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Technofunctional, Pasting, and Microstructural Properties of Watermelon (*Citrullus lanatus*) Peel Powder and Its Application in Gluten-Free Bread

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ABSTRACT

As global food waste continues to rise, the valorisation of agrifood by-products into functional ingredients has become essential for improving food system sustainability. This study investigated the conversion of watermelon peel, an underutilized processing by-product, into a functional powder (WPP) and evaluated its technofunctional, pasting, and microstructural characteristics, as well as its performance in cassava-based gluten-free bread formulated without WPP (0WPP) and with 3% (3WPP) and 6% (6WPP) substitution. WPP exhibited higher water absorption (2.65 g/g) and solubility (23.86%) than 0WPP (1.45 g/g and 12.06%, respectively), but lower swelling power (1.23 g/g), reflecting its low starch content and the presence of rigid cell wall polysaccharides. In gluten-free composite systems, WPP showed negligible torque development throughout the pasting cycle and significantly reduced peak (4.0 cmg), trough (2.7 cmg), breakdown (1.2 cmg), and final viscosities (7.6 cmg), along with an indistinct pasting temperature in 6WPP samples. These effects were consistent with the denser crumb structure and reduced loaf volume in 6WPP bread. The hardness of 0WPP bread was moderate at 1250.543 ± 90.401 g, reflecting the typical gelatinized starch matrix of cassava flour. However, hardness decreased in 3WPP (1189.786 ± 87.54 g) but then increased in 6WPP (1436.754 ± 43.52 g) bread. Instrumental taste revealed dose-dependent increases in bitterness, astringency, umami, and saltiness, likely attributable to the dietary fiber, phenolic compounds, and minerals contributed by WPP, while sourness remained largely unaffected. Overall, these findings demonstrate that the incorporation of WPP at moderate levels serves as a functional and sustainable approach for gluten-free bakery applications and supports the role of watermelon peel as a food waste valorisation strategy.

1 | Introduction

The growing volume of food waste across global food systems represents a major challenge, particularly in terms of sustainability and resource efficiency [1, 2]. Recent estimates indicate that fruits and vegetables account for 25%–50% of total food waste along the supply chain, contributing substantially to environmental burdens and economic losses [1, 3]. Within this

context, the valorisation of fruit and vegetable by-products into functional ingredients has emerged as a key strategy for enhancing circularity and improving the overall sustainability of food systems [4, 5]. However, effective by-product valorisation requires an understanding of such ingredient functionality under processing conditions, as structural and physicochemical characteristics ultimately determine their performance in real food matrices [6, 7].

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Watermelon (*Citrullus lanatus*) is among the most widely consumed fruits worldwide and accounts for approximately 7% of global vegetable production, ranking second after tomato [6, 8, 9]. It is primarily grown in Asia (79.5%), Africa (7.5%), and the Americas (6.9%), with global production reaching 60.9 million tonnes per year, of which China accounts for approximately 67% [10]. Watermelon is low in calories, salt, cholesterol, and fat, and it offers several health benefits, including improving cardiovascular health, decreasing low-density lipoprotein (LDL) oxidation, and helping to manage age-related degenerative diseases and certain cancers [10]. While the pulp is commonly consumed fresh or processed into juices, nectars, concentrates, and jams, the rind is used as pickles in parts of the southern United States and is also incorporated into the formulation of jellies and fruit preserves [9, 10].

Several studies have incorporated watermelon rinds into diverse products including bread [11–14], biscuits [4], cakes [5], beef burger patties [15], noodles [16], and candy [9]. However, the peels, including rind, constituting approximately one-third of the total fruit mass, are largely discarded as waste, contributing to ecological challenges such as increased insect and rodent proliferation, particularly in developing countries where agricultural residue management is less regulated [6]. Compositional studies have shown that watermelon peel is rich in dietary fiber, with substantial cellulose, hemicellulose, and pectic polysaccharides that can exhibit water-binding and thickening in food products [17, 18]. In addition, it contains minerals such as potassium, calcium, and magnesium, as well as bioactive compounds including phenolics with antioxidant activity [17]. These attributes indicate that watermelon peel is a promising functional ingredient capable of contributing to both technological performance and nutritional quality. However, to our knowledge, no studies have yet examined the structural and technofunctional properties of watermelon peels in relation to food applications. In fact, applications in gluten-free foods remain sparse and underresearched.

In gluten-free food systems such as bread, the importance of functional ingredient performance is further amplified due to the absence of gluten, which normally provides elasticity, gas retention, and structural cohesion [19, 20]. Since bread has become an important food product in the human diet worldwide, supported by a centuries-long history of processing and consumption, gluten-free bread, however, is often characterized by low loaf volume, poor crumb structure, and rapid staling, challenges closely linked to limited water availability for starch-hydrocolloid development and weak matrix formation during baking [21, 22]. Fiber-rich nonconventional flours such as in watermelon peels may address these challenges by modifying batter rheology, improving moisture retention, and contributing to structural reinforcement during baking [23, 24].

Despite the growing interest in watermelon peel as a food waste valorisation resource, limited information is available on the technofunctional and pasting behavior of watermelon peel powder (WPP) and how these properties influence the structural and quality characteristics of cassava-based gluten-free bread. A recent study by Kumbaji et al. [14] demonstrated that

the combined incorporation of nettle leaf powder and WPP improved the nutritional, antioxidant, and glycemic properties of cassava-based gluten-free bread. However, the study focused primarily on the quality attributes of the final bread products and did not investigate the intrinsic physicochemical characteristics of WPP or the mechanisms through which it influences gluten-free bread performance. The present study extends previous findings by providing an integrated characterization of WPP and elucidating how its intrinsic properties govern its functionality in cassava-based gluten-free bread systems.

Therefore, this study is aimed at characterizing WPP in terms of its proximate composition, technofunctional, and pasting properties and at evaluating its application in cassava-based gluten-free bread at 3% and 6% substitution levels. The effects of WPP incorporation on bread specific volume, color, crumb texture, microstructure, and electronic-tongue taste responses were subsequently investigated to establish relationships between the physicochemical properties of WPP and bread quality. It was hypothesized that the composition of WPP governs its hydration capacity, which in turn influences the structure and quality of gluten-free bread. The novelty of this work lies in integrating flour functionality, pasting behavior, bread quality, and instrumental taste profiling to elucidate the technological implications of incorporating watermelon peel into a cassava-based gluten-free matrix. The findings provide new insight into the utilization of watermelon peel as a value-added functional ingredient while supporting the development of more sustainable gluten-free bakery products and contributing to food waste valorisation.

2 | Materials and Method

2.1 | Materials

Fresh watermelon (*Citrullus lanatus*) fruits were obtained from a local supermarket (ASDA, Gillingham Pier, Chatham, United Kingdom). Cassava flour (82.3 g/100 g carbohydrate, 1.1 g/100 g protein, 1.2 g/100 g fat, and 2.2 g/100 g dietary fiber), used as the gluten-free base ingredient, was purchased from a local supplier (African Taste, Jumbo, United Kingdom). Other ingredients, Tropical Sun corn starch (88.0 g/100 g carbohydrate, 0.3 g/100 g protein, and 0.1 g/100 g fat, nondetected fiber), dry yeast, salt, sugar, and rapeseed oil, were procured from the same local supermarket. Before use, all flours were sieved through a <250 µm UWL 400T sieve shaker (Haver & Boecker, VWR International, United Kingdom) and stored in airtight containers at ambient temperature until bread preparation and analysis. All chemicals and reagents used were of analytical grade and were obtained from Merck Life Science, Sigma-Aldrich brand, Gillingham, United Kingdom.

2.2 | Production of WPP

WPP was produced according to Kumbaji et al. [14], as illustrated in Figure 1. Fruits of uniform maturity and free from visible defects were selected and thoroughly washed with

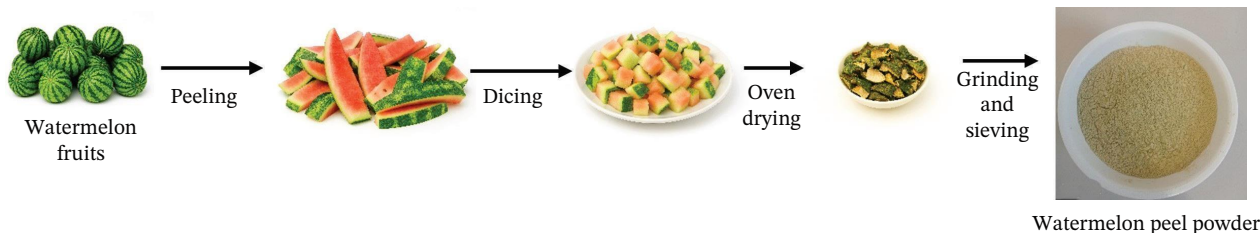


FIGURE 1 | Photo sequence illustrating watermelon peel powder production.

deionized water. The outer green rind and white mesocarp were cut into small pieces (approximately 1–2 cm), then oven-dried in an incubator (GenLab, United Kingdom) at 55°C for 48–60 h to a moisture content below 10%. Dried watermelon peels were milled to fine powders using a Thermomix TM6 (Vorwerk, Wuppertal, Germany). The dried WPP was sieved through a 250 μ m sieve (Section 2.1) to obtain WPP. WPP was stored in airtight containers at ambient temperature until analysis.

2.3 | Gluten-Free Bread Formulation and Baking

Two flour blends (3WPP and 6WPP) were formulated using cassava flour as the base ingredient, with WPP incorporated at 3% and 6% (w/w), alongside a control sample containing 0% WPP (0WPP). Based on preliminary formulation trials that ensured optimal dough processability and baking performance [14], substitution levels of 3% and 6% (w/w) were selected to investigate the effects of low-to-moderate incorporation of WPP on flour functionality and bread quality while maintaining batter processability and structural integrity. Higher substitution levels resulted in excessive fiber incorporation, adversely affecting batter consistency and loaf development. For each formulation, all ingredients were accurately weighed using a digital precision balance (± 0.01 g) and sequentially added into a bread maker pan in the following order: 460 mL water, 6 g oil, 2.5 g sugar, 2.5 g salt, 300 g composite flour (cassava flour + WPP), 5 g corn starch, and 3 g dry yeast.

The bread formulations were prepared using a Breville bread maker (Model BBM800, Breville Group Ltd., Australia). The control bread (0WPP) was formulated using cassava flour without WPP, while WPP was incorporated at 3% and 6% of the flour weight to produce the 3WPP and 6WPP formulations, respectively. All dry ingredients were weighed individually and thoroughly mixed before incorporation into the bread-making vessel. The required liquid and other ingredients were then added according to the respective formulation, and the ingredients were processed using the gluten/yeast-free (Program No. 3) bread-making cycle. According to the manufacturer's guide, the mixing/kneading stage was conducted for approximately 20 min, followed by proofing for 40 min at approximately 35°C. Baking was subsequently performed at 200°C for 70 min. After completion of the baking cycle, the loaves were removed from the bread maker and cooled at room temperature ($25^\circ\text{C} \pm 2^\circ\text{C}$) for 4 h before further analysis. All formulations were processed under identical mixing, proofing, and baking conditions, with WPP incorporation level being the only formulation variable.

2.4 | Proximate Composition

Cassava flour and WPP were analyzed for moisture, fat, protein, starch, and dietary fiber content. Moisture and fat were determined according to the AOAC 2008.06 official method using a CEM Smart 6 moisture analyzer (CEM Corp., Matthews, North Carolina, United States) and Oracle fat analyzer (CEM Corp., Matthews, North Carolina, United States) [14, 25]. Protein content was determined using the Bradford dye-binding assay (Bradford, 1976) with Coomassie Brilliant Blue G-250 reagent according to the manufacturer's protocol. Bovine serum albumin (BSA) was used as the calibration standard, and protein concentrations were calculated from the corresponding standard curve and expressed as g/100 g (dry weight). Dietary fiber content was analyzed using the Total Dietary Fiber Kit following the enzymatic-gravimetric AOAC Method 991.43. Both soluble dietary fiber (SDF) and insoluble dietary fiber (IDF) fractions were determined, and total dietary fiber (TDF) was expressed as the sum of SDF and IDF. Starch content was measured using the Total Starch Assay Kit based on enzymatic hydrolysis of starch to glucose by thermostable α -amylase and amyloglucosidase. All kits were from Merck Life Science, Sigma-Aldrich brand, Gillingham, United Kingdom.

2.5 | Technofunctional Properties

2.5.1 | Hydration and Swelling

Water holding capacity (WHC), oil holding capacity (OHC), swelling power, and solubility of WPP, 0WPP, 3WPP, and 6WPP were determined according to Nilusha et al. [26]. Briefly, 1.0 g of each sample was mixed with 10 mL of deionized water (for WHC) or 10 mL of rapeseed oil (for OHC) in separate centrifuge tubes and incubated at 30°C for 30 min with intermittent mixing. The suspensions were subsequently centrifuged at $3000 \times g$ for 30 min, after which the supernatants were carefully decanted. The amount of water or oil retained by the sediment was determined gravimetrically, and WHC and OHC were expressed as grams of water or oil retained per gram of sample (g/g).

For swelling power and solubility, 1.0 g of each sample was dispersed in 10 mL of distilled water and continuously stirred for 30 min at room temperature. The suspensions were then heated in a water bath at 85°C for 30 min with gentle stirring, followed by centrifugation at $2200 \times g$ for 15 min. The supernatant was decanted into a preweighed aluminum dish and dried at 105°C to constant weight. Swelling power was calculated as the weight of the swollen sediment per unit weight of dry sample, whereas solubility was expressed as the percentage of dry solids dissolved in the supernatant.

2.5.2 | Density and Flow Properties

Density and flow properties of each flour and blend were determined as described by Koç and Dirim [27]. Bulk density was measured by gently filling a graduated cylinder with flour and recording the mass-to-volume ratio. Tapped density was determined after mechanically tapping the cylinder a fixed number of times until a constant volume was obtained. Carr's index (CI) (%) and Hausner ratio (HR) were calculated to assess compressibility and flowability of the powder. Angle of repose was determined using the fixed funnel method by allowing the flours to flow freely onto a flat surface and measuring the height and radius of the resulting cone. According to Carr's flowability classification, a CI value between 5% and 15% indicates excellent flowability, and >25% suggest poor flowability; HR values between 1.0 and 1.1 indicate excellent flowability, 1.1–1.25 indicate moderate flow, between 1.25 and 1.4 suggest poor flow, and >1.4 indicate extremely low flowability [28].

2.6 | Color Measurement

The color of 0WPP, 3WPP, 6WPP, and WPP was measured using a Minolta Chroma Meter (Model CR-400, Konica Minolta Sensing Inc., Osaka, Japan), calibrated with a standard white tile. The CIELAB coordinates were determined, and according to Kavle et al. [29], total color difference (ΔE), hue angle (h°), chroma (C^*), and browning index (BI) were calculated.

2.7 | Pasting Properties

Pasting properties were determined for 0WPP, 3WPP, 6WPP, and WPP as described by Zhou et al. [30] with minor modifications. Minor modifications included the use of the Brabender ViscoQuick system (Brabender GmbH & Co. KG, Germany) with instrument-specific sample loading and heating program according to the manufacturer's operating protocol. Here, the slurry was prepared by mixing 5g of each sample with 100mL of deionized water. It was premixed, then heated at 50°C with continuous stirring for 10s and held for 1 min. The temperature was elevated to 95°C (heating rate 6°C/min) for 7.3 min and held for 5 min and finally cooled at 50°C (cooling rate 6°C/min). In line with standard Brabender/RVA terminology, the evaluation points were beginning of gelatinization (pasting temperature, °C), maximum viscosity hot (peak viscosity, cmg; peak time, min), minimum viscosity (trough viscosity), and maximum viscosity cold (final viscosity). The derived indices were breakdown (MaximumViscosityHot–MinimumViscosity) and setback (MaximumViscosityCold–MinimumViscosity). The results were expressed in Brabender units (cmg) and provide insight into starch gelatinization, viscosity development, and the impact of fiber–starch interactions.

2.8 | Specific Loaf Volume and Crumb Texture

The specific volume of bread loaves was determined using the rapeseed displacement method according to the AACC International Approved Method 10-05.01 [31] and expressed as loaf volume per unit mass (milliliters per gram). Texture profile analysis (TPA)

of the bread samples was performed as previously described [14] using a Texture Analyzer (TA-XT Plus, Stable Micro Systems, Godalming, Surrey, United Kingdom) equipped with a 50 mm diameter cylindrical probe. After cooling to ambient temperature for 24 h, loaves were sliced at the center into 50-mm-thick sections, and the crumb portion was used for analysis to avoid crust interference. Each sample was subjected to a double compression cycle to 50% of its original height at a test speed of 1.0 mm/s, with a trigger force of 5 g and a 5 s interval between compressions. Each measurement was performed on at least five slices per loaf, and mean values were calculated. The texture parameters, hardness, adhesiveness, resilience, gumminess, cohesiveness, springiness, and chewiness were derived automatically from the force-time curve using the Exponent Connect 32 software (Ver. 8.1, Stable Micro Systems, United Kingdom).

2.9 | Instrumental Electronic Tongue Analysis

Bread quality was evaluated using an electronic tongue (TS-5000Z, Intelligent Sensor Technology Inc., Kanagawa, Japan), an analogous mechanism to the human tongue, as described by Kumbaji et al. [14]. Approximately 20 g of each sample was homogenized with 40 mL of deionized water using a Thermomix TM6 (Vorwerk, Wuppertal, Germany) for 2 min at 25°C to obtain a uniform slurry. The homogenate was centrifuged at 4000×g for 15 min, and the clear supernatant was collected for analysis. The supernatants were placed in sample trays and loaded into the e-tongue equipped with cross-selective lipid membrane sensors designed to mimic human taste perception. We quantified taste attributes including sweetness, saltiness, sourness, bitterness, umami, and overall taste intensity. Prior to analysis, the e-tongue system was calibrated with standard taste solutions to ensure accurate discrimination of each taste modality. Between measurements, the sensors were rinsed with a special washing solution and standard solutions and reconditioned in reference solution to prevent carryover effects.

2.10 | Microstructural Analysis

The morphological features of the flour and bread were examined using a ZEISS Sigma Field Emission Scanning Electron Microscope (ZEISS GeminiSEM500, Oberkochen, Germany). Approximately 2–3 mg of powdered or bread samples was mounted on aluminum stubs using double-sided carbon tape and sputter-coated with a 5 nm layer of gold palladium prior to imaging [14]. Micrographs were captured at ×500, ×3000, and ×6000 magnifications to visualize the overall powder porosity and cell wall integrity.

2.11 | FTIR Analysis

FTIR analysis was conducted to assess the presence of chemical functional groups. Dried flour samples were scanned in the range 4000–400 cm^{−1} using an FTIR spectrometer (PerkinElmer Spectrum Two, L1600235, Beaconsfield, Bucks, United Kingdom) and analyzed using the Spectrum IR 10.6.2 software. Key absorption bands corresponding to hydroxyl (–OH), carbonyl (C=O), and C–O–C groups were identified to explain hydration and swelling behavior.

2.12 | Statistical Analysis

All bread formulations were prepared in three independent bread-making trials, with each trial representing an independent experimental unit. For bread-related analyses, including specific volume and TPA, measurements obtained from each independently prepared loaf were considered experimental replicates. Where multiple instrumental readings were collected from the same sample or loaf, these were treated as technical repetitions and averaged before statistical analysis. Thus, technical repetitions were not treated as independent observations. TPA and color values represent five independent measurements obtained from different locations within each loaf. Results are presented as mean $\pm$ standard deviation. Statistical differences among means were evaluated using one-way analysis of variance (ANOVA) followed by Tukey's HSD test at $p < 0.05$. Statistical analyses were conducted using IBM SPSS v.31.0.0.0 (117) (IBM Corp., Armonk, New York, United States).

3 | Results and Discussion

3.1 | Proximate Composition of WPP and Cassava-WPP Blends

The proximate composition of 0WPP, 3WPP, 6WPP, and WPP is presented in Table 1. Moisture content varied between 7.28 and 9.92 g/100 g, suggesting that WPP incorporation did not substantially alter moisture under the applied processing conditions. However, progressive substitution of WPP resulted in a dose-dependent increase in ash, protein, and dietary fiber.

WPP exhibited significantly higher ($p < 0.05$) ash content (7.56 g/100 g) compared with 0WPP (1.23 g/100 g), indicating a greater mineral contribution derived from the peel tissue. Progressive incorporation of WPP into 0WPP led to an increase in ash content to 2.39 g/100 g (6WPP). Similar elevated ash levels have been reported for other fruit peel powders, including passion fruit [32], banana [33], and grape skin [34], reflecting their role as mineral reservoirs in plant tissues. Notably, the mineral-rich ash fraction of WPP may contribute to changes in

ionic strength and thermal behavior during heating, potentially affecting starch pasting and setting of the matrix [20, 35].

Protein content was lowest (1.13 g/100 g) in 0WPP, consistent with its inherently low nitrogenous compounds [26]. WPP exhibited a comparatively higher protein content (5.80 g/100 g). Consequently, protein levels increased significantly ($p < 0.05$) with increasing WPP substitution to 3.56 g/100 g (6WPP). Chakrabarty et al. [16] reported substantially higher crude protein levels in watermelon rind powder, ranging from 17.01% to 19.74%. In contrast to these findings, Ho and Dahri [36] reported that increasing the substitution level of watermelon rind powder for wheat flour to as much as 15% in yellow noodles progressively decreased the protein content from 146.8 to 129.1 g/kg. Moreover, a modest protein level of WPP relative to cereal flours indicates that WPP-enriched foods could be nutritionally relevant to gluten-free systems, which often lack adequate protein diversity [21, 24].

Cassava flour was characterized by high starch content (79.30 g/100 g), confirming its dominance as a starch-based ingredient [20]. Substitution with WPP resulted in a progressive reduction of starch content to 59.89 g/100 g (6WPP). This reduction in starch is critical to the flour's pasting behavior (Figure 2) as well as water competition and crumb setting in gluten-free breads [21, 23].

Dietary fiber composition differed markedly among samples. WPP exhibited high TDF content (13.56 g/100 g), with the insoluble fiber fraction dominating (5.73 g/100 g). This is consistent with the high cellulose and hemicellulose in watermelon peel tissues [17, 37]. As such, incorporation of WPP significantly ($p < 0.05$) increased the TDF in the composite flours from 2.25 to 7.18 g/100 g. The presence of soluble fiber in WPP is of particular technological relevance, as soluble polysaccharides contribute to water binding, viscosity development, and batter stabilization in gluten-free systems [17, 21]. Similar increases in soluble and insoluble fiber fractions have been reported in foods enriched with fruit by-products, including grape skin [34], apple pomace [38], banana peel [33, 37], orange peel [39], passion fruit peel [32], and watermelon rind [6, 17].

From a nutritional perspective, incorporation of WPP into cassava-based gluten-free bread offers a viable strategy for improving dietary fiber intake, addressing a common nutritional limitation

TABLE 1 | Proximate composition (g/100 g) WPP and cassava-WPP blends.

Macronutrients	0WPP	3WPP	6WPP	WPP
Moisture	9.03 $\pm$ 0.61 ^a	7.45 $\pm$ 0.37 ^b	8.62 $\pm$ 0.66 ^a	7.28 $\pm$ 0.52 ^b
Ash	1.23 $\pm$ 0.14 ^c	1.92 $\pm$ 0.20 ^b	2.39 $\pm$ 0.66 ^b	7.56 $\pm$ 0.18 ^a
Protein	1.13 $\pm$ 0.08 ^c	1.46 $\pm$ 0.41 ^c	3.56 $\pm$ 0.66 ^b	5.80 $\pm$ 0.32 ^a
Fats	1.28 $\pm$ 0.21 ^a	0.30 $\pm$ 0.24 ^b	0.38 $\pm$ 0.14 ^b	0.45 $\pm$ 0.22 ^b
Starch	79.30 $\pm$ 0.54 ^a	64.73 $\pm$ 0.44 ^b	59.89 $\pm$ 0.32 ^c	3.48 $\pm$ 0.95 ^d
Soluble fiber	0.81 $\pm$ 0.60 ^c	1.19 $\pm$ 0.23 ^b	2.48 $\pm$ 0.91 ^b	5.73 $\pm$ 0.43 ^a
Insoluble fiber	1.92 $\pm$ 0.22 ^d	2.63 $\pm$ 0.42 ^c	5.73 $\pm$ 0.45 ^b	7.28 $\pm$ 0.61 ^a
Total dietary fiber	2.72 $\pm$ 0.79 ^d	3.82 $\pm$ 0.63 ^c	8.21 $\pm$ 1.15 ^b	13.03 $\pm$ 0.97 ^a

Note: Results are expressed as mean $\pm$ standard deviation ($n = 3$), and means with different superscripts in the same row are significantly ($p < 0.05$) different. Abbreviations: 0WPP, 100% cassava flour; 3WPP, cassava flour substituted with 3% WPP; 6WPP, cassava flour substituted with 6% WPP; WPP, watermelon peel powder.

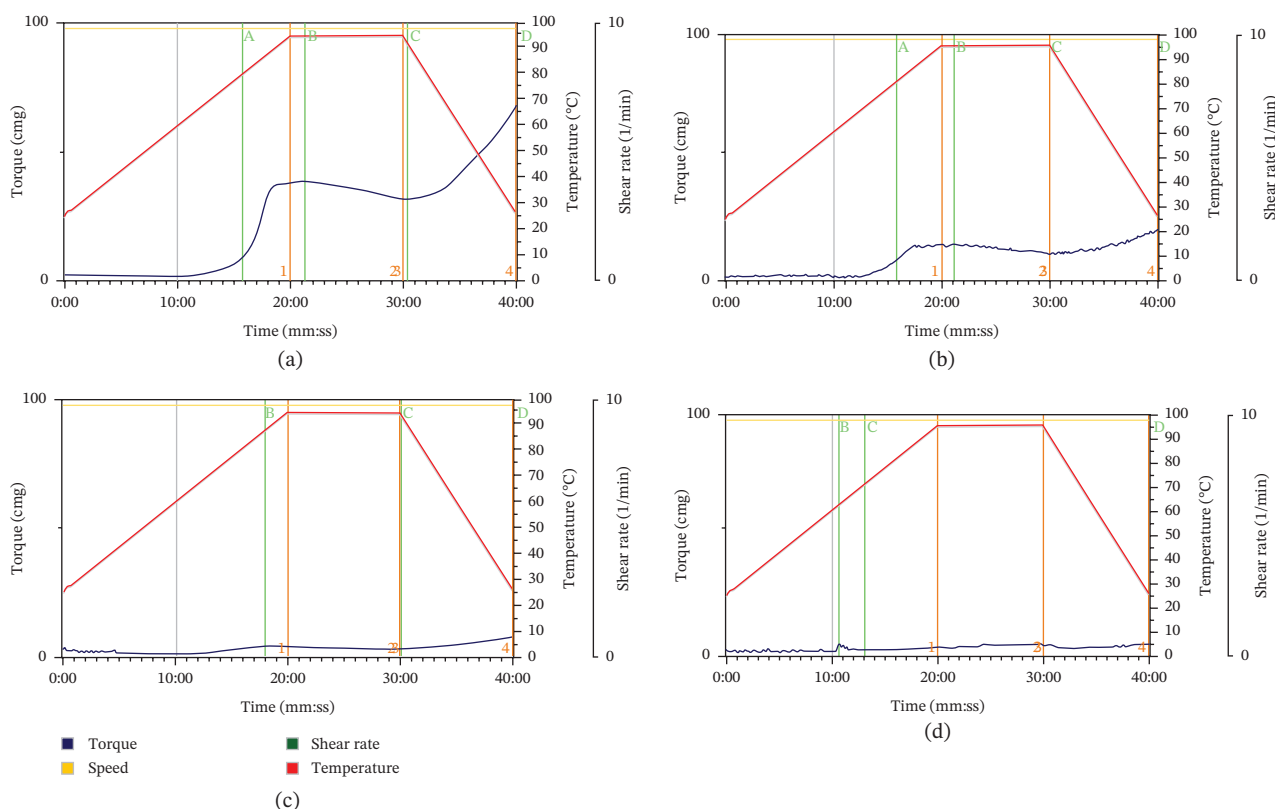


FIGURE 2 | Pasting profiles of (a) cassava flour (0WPP), (b) cassava flour containing 3% watermelon peel powder (3WPP), (c) cassava flour containing 6% watermelon peel powder (6WPP), and (d) watermelon peel powder (WPP) obtained using a Brabender ViscoQuick. Torque (cmg), temperature (°C), shear rate (min⁻¹), and speed were recorded as a function of time. Phase A represents the heating stage and starch gelatinization, Phase B corresponds to peak torque and maximum granule swelling, Phase C indicates the holding phase at elevated temperature and shear where paste stability and breakdown are observed, and Phase D represents the cooling stage associated with viscosity recovery and setback.

of gluten-free products, which are often low in fiber and micro-nutrients [19, 21]. The compositional profile of WPP therefore supports both its functional role in gluten-free bread systems and its potential contribution to the development of nutritionally enhanced, value-added gluten-free bakery products.

3.2 | Technofunctional Properties of WPP and Cassava-WPP Blends

3.2.1 | Hydration and Swelling Properties

The functional properties of 0WPP, 3WPP, 6WPP, and WPP are summarized in Table 2. Significant ($p < 0.05$) differences were observed among samples for water absorption capacity (WAC), oil absorption capacity (OHC), swelling power, and solubility.

WPP exhibited significantly ($p < 0.05$) higher WHC (2.65 g/g) than 0WPP (1.45 g/g), thus increasing the WHC of the composite flours to 2.17 g/g (6WPP). In contrast, 0WPP, dominated by starch granules, showed lower WHC due to its limited nonstarch polysaccharide content. The markedly higher WHC of WPP compared with cassava flour reflects its abundant dietary fiber and hydrophilic polysaccharides, particularly cellulose, hemicellulose, and pectin, which possess numerous hydroxyl groups capable of binding and retaining water through hydrogen bonding [20, 34, 39]. The fibrous cell wall matrix also provides a porous structure that

physically traps water within its capillary network. Similar increases in WHC have been reported for fiber-rich fruit and vegetable by-products incorporated into gluten-free flour systems, where fiber and protein addition improved water retention and matrix stability [23, 30, 40, 41]. For instance, Culetu et al. [23] reported high WAC for chickpea flour (1.92 g/g) when compared with teff and amaranth flours (0.95 g/g). The elevated WHC of WPP is technologically important because it increases batter hydration, influences starch gelatinization, improves moisture retention, and contributes to crumb softness and delayed staling. This is beneficial in food products where good viscosity is critical [41], particularly in gluten-free systems, as it helps improve batter viscosity, gas retention, and crumb moisture [20].

Similarly, WPP exhibited a significantly higher OHC (2.42 g/g) than 0WPP (0.97 g/g), indicating an enhanced ability of the fibrous matrix to retain oil. This behavior is primarily attributed to the porous structure and high dietary fiber content of WPP, which provide numerous capillary spaces and surface sites for the physical entrapment of oil, with a smaller contribution from hydrophobic interactions involving nonpolar constituents [30]. Comparable increases in OHC have been reported for gluten-free flours enriched with fiber-rich plant materials such as banana peel, chestnut flour, and Bambara groundnut, where the porous fiber network enhanced lipid retention [30, 40, 41]. From a technological perspective, increased OHC is advantageous in bakery applications because it promotes flavor retention,

TABLE 2 | Technofunctional properties of WPP, cassava flour, and blends.

Properties	0WPP	3WPP	6WPP	WPP
WHC (g/g)	1.45 ± 0.04 ^d	1.66 ± 0.00 ^c	2.17 ± 0.08 ^b	2.65 ± 0.04 ^a
OHC (g/g)	0.97 ± 0.05 ^c	1.07 ± 0.08 ^c	1.35 ± 0.06 ^b	2.42 ± 0.04 ^a
Swelling power (g/g)	8.93 ± 0.00 ^a	5.78 ± 0.02 ^b	3.71 ± 0.00 ^c	1.23 ± 0.08 ^d
Solubility (%)	12.06 ± 0.22 ^d	13.49 ± 0.08 ^c	19.83 ± 0.34 ^b	23.86 ± 0.00 ^a
Bulk density (g/cm ³)	0.65 ± 0.04 ^a	0.58 ± 0.00 ^b	0.44 ± 0.02 ^c	0.32 ± 0.08 ^d
Tapped density (g/cm ³)	0.72 ± 0.08 ^a	0.69 ± 0.01 ^b	0.57 ± 0.05 ^c	0.43 ± 0.00 ^d
Carr's index (%)	9.62 ± 0.04 ^d	15.92 ± 0.02 ^c	22.86 ± 0.08 ^b	25.56 ± 0.04 ^a
Hausner ratio	1.12 ± 0.02 ^d	1.19 ± 0.02 ^c	1.30 ± 0.00 ^b	1.34 ± 0.08 ^a
Angle of repose (°)	29.5 ± 0.08 ^d	33.4 ± 0.00 ^c	39.7 ± 0.01 ^b	43.2 ± 0.04 ^a

Note: Results are expressed as mean ± standard deviation (*n* = 3), and means with different superscripts in the same row are significantly (*p* < 0.05) different. Abbreviations: 0WPP, 100% cassava flour; 3WPP, cassava flour substituted with 3% WPP; 6WPP, cassava flour substituted with 6% WPP; WPP, watermelon peel powder.

improves mouthfeel, and may contribute to a softer crumb by reducing moisture migration during storage [30, 40].

0WPP exhibited the highest swelling power (8.93 g/g), consistent with the high amylopectin content and unrestricted swelling of starch granules during hydration [42]. In contrast, WPP showed significantly lower swelling power (1.23 g/g), reflecting its low starch content and the presence of rigid cell wall polysaccharides that do not undergo granular swelling [6, 43]. Progressive substitution with WPP resulted in a reduction in swelling power to 3.71 g/g (6WPP). This decrease can be attributed to both starch dilution and competition for water between starch granules and fiber components [42]. When compared with 0WPP, which is predominantly starch-based and exhibits high swelling due to starch granule gelatinization but limited water retention at ambient temperatures [20], WPP demonstrated a fundamentally different hydration mechanism governed by fiber–water interactions rather than starch swelling. Similar trends have been observed in nonconventional flours derived from fruit and vegetable by-products, where water absorption is primarily driven by fiber content and particle porosity rather than starch composition [44].

Solubility was significantly (*p* < 0.05) higher in WPP than in 0WPP (Table 2), reflecting the presence of water-soluble components such as pectin and low-molecular-weight polysaccharides. Similar increases in solubility have been reported in gluten-free flours enriched with fiber-rich apple pomace and citrus peels [45]. Higher solubility is associated with improved viscosity development and batter stabilization in gluten-free systems, as soluble polymers contribute to continuous phase thickening and gas cell stabilization [20, 30].

These results demonstrated that the incorporation of WPP shifted the functional profile of cassava flour from a starch-dominated system toward a fiber-enriched, water-binding matrix. As such, increased WHC, OHC, and solubility, combined with reduced swelling power, highlight the role of fiber–starch interactions and water competition in governing batter behavior and bread structure [20].

3.2.2 | Density and Flow Properties

The bulk and tapped densities of WPP, 0WPP, 3WPP, and 6WPP are presented in Table 2. 0WPP exhibited significantly (*p* < 0.05) higher bulk and tapped densities compared with WPP, reflecting the compact, spherical morphology of starch granules (Figure 3) that allows efficient particle packing. This was further reduced to 0.44 g/cm³ (bulk) and 0.57 g/cm³ (tapped) at 6WPP. This reduction indicated that even low proportions of fibrous particles can alter the packing behavior of starch-based flours. Similar reductions in bulk density have been reported for fiber-rich fruit flours. For instance, comparing gluten-free flours such as sorghum, rice, moong, water chestnut, and unripe banana, Patil and Arya [41] recorded bulk densities ranging between 0.45 and 0.66 g/cm³ while the tapped densities varied from 1.32 to 1.76 g/cm³. Moreover, low bulk density is advantageous for product formulation where volume expansion and hydration are desirable, although it may increase storage and transport volume requirements.

Flowability classification based on CI and HR revealed notable differences among 0WPP, 3WPP, 6WPP, and WPP (Table 2). 0WPP exhibited a lower CI (9.62%) and HR (1.12), indicative of good flowability and low compressibility. In contrast, WPP showed higher CI (25.56%) and HR (1.34), reflecting a good to fair flow behavior in the composite flours. The results indicated that increasing WPP substitution could compromise flowability, although values remained within acceptable ranges for dry mixing operations. This reduced flowability is associated with the irregular shape, higher surface roughness, and greater interparticle friction of WPP particles [10, 12]. Similar trends have been reported in composite flours enriched with dietary fiber or plant-based flours, where increased cohesiveness and compressibility are common due to fiber-induced interlocking [10, 40, 41].

The angle of repose further confirmed differences in powder flow behavior. 0WPP exhibited the lowest angle of repose (29.5°), indicative of free-flowing behavior, while WPP showed a higher angle of repose (43.2°), reflecting increased cohesiveness and reduced flowability. Higher angles of repose are commonly

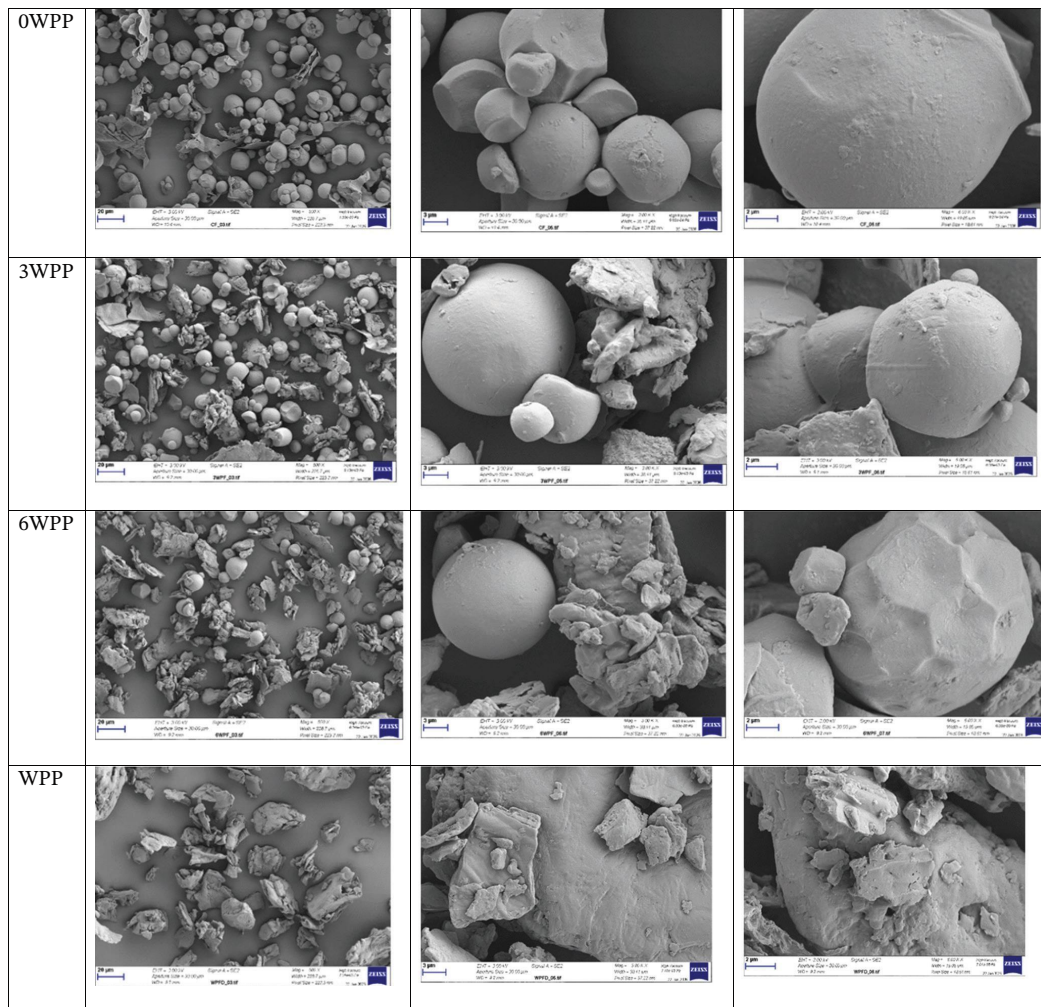


FIGURE 3 | SEM micrographs of cassava flour (0WPP), cassava flour substituted with 3% (3WPP) and 6% (6WPP) watermelon peel powder, and watermelon peel powder (WPP), at $\times 500$, $\times 3000$, and $\times 6000$ magnification.

associated with fibrous powders and have been reported for legume flours and vegetable fibers used in bakery formulations [41].

From a processing perspective, the density and flow properties of WPP have practical implications for industrial handling, mixing, and scaling. Moderate flowability suggests that WPP can be handled using conventional dry-mixing equipment, although precautions such as controlled feeding rates or vibration-assisted hoppers may be required at higher inclusion levels to prevent bridging or segregation [28]. Moreover, these findings are consistent with the observed variations in hydration (Table 2) and pasting properties (Figure 2), as reduced packing density and increased porosity facilitate rapid water uptake during mixing.

3.2.3 | Color Characteristics of WPP and Cassava-WPP Blends

The visual appearance and instrumental color parameters of WPP, 0WPP, 3WPP, and 6WPP are shown in Figure 4 and Table 3. 0WPP exhibited a bright white appearance, consistent with its high L^* value (98.71) and low chroma (3.42), characteristic of starch-rich flours with minimal pigment content [46, 47].

In contrast, WPP displayed a distinctly yellow-beige color, reflecting its lower L^* value (70.46) and significantly ($p < 0.05$) higher b^* (29.71) and chroma (27.60) values. Progressive substitution of 0WPP with WPP resulted in a dose-dependent decrease in L^* values to 75.45 (6WPP). Increased chroma has been similarly observed in fiber-enriched passion fruit peel flour ($C^* = 23.04 \pm 1.54$) [32] and watermelon rind powders ($264.04 \pm 14.57 - 429.7 \pm 11.66$) [16] containing plant-derived pigments. Contrarily, a^* increased from -0.38 (0WPP) to 3.50 (WPP). Chakrabarty et al. [16] reported a positive a^* value only for the yellow watermelon powder (5.00) and negative for both dark green (-3.88) and pale green (-1.90) watermelon rind. This reduction in lightness is attributed to the presence of natural chlorophyll-like pigments, fiber, and phenolic compounds [17, 38] and possible nonenzymatic browning reactions occurring during peel drying [32].

According to commonly accepted thresholds, ΔE values above 3 ($\Delta E > 3$) are perceptible to the human eye, suggesting that color changes at higher WPP levels may be noticeable to consumers. While total color difference (ΔE) increased with increasing WPP substitution, hue angle (h°) decreased progressively, indicating a shift from a neutral pale color toward a more yellow-brown hue (Figure 4). This is reflected by the BI that increased from

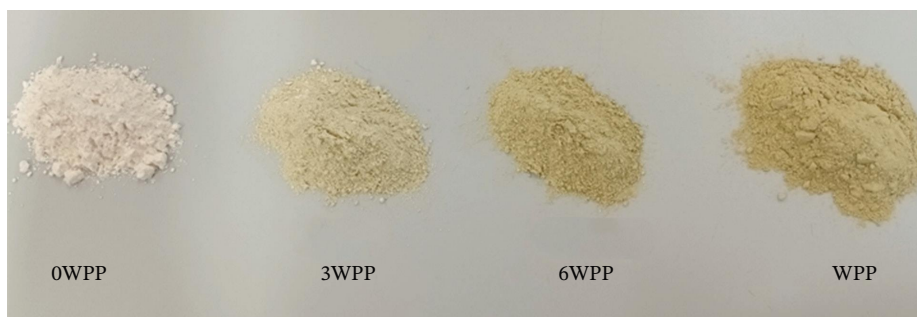


FIGURE 4 | Color of 0WPP (100% cassava flour [bright white]), 3WPP (cassava flour substituted with 3% WPP [light cream]), 6WPP (cassava flour substituted with 6% WPP [pale-yellow beige]), and WPP (watermelon peel powder [yellow brown]).

TABLE 3 | Color characteristics of WPP and cassava-WPP flour blends.

Parameters	0WPP	3WPP	6WPP	WPP
L^*	98.71 ± 0.83^d	87.63 ± 0.42^c	75.45 ± 0.23^b	70.46 ± 0.69^a
a^*	-0.38 ± 0.66^a	1.09 ± 0.04^{ab}	1.99 ± 0.20^{bc}	3.50 ± 0.61^d
b^*	2.21 ± 0.11^a	15.34 ± 0.73^b	19.95 ± 0.44^c	29.71 ± 0.30^d
Chroma (C^*)	3.42 ± 0.55^a	12.54 ± 0.11^b	21.32 ± 0.50^c	27.60 ± 0.21^d
Hue angle (h°)	87.65^d	84.35^c	76.57^b	71.42^a
ΔE	5.71 ± 0.43^a	11.54 ± 0.61^b	17.68 ± 0.43^c	27.71 ± 0.52^d
Browning index	13.67 ± 0.63^a	26.54 ± 0.55^b	38.79 ± 0.90^c	51.23 ± 0.88^d

Note: Results are expressed as mean $\pm$ standard deviation ($n = 3$), and means with different superscripts in the same row are significantly ($p < 0.05$) different. Abbreviations: 0WPP, 100% cassava flour; 3WPP, cassava flour substituted with 3% WPP; 6WPP, cassava flour substituted with 6% WPP; WPP, watermelon peel powder.

13.67 to 51.23. The increase in BI may be attributed to the concentration of phenolic compounds in WPP and the occurrence of nonenzymatic browning reactions during drying and powder processing [33]. Elevated BI values have also been reported in composite flours containing fruit and vegetable by-products including banana peels subjected to thermal treatments [33]. Drying conditions are known to significantly promote pigment degradation and Maillard-type reactions, leading to reduced lightness and increased yellowness or redness [29]. Similar color profiles have been reported for watermelon rind [6, 17], banana peels [37], and grape skin [34] when incorporated into bakery products. For instance, Ho and Dahri [36] reported that substituting watermelon rind powder in yellow noodles did not affect the L^* values of the noodles (47.23–50.98); however, the a^* values decreased from -1.94 to -4.30 , and the b^* values increased from 14.04 to 22.93. Nevertheless, moderate color variation as in this research could be perceived positively when associated with fiber enrichment and natural ingredients, particularly in gluten-free products where consumers often expect differences in appearance [21, 34].

3.3 | Pasting Properties of WPP and Cassava-WPP Blends

The pasting profiles of WPP, 0WPP, 3WPP, and 6WPP are presented in Figure 2. Torque values (cmg) were used to describe pasting behavior during heating, holding, and cooling stages

(Table 4). Significant differences ($p < 0.05$) were observed among samples for all pasting parameters, with setback viscosity being zero for all samples, suggesting minimal amylose reassociation under the applied testing conditions.

In Figure 2a, 0WPP exhibited a typical starch-dominated pasting profile, characterized by a sharp increase in torque during heating, corresponding to starch granule swelling and gelatinization [20]. The pronounced peak torque reflects unrestricted water uptake and extensive swelling of cassava starch granules, consistent with its high starch and low fiber content [47]. Following peak viscosity, a noticeable decrease in torque during the holding phase indicates starch granule disintegration under thermal and shear stress (breakdown). During cooling, torque increased again, reflecting amylose reassociation and paste setback [47, 48]. In line with this, 0WPP exhibited the highest values for all pasting properties including peak (38.4 cmg), trough (31.5 cmg), final (68.2 cmg), and breakdown (6.7 cmg) velocities as well as peak time (21:16 min), reflecting extensive starch granule swelling, gelatinization, and subsequent disintegration under heat and shear [23]. This behavior is a characteristic of tuber and many root flours/starches and is frequently reported for cassava systems [34], and it is correlated with its crumb firming and retrogradation in gluten-free breads [20, 21].

However, following WPP incorporation, 3WPP showed a reduced peak torque (Figure 2b) which substantially flattened the pasting

TABLE 4 | Pasting properties of WPP and cassava-WPP blends.

Parameter	0WPP	3WPP	6WPP	WPP
Peak viscosity (cmg)	38.4 ± 0.55 ^a	15.1 ± 0.31 ^b	4.0 ± 0.04 ^c	5.3 ± 0.06 ^d
Peak time (min)	21: 16 ± 0.02 ^a	21: 10 ± 0.04 ^a	17: 58 ± 0.00 ^b	10: 40 ± 0.00 ^c
Trough viscosity (cmg)	31.5 ± 0.69 ^a	10.7 ± 0.88 ^b	2.7 ± 0.08 ^c	2.3 ± 0.19 ^c
Breakdown viscosity (cmg)	6.7 ± 0.27 ^a	4.4 ± 0.43 ^b	1.2 ± 0.39 ^c	0.8 ± 0.93 ^c
Final viscosity (cmg)	68.2 ± 0.14 ^a	21.0 ± 0.01 ^b	7.6 ± 0.33 ^c	5.1 ± 0.52 ^d
Setback viscosity (cmg)	36.7 ± 0.21 ^a	10.3 ± 0.08 ^b	4.9 ± 0.17 ^c	2.8 ± 0.04 ^d
Pasting temperature (°C)	80.7 ± 0.02	80.9 ± 0.31	—	—

Note: Results are expressed as mean ± standard deviation ($n = 3$), and means with different superscripts in the same row are significantly ($p < 0.05$) different. Abbreviations: 0WPP, 100% cassava flour; 3WPP, cassava flour substituted with 3% WPP; 6WPP, cassava flour substituted with 6% WPP; WPP, watermelon peel powder.

curve, with markedly lower torque throughout the heating, holding, and cooling stages at 6WPP (Figure 2c), indicating restricted starch swelling. The presence of fiber and pectin-rich components likely competed with starch for available water, limiting granule expansion during gelatinization. The reduced breakdown torque in 3WPP suggested improved paste stability under heating and shear. This stabilization effect can be attributed to the formation of a starch-fiber network in which WPP components reinforce the paste structure and reduce granule rupture. These pasting characteristics are consistent with the improved crumb softness observed in 3WPP bread (Table 5). In 6WPP, the diminished peak torque reflected strong limitation of starch gelatinization due to extensive water competition and dilution of starch content. The incorporation of WPP significantly reduced peak (4.0 cmg), trough (2.7 cmg), breakdown (1.2 cmg), and final (7.6 cmg) viscosities with negligible pasting temperature in 6WPP samples. This reduction indicated restricted starch swelling due to dilution of starch content and competition for water between starch granules and hydrophilic fiber components present in WPP, which aligns with the denser crumb microstructure, reduced loaf volume, and increased crumb hardness observed in 6WPP bread.

In contrast to 0WPP, WPP exhibited negligible torque development throughout the pasting cycle (Figure 2d), with very low peak (5.3 cmg), trough (2.3 cmg), breakdown (0.8 cmg), and final (5.1 cmg) viscosities (Table 4). Similarly, peak time was significantly longer for 0WPP, 3WPP, and 6WPP compared with WPP, with 0WPP and 3WPP exhibiting similar values (~21 min); 6WPP showed a reduced peak time (17.6 min) which was further reduced to 10 min in WPP. The absence of a distinct peak viscosity reflects the low starch content of WPP and the dominance of nonstarch polysaccharides such as cellulose and pectin, which do not undergo granular gelatinization [23]. This reflected the absence of a defined gelatinization peak, indicating that WPP did not undergo starch swelling but instead contributed its viscosity primarily through hydration and gel formation of fiber and pectin components. Similar low-viscosity pasting profiles have been reported for fruit peel flours and fiber concentrates derived from citrus peels [49], passion fruit peel [32], and watermelon products [5, 10, 12, 13].

Setback viscosity values decreased significantly ($p < 0.05$) from 36.7 cmg in the control flour (0WPP) to 10.3 and 4.9 cmg in the

3WPP and 6WPP blends, respectively, while WPP exhibited the lowest value (2.8 cmg). Setback viscosity reflects the tendency of starch molecules, particularly amylose, to reassociate during cooling and is commonly associated with retrogradation behavior [32]. The progressive reduction in setback with increasing WPP substitution suggests that the incorporation of fiber-rich watermelon peel flour restricted amylose reassociation through starch dilution and competition for available water. Similar reductions in setback viscosity have been reported following the incorporation of fruit and vegetable fibers into starch-based systems [12, 13, 32].

Collectively, these results demonstrate that WPP incorporation modifies cassava flour pasting behavior in a dose-dependent manner, and the moderate inclusion of WPP (3WPP) achieved a balance between starch gelatinization and fiber-induced stabilization. This effect is particularly relevant for gluten-free bread, as excessive retrogradation was found to increase crumb firming and staling [20].

3.4 | Microstructural Characteristics of WPP and Cassava-WPP Blends

SEM micrographs of WPP, 0WPP, 3WPP, and 6WPP are presented in Figure 3.

0WPP exhibited predominantly smooth, discrete, and rounded starch granules with relatively uniform size distribution and minimal surface irregularities. This morphology was consistent with its high swelling power (Table 2) and peak viscosity (Table 4) observed in this study. It is typical of cassava starch and facilitates efficient packing, rapid hydration, and extensive swelling during gelatinization [20].

In contrast, WPP showed highly irregular, elongated, and fragmented particles with rough surfaces. The fibrous network observed in WPP is a characteristic of plant cell wall materials rich in cellulose, hemicellulose, and pectin [33]. Since microstructure plays a critical role in pasting behavior, the lack of starch granules in WPP explains its low peak viscosity (Table 4) and absence of a pronounced gelatinization peak (Figure 2). Similar microstructural features have been reported for fruit peel powders, including citrus [46], banana [33], and watermelon peels [14].

TABLE 5 | Physical characteristics of bread formulations.

Parameters	0WPP	3WPP	6WPP
Specific volume (mL/g)	4.59 ± 0.44 ^a	3.78 ± 0.61 ^a	2.03 ± 0.28 ^b
TPA			
Hardness (g)	1250.543 ± 90.401 ^a	1189.786 ± 87.54 ^b	1436.754 ± 43.52 ^c
Adhesiveness (gs)	0.560 ± 0.632 ^b	0.487 ± 0.489 ^b	− 0.348 ± 0.750 ^a
Resilience (%)	15.897 ± 2.674 ^a	19.786 ± 2.076 ^b	21.684 ± 1.864 ^c
Cohesiveness	0.467 ± 0.227 ^b	0.378 ± 0.0721 ^b	0.245 ± 0.562 ^a
Springiness (%)	80.653 ± 2.675 ^a	72.564 ± 7.680 ^a	55.786 ± 8.643 ^b
Gumminess	818.964 ± 65.834 ^c	675.475 ± 44.971 ^b	465.670 ± 73.894 ^a
Chewiness	1387.540 ± 452.383 ^a	1287.089 ± 212.785 ^a	4563.195 ± 145.670 ^b

Note: Results are expressed as mean ± standard deviation ($n = 3$ for specific volume and $n = 5$ for TPA), and means with different superscripts in the same row are significantly ($p < 0.05$) different.

Abbreviations: 0WPP, 100% cassava flour; 3WPP, cassava flour substituted with 3% WPP; 6WPP, cassava flour substituted with 6% WPP; WPP, watermelon peel powder.

In 3WPP, starch granules remained clearly visible and were interspersed with fibrous fragments of WPP. The fiber particles appeared to partially surround and bridge starch granules, forming a loosely interconnected network. This structural arrangement likely contributes to improved water distribution and moderated starch swelling, supporting enhanced paste stability and batter consistency [41]. At higher substitution levels (6WPP), the microstructure became more compact and heterogeneous, with a higher proportion of fibrous material disrupting the continuity of the starch matrix. Starch granules appeared less distinct and more embedded within the fiber-rich network [47, 48], consistent with the observed reductions in swelling power, peak viscosity, and loaf volume with increasing WPP incorporation.

The SEM observations provide direct visual evidence supporting the functional and pasting behavior of the composite flours. The porous and fibrous structure of WPP explains its high-water absorption, moderate flowability, and low pasting viscosity. In composite systems, moderate WPP inclusion (3WPP) promotes beneficial starch-fiber interactions, enhancing paste stability and batter structure without excessively restricting starch swelling. Conversely, excessive fiber incorporation (6WPP) leads to structural discontinuities and water competition, negatively affecting starch functionality and bread quality. From a functional standpoint, the microstructural characteristics of WPP contribute to its ability to modify gluten-free batter structure. The fibrous, irregular particles can reinforce the continuous phase, improve water structuring, and enhance the stability of gas cells during baking [13, 41]. However, increasing WPP incorporation may lead to discontinuities in the starch matrix, emphasizing the importance of optimizing substitution levels.

3.5 | FTIR Spectra of WPP and Cassava-WPP Blends

The FTIR spectra of 0WPP, 3WPP, 6WPP, and WPP are presented in Figure 5a,b. The FTIR results provide molecular-level

evidence supporting the compositional and microstructural modifications induced by WPP incorporation and corroborate the observed changes in hydration, pasting behavior, and gluten-free bread quality.

All samples exhibited characteristic absorption bands associated with carbohydrate-rich matrices. A broad absorption band observed in the region of approximately 3200–3600 cm^{−1} across all spectra corresponds to O–H stretching vibrations of hydroxyl groups from starch, cellulose, hemicellulose, and pectic substances, as well as bound water [33]. This band was more intense and broader in WPP and progressively increased in intensity in 3WPP and 6WPP, reflecting the higher concentration of hydroxyl-rich dietary fiber and pectin introduced by WPP. Ateeq et al. [22] reported the presence of a similar O–H stretching group in bread incorporated with onion peel flour.

Absorption bands around 2920–2850 cm^{−1} were attributed to C–H stretching vibrations of aliphatic –CH₂ and –CH₃ groups present in polysaccharide backbones [33, 50]. These bands were present in all samples, indicating that substitution with WPP modified functional performance without altering the fundamental carbohydrate framework of the flour blends. Distinct absorptions in the region of 1730–1600 cm^{−1} were more evident in WPP and the composite flours compared to the cassava control (Figure 5b). These bands correspond to C=O stretching of esterified and nonesterified carboxyl groups which are characteristic of pectic polysaccharides and organic acids [33]. In addition, peaks appeared between 1600 and 600 cm^{−1}, revealing the presence of biomolecules (polyphenols, lipids, proteins, and carbohydrates) [22]. The increased intensity of these bands with rising WPP inclusion supports the higher SDF content (Table 1) and could explain the modified pasting behavior observed in the composite flours (Figure 2).

The most intense and complex spectral features were observed in the fingerprint region between 1200 and 900 cm^{−1}, particularly around 1000–1040 cm^{−1}, corresponding to C–O–C and C–O stretching vibrations of glycosidic linkages in starch and

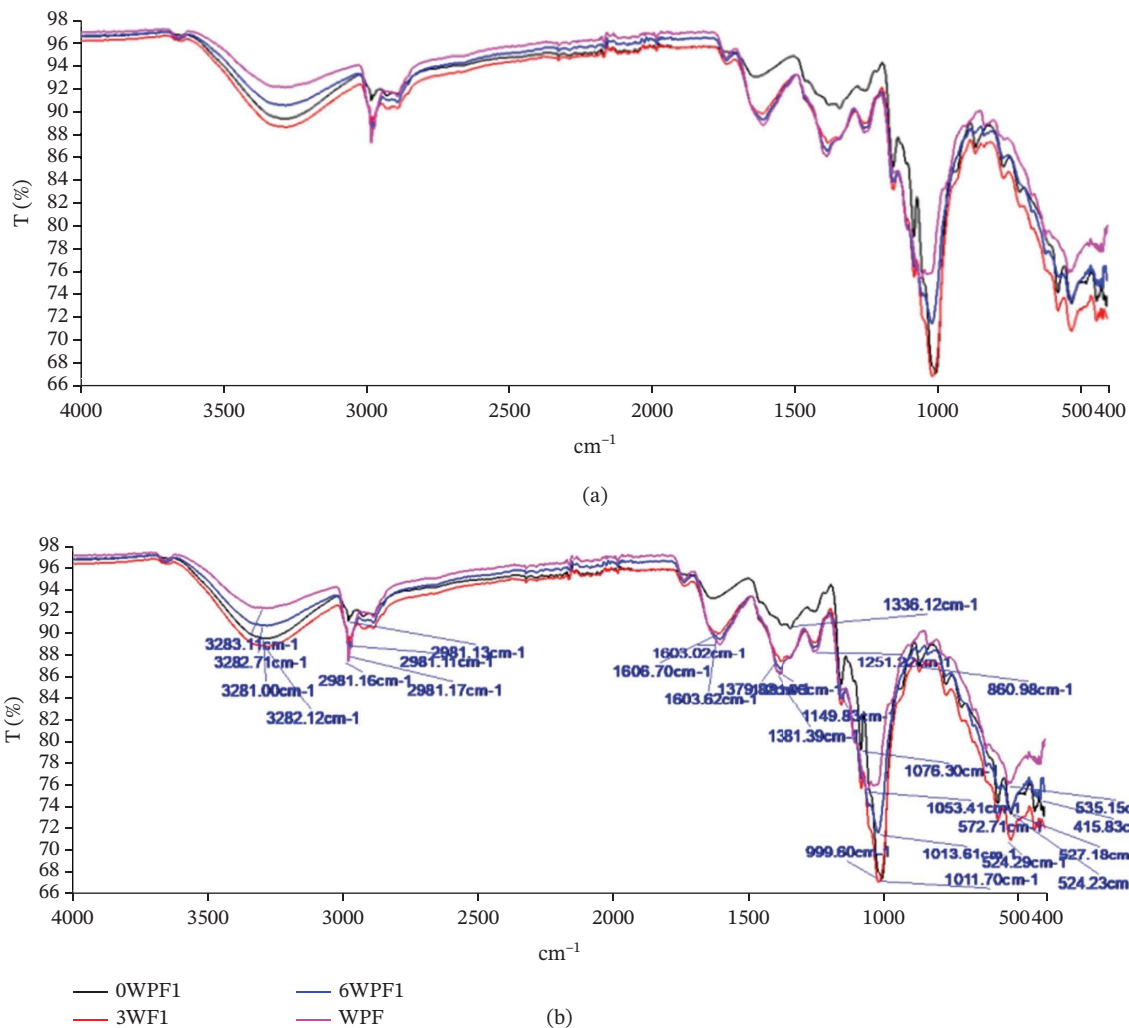


FIGURE 5 | (a) Unlabelled spectra. (b) Spectra with labelled characteristic bands. FTIR spectra of cassava flour (0WPF1), cassava flour substituted with 3% (3WPF1) and 6% (6WPF1) watermelon peel powder, and watermelon peel powder (WPF).

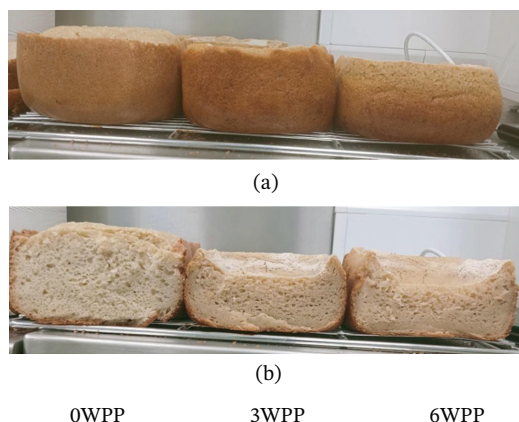


FIGURE 6 | Representative photographs of (a) whole loaves and corresponding (b) crumb cross-sections of cassava-based gluten-free breads containing 0% WPP (0WPP), 3% WPP (3WPP), and 6% WPP (6WPP). WPP, watermelon peel powder.

nonstarch polysaccharides [22, 33, 50]. Progressive changes in band shape and intensity from 0WPP to 6WPP indicate increasing structural heterogeneity due to fiber–starch interactions.

These interactions are consistent with the reduced peak viscosity, lower loaf volume, and denser crumb structure observed at increasing WPP substitution. Notably, minor variations in the low-wavenumber region below 900 cm^{-1} may be associated with skeletal vibrations of polysaccharides and mineral-related bonds, in agreement with the higher ash content of WPP (Table 1).

3.6 | Effect of WPP on Gluten-Free Bread Quality

3.6.1 | Specific Loaf Volume

The specific loaf volume of the gluten-free breads is presented in Table 5. 0WPP exhibited the highest specific volume ($4.59 \pm 0.44\text{ mL/g}$), reflecting the ability of cassava starch to expand effectively during baking [20]. Partial substitution with WPP at 3% resulted in a moderate but noticeable reduction ($3.78 \pm 0.61\text{ mL/g}$), which became pronounced at 6% substitution ($2.03 \pm 0.28\text{ mL/g}$). This reduction in specific volume with increasing WPP content can be attributed to the high dietary fiber content (Table 1) and limited starch contribution of WPP. Fiber-rich materials are known to compete with starch for available water, restricting starch gelatinization and

impairing gas cell expansion during baking [39]. In 0WPP, this effect could have been partially mitigated by the water-binding capacity of WPP, which may have contributed to improved batter viscosity and gas retention. However, in 6WPP, a further increase in fiber likely disrupted the continuity of the starch matrix, resulting in reduced gas retention and premature collapse of gas cells during thermal setting [20, 34]. This indicated that the absence of a gluten network in gluten-free systems renders loaf volume highly sensitive to changes in batter rheology and solid phase composition [21, 51]. Similar reductions in loaf volume have been reported in gluten-free breads enriched with fruit peel powders, pectin-rich fibers, and other nonconventional flours, where fiber-induced densification outweighed any hydrocolloid-like benefits at higher inclusion levels [45, 49, 50]. Overall, the results indicated that while low-level incorporation of WPP (3%) remains technologically feasible, higher substitution (6%) imposes significant constraints on loaf expansion.

Visual examination of the bread loaves further supported the instrumental measurements (Figure 6). The 0WPP bread exhibited the greatest loaf expansion and a relatively open and uniform crumb structure, whereas increasing WPP incorporation progressively reduced loaf height and produced a more compact crumb. The effect was particularly evident in 6WPP, which showed the lowest specific volume ($2.03 \pm 0.28 \text{ mL/g}$) and a visibly denser crumb. These changes are consistent with the increased fiber content and water-binding capacity of WPP, which may limit water availability for starch gelatinization and gas-cell expansion during baking, thereby restricting loaf development.

3.6.2 | Crumb Texture

The TPA of gluten-free breads is summarized in Table 5. Significant differences ($p < 0.05$) were observed across most texture parameters, indicating that WPP substitution influenced crumb texture.

The hardness of 0WPP was moderate at $1250.543 \pm 90.401 \text{ g}$, reflecting the typical gelatinized starch matrix characteristic of cassava-based gluten-free breads [20]. However, hardness decreased in 3WPP ($1189.786 \pm 87.54 \text{ g}$) but then increased in 6WPP ($1436.754 \pm 43.52 \text{ g}$). This reduction in 3WPP can be attributed to the water-binding and gel-forming properties of WPP, which promote a hydrated, cohesive matrix capable of retaining gas and resisting excessive compression [6, 16]. Similarly, Caponio et al. [39] reported that incorporating orange peel flour increased the hardness of muffins to between 15.22 ± 1.24 and $20.83 \pm 1.29 \text{ N}$, which they attributed to the high fiber content of the flour. In contrast, Kuchtová et al. [34] reported a decrease in cookie hardness from 1870 to 1583, 1543, and 1427 g with increasing incorporation of grape skin at 5%, 10%, and 15%, respectively.

In bread, adhesiveness represents how much the crumb sticks to surfaces, such as the mouth, teeth, or equipment. Resilience characterizes the beginning of a sample's elasticity, and springiness is associated with freshness; products with low values are linked with crumb brittleness [52]. Adhesiveness

decreased with WPP incorporation, from 0.56 ± 0.63 in 0WPP to -0.35 ± 0.75 in 6WPP. In contrast, resilience increased modestly with WPP (from 15.9% to 21.7%), whereas springiness decreased markedly (from 80.7% to 55.8%) and cohesiveness also declined (from 0.467 to 0.245). Adhesiveness is usually due to swelling of amylose [36], and this trend is consistent with the presence of soluble fiber and pectin in WPP, which can reduce stickiness by forming a cohesive gel network that distributes moisture more evenly throughout the crumb [11]. The combination of lower springiness and cohesiveness but slightly higher instantaneous recovery (resilience) is typical of low-volume, fiber-rich crumbs: Elastic rebound upon short-time compression can persist even as the continuous starch gel weakens and the crumb loses its ability to recover shape over longer deformations [33, 37]. Decreases in dough stability and elasticity with citrus peel powders have been documented [39], especially as inclusion increases, and are chiefly attributed to water competition and particle interference with starch-based network formation.

The increased cohesiveness observed in WPP-containing formulations could be attributed to the high dietary fiber content of WPP, particularly its insoluble fiber fraction, which possesses a strong capacity to bind and retain water within the batter matrix. The hydrated fiber network may have increased batter viscosity and facilitated the formation of a more continuous and interconnected structure capable of entrapping starch granules and air cells during baking. Consequently, the crumb exhibited greater internal structural integrity and resistance to fracture during compression, resulting in higher cohesiveness and compressibility. Similar improvements in crumb cohesion have been reported in gluten-free breads enriched with fiber-rich fruit and vegetable by-products, where enhanced water retention and fiber-starch interactions strengthened the crumb matrix [30, 40, 41]. Nevertheless, excessive fiber incorporation may compete with starch for available water, restricting starch gelatinization and gas cell expansion, thereby producing a denser crumb with increased firmness despite improved structural cohesion [42, 43].

Gumminess decreased with WPP incorporation (from 819 to 466), mirroring the trend observed for hardness. Chewiness decreased slightly at 3% WPP substitution (from 1388 to 1288) but increased sharply at 6% (4564 ± 146), representing an approximately 3.3-fold rise. This spike in chewiness at 6% corresponds to the markedly low specific volume: A dense, compact crumb can require disproportionately greater masticatory energy even when instrumental hardness at small deformation is relatively low. Similar behavior has been reported in high-fiber bakery systems where excessive substitution disrupts gas-cell expansion, leading to collapsed structures and dense, rubbery crumbs [46, 52].

The TPA results align with a broader literature showing that fruit peel fibers such citrus/orange and banana enrich food matrices with dietary fiber and phenolics but reduce loaf volume and alter texture [33, 39]. For orange peel ingredients, for example, extruded dietary fiber concentrate at 5%–10% maintained technological performance better than unprocessed peel and improved biscuit textural shelf-life; for gluten-free matrices, peel-fortified products (cookies, muffins, and breads) showed

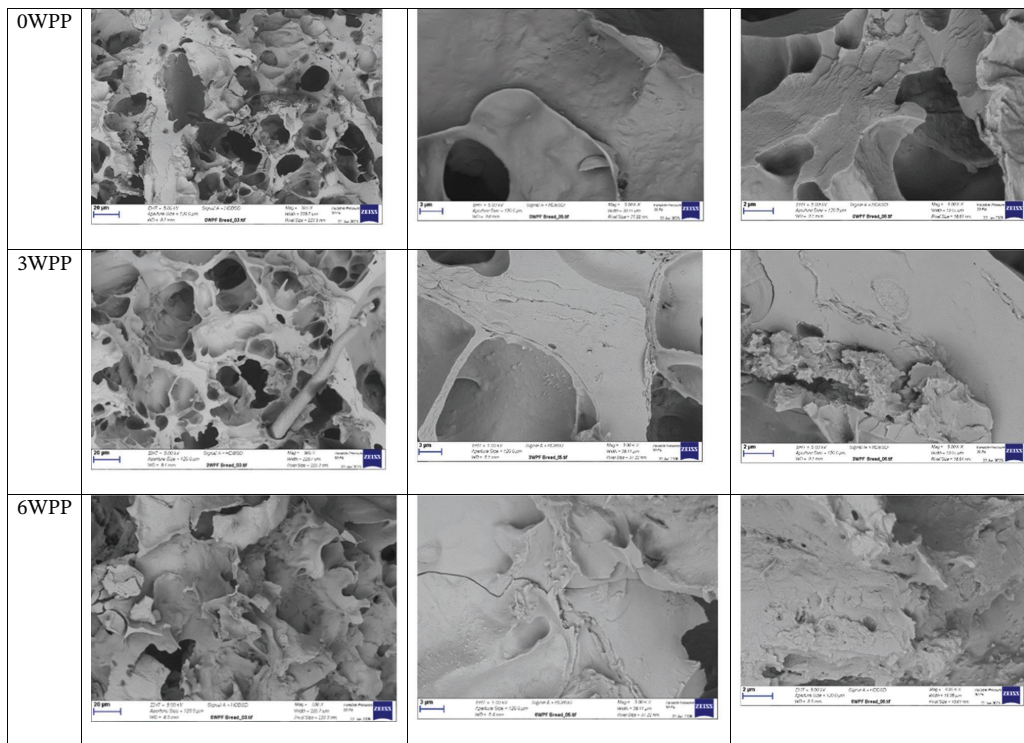


FIGURE 7 | SEM micrographs of gluten-free breadcrumb. 0WPP, 100% cassava flour; 3WPP, cassava flour substituted with 3% WPP; 6WPP, cassava flour substituted with 6% WPP; WPP, watermelon peel powder, at $\times 500$, $\times 3000$, and $\times 6000$ magnifications.

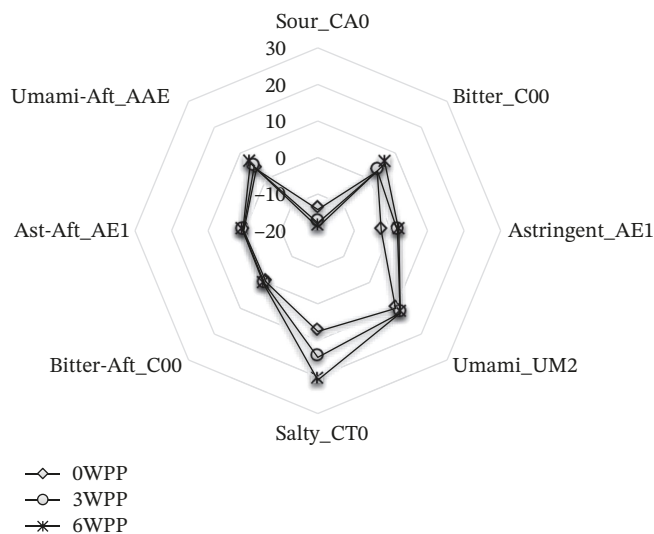


FIGURE 8 | E-tongue radar plot showing the taste-related profiles of 0WPP, 3WPP, and 6WPP gluten-free breads.

antioxidant gains with acceptable sensory quality at 5%–10% substitution when processing aids were used (sourdough fermentation and encapsulation) [49].

3.6.3 | Crumb Microstructure

The SEM images of the formulated gluten-free breads are shown in Figure 7. 0WPP exhibited a relatively uniform pore size

distribution with a continuous starch-based matrix. Gas cells appeared moderately expanded but showed limited interconnectivity, which is characteristic of cassava-based gluten-free breads that rely primarily on starch gelatinization for structure development [20]. Although the crumb structure was cohesive, the absence of reinforcing hydrocolloids or fibers likely contributed to moderate loaf volume and limited gas retention during baking.

Incorporation of 3% WPP resulted in a visibly improved crumb microstructure, characterized by more uniformly distributed pores and thicker, well-defined cell walls. The presence of fibrous WPP particles within the starch matrix appeared to reinforce the crumb structure, enhancing gas cell stability [53]. This structural reinforcement is consistent with the increased specific loaf volume and improved crumb cohesiveness observed for 3WPP breads (Table 5). The improved microstructure can be attributed to the high-water absorption and soluble fiber content of WPP, which promote better hydration and formation of a continuous viscous matrix capable of stabilizing gas bubbles during fermentation and early baking stages [41, 45]. Similar improvements in crumb microstructure have been reported in breads enriched with fruit-derived fibers and pectin-rich by-products such as banana peels [33] and watermelon peel [14].

However, at 6% WPP substitution, the crumb microstructure became more heterogeneous, with irregular pore sizes and localized regions of compacted, fiber-rich matrix. Gas cells appeared smaller and less uniformly distributed, and cell walls were thicker but less elastic, indicating restricted gas

expansion [34]. In addition, competition for water between starch and fiber components may have restricted starch gelatinization, weakening the continuity of the starch matrix [20, 22]. This microstructural pattern is consistent with the reduced loaf volume and increased crumb hardness observed at higher WPP levels (Table 5). This indicated that moderate WPP incorporation (3WPP) promoted a balanced starch-fiber network that optimized gas retention, crumb structure, and texture. In contrast, higher WPP levels (6WPP) disrupted starch continuity and reduced structural flexibility, resulting in a denser and firmer crumb.

3.6.4 | Instrumental Taste

The electronic tongue radar plot illustrates the effect of WPP substitution on the taste-related profiles of gluten-free bread formulations (Figure 8). The responses, sourness (CA0), bitterness (C00), astringency (AF1), umami (UM2), saltiness (CT0), and their corresponding aftertaste responses, revealed distinct and concentration-dependent modifications in taste attributes, indicating that WPP incorporation significantly ($p < 0.05$) influenced the overall flavor profile of the breads.

Sourness (CA0) showed minimal variation among samples (ranging from -14.206 to -19.046), with all formulations exhibiting values close to 0WPP. This suggests that the incorporation of WPP did not substantially increase organic acid perception, consistent with previous reports indicating that watermelon peel contains relatively low levels of free organic acids compared to other fruit by-products [15, 17, 36]. This stability in sourness is technologically advantageous, as excessive acidity is often detrimental to consumer acceptance of gluten-free baked products [53].

In contrast, bitterness (C00) and bitter aftertaste (C00-Aft) increased progressively with higher WPP substitution, with 6WPP exhibiting the strongest responses at 5.982 and -0.829 , respectively. This trend is attributable to the presence of phenolic compounds and flavonoids naturally occurring in watermelon peels [14, 36]. Notably, Al-Sayed and Ahmed [17] reported that watermelon rind contained high phenolic content due to the presence of abundant active components such as 4-hydroxybenzoic acid, vanillin, chlorogenic acid, sinapinic acid, P-anisic acid, hydroxycinnamic acid, caffeic acid, cinnamic acid, syringic acid, and coumaric acid. Similarly, Rezagholizade-Shirvan et al. [9] reported significant differences in the perceived sweetness of watermelon rind candies dried at 60°C with 50% sugar concentration for 1 h and at 40°C with 70% sugar concentration for 5 h, indicating that drying conditions can influence the taste characteristics of watermelon peel-based products. Similar dose-dependent increases in bitterness have been reported in breads and bakery products fortified with fruit peel powders and polyphenol-rich fibers [10, 12, 53].

Similarly, astringency (AF1) followed a comparable increasing trend with WPP level from -2.661 (0WPP) to 2.156 (6WPP). Astringent perception is commonly associated with interactions between dietary fiber or polyphenols and salivary proteins, leading to reduced lubrication and mouthfeel changes [16, 53]. The

elevated astringency at higher WPP inclusion aligns with the increased IDF and phenolic content of the composite flours, as confirmed by proximate composition (Table 1) and FTIR analyses (Figure 5).

Umami (UM2) and umami aftertaste (UM-Aft) responses increased noticeably with WPP incorporation, particularly at 6%. This enhancement may be linked to the higher mineral (ash) content and the presence of free amino acids or organic salts in watermelon peel, which are known to contribute to umami perception [10]. The observed increase in umami suggests a potential flavor-enhancing effect of WPP, which may partially offset bitterness and improve overall taste complexity in gluten-free bread formulations.

Saltiness (CT0) also increased in a concentration-dependent manner, with 6WPP showing the highest response. This finding is consistent with the elevated mineral content of WPP and supports previous observations that mineral-rich plant by-products can enhance perceived saltiness in food systems [36, 53]. From a formulation perspective, this effect may be advantageous for reducing added sodium in gluten-free products without compromising flavor intensity [52, 53].

The electronic tongue results demonstrate that WPP incorporation induces systematic and predictable changes in taste-related attributes. While higher substitution levels intensified bitterness and astringency, moderate inclusion (3% WPP) achieved a balanced sensory profile with enhanced umami and saltiness and limited negative taste impacts. These findings reinforce the suitability of WPP as a functional ingredient in gluten-free bread when applied at optimized levels and highlight the usefulness of e-tongue analysis as an objective tool for screening flavor modifications in novel food formulations. Although the electronic tongue provided objective discrimination of taste attributes among formulations, future studies involving sensory panelists and consumer acceptance testing are recommended to validate the instrumental responses and assess market acceptability.

4 | Conclusion

This study is aimed at converting watermelon peel, an underutilized processing by-product, into a functional powder (WPP) and at evaluating its technofunctional, pasting, and microstructural properties, as well as its performance in cassava-based gluten-free bread formulations. WPP exhibited a porous, fibrous microstructure and abundant hydrophilic functional groups, as revealed by SEM and FTIR analyses, which underpin its high-water absorption and solubility. At moderate inclusion levels (3% WPP), the powder blend achieved desirable pasting properties and breads displayed optimal performance in terms of specific loaf volume, with a softer and more cohesive crumb. However, higher incorporation (6% WPP) limited starch gelatinization, and produced a denser, firmer crumb with reduced volume, highlighting the importance of balancing WPP to achieve desirable product quality. Although the present study provides a comprehensive evaluation of the physicochemical, structural, and technological properties of WPP and its application in gluten-free bread,

further investigations should quantify phenolic compounds, antioxidant capacity, mineral composition, and SDF and IDF fractions using advanced analytical techniques. In addition, sensory evaluation, storage stability, rheological and thermal analyses, in vitro starch digestibility, and pilot-scale production studies are warranted to support the commercial implementation and consumer acceptance of WPP.

Author Contributions

Mary Nkongho Tanyitiku: conceptualization, methodology, investigation, formal analysis, funding acquisition, supervision, writing – original draft, writing – review and editing. **Rakshya Pandit:** conceptualization, validation, writing – review and editing. **Saritha Kagula:** conceptualization, formal analysis, writing – review and editing. **Srivathsa Kumbaji:** conceptualization, methodology, data curation, investigation, formal analysis, validation, writing – review and editing.

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Consent

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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