that the interaction was mainly physical and that the red dragon fruit peel did not create any new chemical interactions with the biscuit matrix. This finding aligns with previous FTIR research on edible coatings, where incorporating bioactive components led to broadening existing peaks without forming new chemical bonds (Esmaeili et al., 2024). These results indicate that adding red dragon fruit peel to biscuits improves their bioactive and functional qualities, possibly providing them with dietary fiber and antioxidants.

3.5. SEM analysis of RDFPP fortified biscuits

Microstructural changes in the biscuits added with varying levels of RDFPP (0 %, 3 %, 6 %, and 9 %) were analyzed using SEM. To analyze the surface morphology and structural changes by the incorporation of RDFPP, the SEM images were taken at magnifications of 5000×, 10,000×, and 20,000× (Fig. 4). The texture of the control biscuit was smooth, compact, and homogeneous with fewer destructed pores, suggesting that the control biscuit had a more complete gluten network which resulted in a more homogeneous texture and higher structural integrity. With the rising levels of RDFPP, substantial structural changes were noted. With 3 % RDFPP, a small number of porous regions were present, indicating slight inhibition in the gluten formation due to the contribution of dietary fiber. At 6 % RDFPP, the porosity increased considerably, in this case clearly disrupting the gluten-starch network and resulting in a rougher texture. The microstructure appeared highly

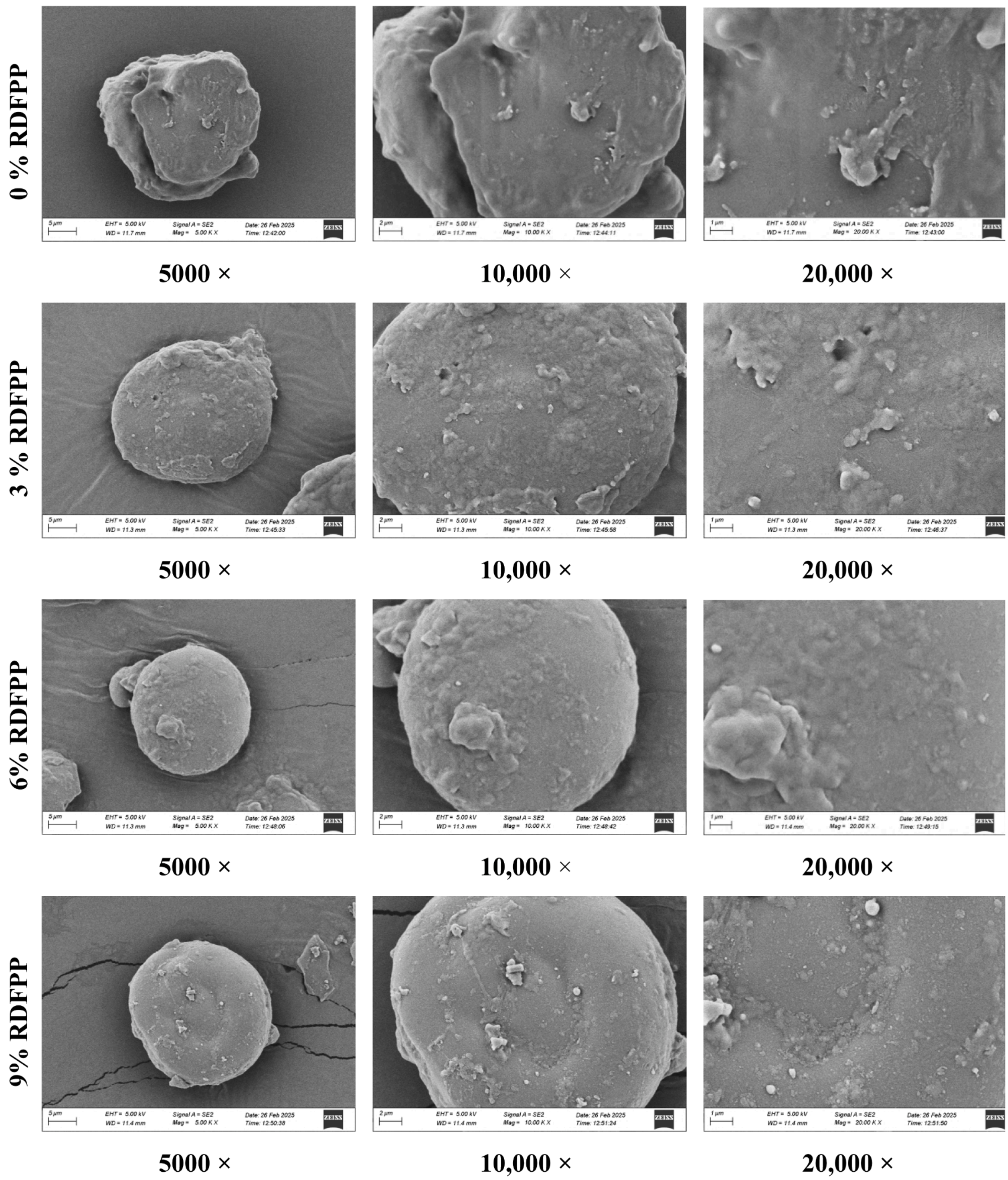

Fig. 4. SEM of 0 %, 3 %, 6 %, and 9 % RDFPP Fortified Biscuits with Magnification of 5000 ×, 10,000 × and 20,000 ×.

porous and irregular with >9 % RDFPP, which may be attributed to a higher concentration of fibrous content interfering with the formation of gluten, contributing to a decrease in structural integrity and an increase in fragility. The results agreed with previous work showing fiber fortification of baked goods to cause increased porosity and decreased mechanical strength and disruption of the starch-protein matrix (Elleuch et al., 2011; Rosell et al., 2010; Sabanis et al., 2009). The fiber content highlights affecting crispness, quality, and texture have shown the relation between microstructural changes observed due to varying RDFPP concentrations. The SEM data thus presented useful information which can be used for optimization of RDFPP levels in biscuit formulations in which the nutritional benefit of the RDF can be balanced with the desirable textural properties.

3.6. *Microbial shelf-life evaluation*

The microbiological stability of biscuits fortified with varied amounts (0 %, 3 %, 6 %, and 9 %) of RDFPP was tested over 15 days at room temperature (Table 4). Total bacterial plate counts were not observed (N.O.) until day 6 across all samples. On Day 6, the control (0 % RDFPP) had a significantly higher bacterial load (2.68±0.03 $\log_{10}$ CFU/g) than fortified samples, with bacterial counts decreasing as RDFPP concentration increased ($p < 0.05$). By day 15, all samples showed a significant increase in bacterial counts; however, the 9 % RDFPP fortified biscuits had the lowest number of bacteria (8.09±0.05 $\log_{10}$ CFU/g) compared to the control (8.45±0.03 $\log_{10}$ CFU/g). No yeast or mold was found in any of the samples during storage. These findings indicated that RDFPP fortification enhanced the

Table 4
Shelf-life parameters of RDFPP fortified biscuits.

Parameters	Sample	Day 0	Day 3	Day 6	Day 9	Day 12	Day 15
Total bacterial plate count ($\log_{10}$ CFU/g)	0 % RDFPP	N.O.	N.O.	2.68±0.03[a]	3.76±0.05[a]	6.00±0.04[a]	8.45±0.03[a]
	3 % RDFPP	N.O.	N.O.	2.53±0.04[b]	3.62±0.05[a]	5.86±0.05[b]	8.34±0.03[b]
	6 % RDFPP	N.O.	N.O.	2.35±0.05[c]	3.45±0.04[b]	5.69±0.04[c]	8.24±0.06[c]
	9 % RDFPP	N.O.	N.O.	2.17±0.04[d]	3.28±0.06[c]	5.43±0.05[d]	8.09±0.05[c]
Yeast ($\log_{10}$ CFU/g)	0 % RDFPP	N.O.	N.O.	N.O.	N.O.	N.O.	N.O.
	3 % RDFPP	N.O.	N.O.	N.O.	N.O.	N.O.	N.O.
	6 % RDFPP	N.O.	N.O.	N.O.	N.O.	N.O.	N.O.
	9 % RDFPP	N.O.	N.O.	N.O.	N.O.	N.O.	N.O.
Molds ($\log_{10}$ CFU/g)	0 % RDFPP	N.O.	N.O.	N.O.	N.O.	N.O.	N.O.
	3 % RDFPP	N.O.	N.O.	N.O.	N.O.	N.O.	N.O.
	6 % RDFPP	N.O.	N.O.	N.O.	N.O.	N.O.	N.O.
	9 % RDFPP	N.O.	N.O.	N.O.	N.O.	N.O.	N.O.

Values are presented at mean±SD. Values with different superscripts within the same column are statistically significantly different ($p < 0.05$). N.O.: Not Observed.

microbiological shelf-life of biscuits, most likely due to its natural antibacterial characteristics. No yeast or mold growth was observed in the RDFPP biscuits over the 15-day period, likely due to the high temperatures used during processing, which is similar to the findings of Egodavitharana et al. (2023). Furthermore, these findings were aligned with the findings of Raiyan et al. (2024), who found that incorporating seaweed into crackers effectively inhibited microbial colony formation, improving freshness and extending shelf life.

3.7. Sensory evaluation of RDFPP fortified biscuits

The sensory evaluation of biscuit attributes such as appearance, color, taste, aroma, texture, and overall acceptability were illustrated in Fig. 5. Since none of the biscuit samples scored lower than the minimum acceptable rating of 7 on a 9-point hedonic scale, the findings of the sensory evaluation showed that all of the samples were considered acceptable across all evaluated characteristics. Except for color, flavor and overall acceptability, the substitution of RDFPP did not affect the sensory characteristics of biscuits compared to the control group. Biscuits fortified with up to 6 % RDFPP showed a minor but acceptable color change, with scores of 8.30±0.34[a] at 3 % RDFPP and 8.38±0.41[a] at 6 % RDFPP, compared to the control (8.22±0.36[a] at 0 % RDFPP). However, at 9 % fortification, the color acceptability decreased to 7.93 ±0.52[b], making it significantly less desirable. From the graph, the taste scores remained stable or slightly improved up to 6 % RDFPP but dropped significantly at 9 % fortification. The reduction in the plotted area at the 9 % RDFPP axis visibly highlighted a decrease in consumer preference. This revealed that 6 % fortification was optimal for maintaining or even increasing taste, but greater levels caused undesirable flavor change. The findings of color and flavor could be related to the darker color, slightly sour, and possibly bitter taste obtained by RDFPP, as previously reported (Ho and Abdul Latif, 2016). The sensory scores for appearance, aroma, and texture of biscuits fortified with up to 9 % DFP remained statistically similar, indicating no significant differences among treatments. All values ranged between 8.18 and 8.38, reflecting consistent consumer acceptability across attributes. The results for aroma and texture were consistent with the findings of Ho and Abdul Latif (2016), who reported that incorporating *Hylocereus undatus* peel flour into cookies did not significantly affect these sensory characteristics. Biscuits with up to 6 % RDFPP showed high overall acceptability, while 9 % RDFPP significantly reduced consumer preference. So the sensory evaluation indicated that RDFPP may be successfully incorporated into biscuits up to 6 % without negatively impacting consumer acceptance, but a higher addition (9 %) has a negative effect on key sensory properties such as color, taste, and overall acceptability.

4. Conclusion

This study showed the successful valorization of red dragon fruit peel powder as a functional ingredient in biscuits, utilizing agro-industrial waste into a valuable resource while enhancing nutritional and functional properties. Fiber (0.74 %), ash (2.27 %), and antioxidant activity

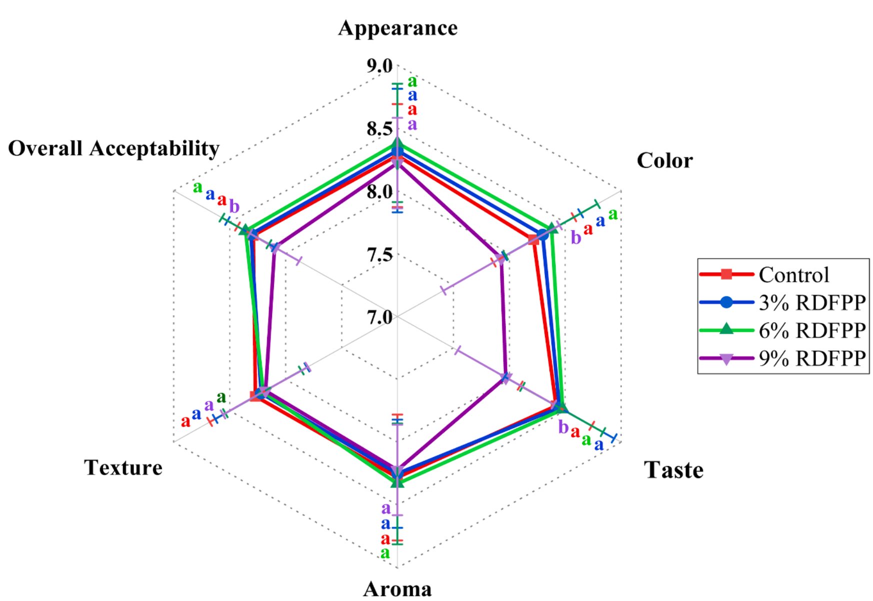

Fig. 5. Sensory evaluation of RDFPP fortified biscuits.

(38.79 % DPPH scavenging) were all significantly improved by RDFPP fortification; FTIR confirmed the presence of bioactive components (phenolics, polysaccharides), and SEM revealed structural porosity associated with textural change. Sensory evaluation identified 6 % RDFPP as optimal, balancing consumer acceptance with improved shelf stability (moisture: 4.21 %) and delayed microbial growth (8.09 $\log_{10}$ CFU/g). These results highlighted the RDFPP's ability to convert waste peels into sustainable and nutrient-rich food additives, providing an economical solution for food sector uses.

Ethical statement

As this study involves a plant-based sample with no interaction or testing on animals or humans, it poses no risk to biological systems. Therefore, it aligns with ethical research standards and does not raise concerns regarding the welfare of living organisms.

CRediT authorship contribution statement

Mrityunjoy Biswas: Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mahfujul Alam:** Writing – review & editing, Data curation. **Md. Akhtaruzzaman:** Writing – review & editing, Supervision, Investigation. **Shafi Ahmed:** Writing – review & editing. **M. Shalim Uddin:** Formal analysis, Data curation. **AHMM Rhaman Talukder:** Writing – review & editing, Formal analysis, Data curation. **Asraful Alam:** Writing – review & editing, Formal analysis, Data curation. **Bikramjit Biswas:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank Ministry of Science and Technology, Bangladesh (MOST) for the financial support. We would also like to acknowledge the kind support from the lab assistant of departments of Food Engineering (Former Agro Product Processing Technology Department), Chemical Engineering and Microbiology of Jashore University of Science and Technology, Jashore- 7408, Bangladesh.

Data availability

Data will be made available on request.

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