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Valorization of Potato, Cassava, and Yam Starch Extraction Residues in Wheat Bread: Effects on Dough Extensibility, Expansion, Crumb Structure, Texture, and Consumer Acceptance

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Abstract

Starch extraction generates solid residues that could be valorized as alternative ingredients in bakery products. This study evaluated potato, cassava, and yam starch extraction residue flours as partial substitutes for wheat flour in bread at 15, 25, and 35% replacement. Residue flours were characterized for proximate composition, particle size distribution, and physicochemical properties, and their incorporation was evaluated through dough extensibility, bread quality, and consumer acceptance. Potato residue flour exhibited water retention and swelling capacities of 74.12% and 22.49 mL/g, respectively, compared with 56.41% and 6.53 mL/g for cassava and 64.79% and 12.24 mL/g for yam. At 15% substitution, cassava-containing dough showed no significant difference in extensibility relative to the control (89.09 versus 85.34 mm), whereas potato and yam formulations showed reductions of approximately 12% and 21%, respectively. At 35% substitution, extensibility decreased by 30–43% across the formulations. Bread expansion decreased with all three residue flours. At 35% replacement, the crumb cell area fraction decreased by 81% and 66% in potato- and cassava-containing breads, respectively, whereas yam formulations showed no significant differences from the control throughout the substitution range. Potato substitution increased hardness by 168% and 121% at 25% and 35% replacement, respectively, whereas cassava formulations showed reductions of approximately 19–32% relative to the control. Moisture and water activity showed no significant changes. Favorable sensory ratings were observed for potato at 15%, cassava at 15–25%, and yam at 25–35% substitution. These findings identify opportunities for incorporating starch extraction residues into bread under a fixed-water formulation, with substitution levels selected according to the technological and sensory responses of each residue flour.

Keywords: agro-industrial by-product; bagasse; circular food processing; bread; dough extensibility; root and tuber residues

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1. Introduction

Roots and tubers, including potato, cassava, and yam, are strategically important crops in tropical, subtropical, and Andean food systems because they contribute to food security, dietary energy supply, rural livelihoods, and agro-industrial development [1,2].

Their relevance extends beyond their role as staple foods, as they also contribute to the resilience of production systems exposed to climatic variability, limited soil fertility, and restricted access to agricultural inputs [2]. Cassava, in particular, is an important food source for more than 600 million people, while potato and yam also play major roles in regional diets and agricultural economies [2–4]. Their adaptability to diverse agroecological conditions, together with their high carbohydrate content and processing versatility, has supported their use not only for direct consumption but also as raw materials for flours, starches, fermented foods, snacks, and several industrial products [5–8].

The increasing transformation of these crops also generates substantial secondary biomass streams [6,7]. During starch extraction, mechanical disintegration and separation produce a starch-rich liquid phase and a moist fibrous fraction commonly referred to as pulp, bagasse, pomace, or bran [7]. In cassava starch production, for example, approximately 928.6 kg of wet fibrous residue is reportedly generated per ton of roots processed [9]. At industrial scale, such volumes can rapidly become a handling and disposal challenge when no subsequent use is established. The issue is particularly relevant because starch-processing residues are generated continuously and usually leave the process with high moisture contents, which restrict storage and favor rapid deterioration [10,11].

From this perspective, stabilization and subsequent utilization of these residues can contribute to a more efficient use of root- and tuber-derived biomass. Drying reduces their susceptibility to deterioration, while milling transforms the stabilized material into flour-like ingredients that are easier to store, handle, and incorporate into further processing [10,11]. Their incorporation into food formulations is particularly attractive because it provides a direct route for returning part of the material generated during primary processing to the food chain. However, the environmental benefits of this approach depend partly on the energy required for stabilization. Life cycle assessment studies addressing the carbon footprint of potato pulp valorization and bakery surplus upcycling highlight the importance of processing energy and the conventional products replaced [12,13]. Alongside these environmental considerations, the technological suitability of residue flours requires evaluation, since differences in botanical source and processing conditions may influence their performance in food manufacture.

Bread is a practical food matrix for the valorization of plant-derived side streams because partial flour replacement can be introduced within conventional breadmaking while allowing the technological consequences of ingredient substitution to be assessed under a well-established processing system. Previous studies have explored the incorporation of root- and tuber-derived materials into bakery products, including potato pulp, tuber flours, peels, and other processing residues, mainly as strategies to increase the utilization of underused biomass and introduce additional functional components into cereal-based foods [5,14]. However, the reported effects on dough and bread quality are highly variable and depend on the botanical source, the nature of the material, the processing history, and the level of incorporation [14]. Moreover, several works in the available literature have focused on whole flours or other tuber-derived ingredients rather than specifically on the fibrous residues generated during starch extraction [15,16].

This study compared flours produced from potato, cassava, and yam starch extraction residues under a common processing protocol. The objective was to determine how botanical source and wheat flour replacement level affect residue functionality, dough extensibility, bread expansion, crumb structure, texture, and consumer acceptance. The working hypothesis was that the maximum technically useful replacement level would depend on the source-specific hydration and structural properties of each residue.

2. Materials and Methods

2.1. Raw Materials

Potato (*Solanum tuberosum* L., Diacol Capiro R12) was obtained from Ventaquemada, Boyacá, Colombia; cassava (*Manihot esculenta* Crantz, Venezuelan cultivar MCol 2215) was obtained from El Carmen de Bolívar, Bolívar, Colombia; and yam (*Dioscorea* spp., Espino cultivar) was obtained from Pueblo Nuevo, Córdoba, Colombia. Roots and tubers without visible physiological or microbial damage were washed and disinfected in 100 mg L^{-1} sodium hypochlorite for 10 min.

Commercial type 000 wheat flour (Molinos San José, Duitama, Colombia), dry yeast (Levapan, Bogotá, Colombia), white sugar (Mayagüez, Candelaria, Colombia), iodized salt (Refisal, Cajicá, Colombia), and margarine (Don Olio, Bogotá, Colombia) were purchased from the local market.

2.2. Production of Starch Extraction Residue Flours

The cleaned roots and tubers were peeled, cut, and immersed in a 1% w/v citric acid solution to limit enzymatic browning. Each material was pulped using a Wurden electric juice extractor (model WJE-DCSS, Falabella S.A., Santiago, Chile), producing a starch-rich liquid fraction and a fibrous solid residue. The potato, cassava, and yam starch extraction residues were filtered and manually pressed to remove excess liquid, spread in layers <5 mm thick, and dried in a forced convection oven (Memmert, model UF110, Schwabach, Germany) at 50 °C, with the fan set to 80%, until the moisture content was below 13%. Drying conditions were established through preliminary laboratory trials, following previously reported drying procedures for starch extraction residues [17,18].

The dried material was milled using an electric grinder (Cuisinart, model DCG-20BKN, Stamford, CT, USA), passed through a No. 120 test sieve with a nominal aperture of 125 µm according to ASTM E11-24 [19], and stored in sealed bags until use. Flour yield was calculated as the percentage ratio between the mass of dried residue flour obtained after processing and the initial mass of the peeled raw material.

2.3. Characterization of Residue Flours

The proximate composition of the starch extraction residue flours was determined using the methods of the Association of Official Analytical Chemists (AOAC) [20]. Analyses included moisture, ash, crude protein (N × 6.25), lipids, and crude fiber contents. Carbohydrate content was calculated by difference.

Particle size distributions of the starch extraction residue flours were determined using a Mastersizer 3000 laser diffraction particle size analyzer (Malvern Panalytical, Malvern, UK). Samples were dispersed in water using a dispersant refractive index of 1.330. Distributions were calculated using the Mie scattering model and expressed on a volume basis. The volume-weighted mean diameter, D [4,3], and the cumulative volume percentiles Dv10, Dv50, and Dv90 were obtained directly from the instrument reports. These percentiles represent the diameters below which 10%, 50%, and 90% of the particle volume occurs, respectively. Distribution width was expressed as the span, calculated as $(Dv90 - Dv10)/Dv50$.

Water activity (a_w) was measured with an Aqualab instrument (Decagon Devices, Pullman, WA, USA). Color was measured using a CR-10 tristimulus colorimeter (Konica Minolta, Osaka, Japan), calibrated with a white reference plate before measurement. Results were expressed as CIELAB coordinates: L* indicates lightness, a* represents the green

(negative)–red (positive) axis, and b* represents the blue (negative)–yellow (positive) axis. Chroma (C) and hue angle (h°) were calculated using Equations (1) and (2), respectively:

$$C = \left((a^*)^2 + (b^*)^2\right)^{1/2} \quad (1)$$

$$h^\circ = \tan^{-1}\left(\frac{b^*}{a^*}\right) \quad (2)$$

Water retention capacity was determined with 1.0 g of flour dispersed in 10 mL of distilled water. The suspension was vortexed for 2 min, held for 30 min, and centrifuged at 3500 rpm for 25 min. The supernatant was decanted, and the tube was drained at 45° for 10 min. Water retention was expressed as the mass gain of the hydrated sediment relative to the dry sample, multiplied by 100.

Water solubility was determined from solids recovered after drying the supernatant at 105 °C for 24 h and was expressed relative to the initial sample mass.

Swelling capacity was determined as reported in previous works [21,22]. Briefly, 0.5 g of residue flour was placed in a graduated Falcon tube, and the initial volume occupied by the sample was recorded. Then, 5 mL of distilled water was added, the mixture was shaken, and allowed to stand for 24 h. After hydration, the final sample volume was recorded. Swelling capacity was calculated using Equation (3):

$$\text{Swelling capacity (mL/g)} = (V_f - V_i)/m \quad (3)$$

where V_f and V_i are the final hydrated sample volume and initial sample volume (mL), respectively, and m is the sample mass (g).

2.4. Bread Formulation and Processing

The control breads and breads containing potato, cassava, or yam starch extraction residue flour were prepared using a formulation adapted from a previous study, with partial flour replacement and fixed water addition at 60 g per 100 g of total flour to compare the effects of residue source and replacement level under the same formulation and processing conditions [23]. The products were small, rounded breads prepared with added sugar and margarine (12 g each per 100 g of total flour) and baked on trays.

Wheat flour was replaced with each starch extraction residue flour at 15%, 25%, or 35% of total flour mass. All other ingredients were maintained at constant levels on a total flour basis (Table 1).

Table 1. Bread formulations expressed as g per 100 g of total flour.

Ingredient	Control	15% Replacement	25% Replacement	35% Replacement
Wheat flour	100	85	75	65
Starch extraction residue flour	0	15	25	35
Salt	2	2	2	2
Sugar	12	12	12	12
Dry yeast	4	4	4	4
Margarine	12	12	12	12
Water	60	60	60	60

The dry ingredients were mixed in a RECCO mixer–kneader (model RMP-1129S, Falabella S.A., Santiago, Chile) for 10 min. Dough was fermented at 30 °C and 80% relative humidity for 60 min under plastic film, manually degassed for 2 min, divided

into 20 g portions, rounded, and proofed for 30 min on greased trays. The pieces were baked in a forced convection oven (Memmert, model UF110, Schwabach, Germany) at 190 °C and 30% ventilation for 13 min. Breads were cooled at room temperature before analysis. Texture profile analysis was performed 2 h after removal from the oven. Samples reserved for the remaining analyses were kept in sealed polyethylene bags after cooling. All physicochemical, crumb structure, and sensory evaluations were performed on the day of baking. Three independent breadmaking batches were prepared for each formulation. Each batch yielded 15 bread units, resulting in 45 units per formulation.

2.5. Dough Extensibility and Bread Expansion

Dough extensibility was measured using a uniaxial tensile test [24]. Dough strips (100 mm × 15 mm × 3 mm) were analyzed after fermentation with a CTX texture analyzer (AMETEK Brookfield, Middleboro, MA, USA), a 10 kg load cell, a hook attachment, a test speed of 3.3 mm s^{-1}, and a trigger force of 5 g. Six dough extensibility measurements were performed per independent batch, resulting in 18 measurements per formulation. The expansion factor was calculated as the ratio of baked bread volume to the initial volume of the dough piece.

2.6. Bread Physicochemical Properties

Bread moisture and water activity were determined as described for the residue flours. Crumb pH was measured directly using a conical solid sample pH electrode (Hanna Instruments, model FC230B, Woonsocket, RI, USA) connected to a benchtop pH meter (Hanna Instruments, model HI5521, Woonsocket, RI, USA). Color was measured separately on bread crust and crumb using a CR-10 tristimulus colorimeter (Konica Minolta, Osaka, Japan). Results were expressed as CIELAB L*, a*, and b* coordinates.

2.7. Crumb Image Analysis

Digital images of transverse bread sections were analyzed using ImageJ2 software (National Institutes of Health, Bethesda, MD, USA). Image brightness was standardized before conversion to grayscale. A fixed black-and-white threshold was then applied to distinguish the solid crumb matrix (white regions) from gas cell spaces (black regions). Crumb cell area was determined as the percentage of the total bread slice area occupied by gas cells.

2.8. Texture Profile Analysis

Texture profile analysis was performed on whole breads 2 h after removal from the oven, allowing them to cool to room temperature before testing. Measurements were conducted using a texture analyzer (AMETEK Brookfield, model CTX, Middleboro, MA, USA), following a double compression approach previously used for instrumental texture evaluation of bread products [25,26]. Each bread was subjected to two compression cycles using a 60 mm circular compression probe and a 10 kg load cell at a test speed of 1 mm s^{-1}. Fracturability, hardness, cohesiveness, springiness, gumminess, and chewiness were obtained from the force–time curves. Five whole breads from each independent batch were analyzed, resulting in 15 texture measurements per formulation.

2.9. Consumer Acceptance

Consumer acceptance was evaluated with a nine-point hedonic scale, where 1 represents “dislike extremely”, 5 represents “neither like nor dislike”, and 9 represents “like extremely”. A total of 150 untrained consumers aged 20–50 years participated in Duitama, Boyacá, Colombia. Each consumer received four samples: the wheat control and the breads containing 15%, 25%, and 35% residue flour. Samples were prepared on the day of

evaluation, served at room temperature on white disposable plates, coded with random three-digit numbers, and presented in randomized order. Water was provided for palate cleansing. Overall acceptability, color, flavor, texture, and aroma were evaluated.

The consumer acceptance study was conducted in accordance with Resolution 008430 of 1993 of the Colombian Ministry of Health governing research involving human participants. The research project received institutional funding through UPTC's VIE Call 08 of 2025, which included ethical requirements and assigned ethical review responsibilities to the university's Research Ethics Committee. Informed consent was obtained from all participants before the evaluation. Participation was voluntary, and participants could withdraw at any time. Collected data were handled in accordance with applicable personal data protection regulations and used exclusively for research purposes.

2.10. Statistical Analysis

Results are reported as means ± standard deviations. For each response, formulations were compared by one-way analysis of variance followed by Tukey's honestly significant difference test at a 95% confidence level. Analyses were performed in Minitab version 16 (Minitab LLC, State College, PA, USA).

3. Results and Discussion

3.1. Proximate Composition, Yield, and Physicochemical Properties of Residue Flours

Proximate analysis showed significant differences among residue flours in crude protein, ash, and crude fiber contents, whereas moisture contents and total fat did not differ significantly (Table 2). Yam residue flour had the highest crude protein, ash, and crude fiber contents. Potato residue flour contained more crude protein than cassava residue flour, but less ash and crude fiber. The protein and ash contents of cassava residue flour were close to those reported for industrial cassava bagasse, although the latter contained substantially more crude fiber [10]. Conversely, higher protein and ash contents have been reported for potato pulp recovered after starch isolation [27]. The protein content of yam residue flour was also close to values reported for whole-tuber yam flours [28]. Carbohydrates have also been reported as the predominant component of potato-, cassava-, and yam-derived flours and processing residues [10,27,28].

Table 2. Proximate composition of starch extraction residue flours.

Residue Flour	Moisture (g/100 g Sample)	Crude Protein (g/100 g Dry Matter)	Total Fat (g/100 g Dry Matter)	Ash (g/100 g Dry Matter)	Crude Fiber (g/100 g Dry Matter)	Carbohydrates (g/100 g Dry Matter)
Potato	9.89 ± 0.69 ^{a}	2.64 ± 0.14 ^{b}	0.06 ± 0.01 ^{a}	1.22 ± 0.01 ^{c}	1.17 ± 0.05 ^{c}	94.91 ± 0.10 ^{a}
Cassava	10.32 ± 0.45 ^{a}	1.61 ± 0.13 ^{c}	0.17 ± 0.05 ^{a}	1.70 ± 0.01 ^{b}	2.20 ± 0.16 ^{b}	94.31 ± 0.32 ^{a}
Yam	9.56 ± 0.31 ^{a}	6.24 ± 0.17 ^{a}	0.16 ± 0.03 ^{a}	2.18 ± 0.01 ^{a}	3.10 ± 0.02 ^{a}	88.31 ± 0.17 ^{b}

Values are mean ± standard deviation. Different superscript letters within a column indicate significant differences ($p < 0.05$).

Flour yields ranged from 20.0% for yam to 24.2% for cassava (Table 3). Potato and cassava yields did not differ significantly, whereas yam produced less dried flour. These differences are consistent with the influence of botanical source, proximate composition, tissue structure, and starch extractability on the amount of solid residue recovered during starch processing [29]. Residue yields of approximately 20% of the processed raw material have also been reported for cassava bagasse [30].

Table 3. Yield and physicochemical and hydration properties of starch extraction residue flours.

Residue Flour	Yield (%)	Moisture (%)	Water Activity (a_w)	Water Retention (%)	Swelling Capacity (mL/g)	Water Solubility (%)
Potato	23.4 ± 1.2 [a]	9.89 ± 0.69 [a]	0.36 ± 0.02 [a]	74.12 ± 0.58 [a]	22.49 ± 1.08 [a]	7.27 ± 0.19 [a]
Cassava	24.2 ± 1.5 [a]	10.32 ± 0.45 [a]	0.46 ± 0.01 [a]	56.41 ± 0.38 [b]	6.53 ± 1.05 [b]	9.81 ± 0.06 [b]
Yam	20.0 ± 1.0 [b]	9.56 ± 0.31 [a]	0.46 ± 0.02 [a]	64.79 ± 0.55 [c]	12.24 ± 1.03 [c]	8.99 ± 0.10 [c]

Values are means ± standard deviations. Different superscript letters within a column indicate significant differences ($p < 0.05$).

The particle size distributions of potato, cassava, and yam starch extraction residue flours are shown in Figure 1. The volume-weighted mean diameters (D [4,3]) were 67.57, 21.18, and 28.42 µm for potato, cassava, and yam residue flours, respectively. The corresponding Dv10, Dv50, and Dv90 values were 17.27, 46.83, and 152.01 µm for potato; 8.11, 15.29, and 35.56 µm for cassava; and 12.74, 26.10, and 47.88 µm for yam. Potato residue flour exhibited the broadest relative distribution, with a span of 2.88, consistent with the broad curve and shoulder around 90–120 µm visible in Figure 1. Cassava and yam residue flours had spans of 1.80 and 1.35, respectively, indicating a narrower relative distribution for yam despite its larger median diameter.

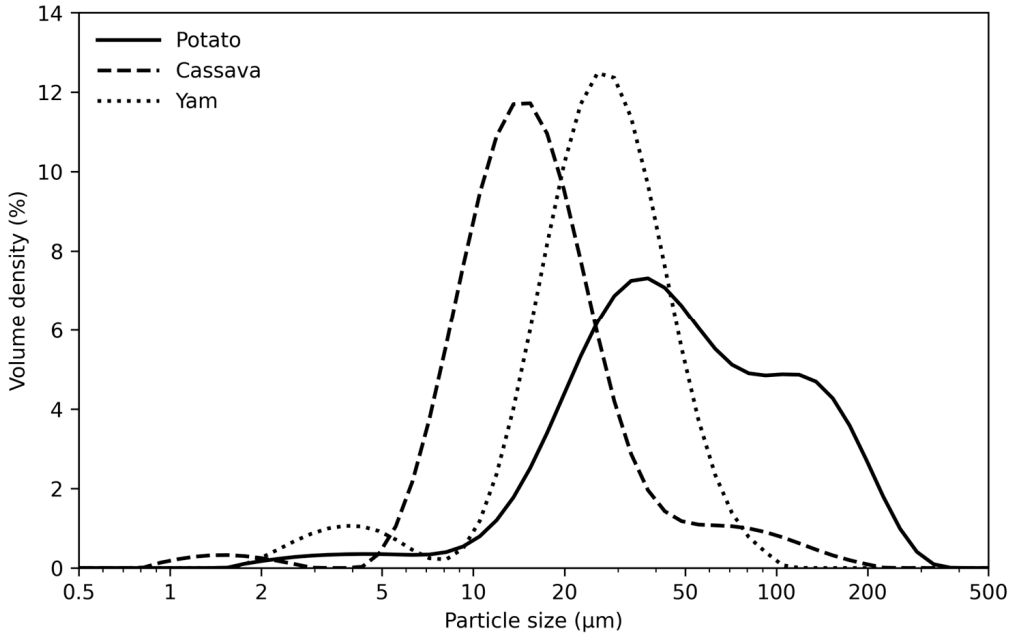


Figure 1. Volume-based particle size distributions of potato, cassava, and yam starch extraction residue flours.

Water activity values ranged from 0.36 to 0.46, with no significant differences among botanical sources (Table 3). Potato residue flour showed the highest water retention and swelling capacities and the lowest water solubility, whereas cassava residue flour presented the lowest retention and swelling capacities but the highest solubility (Table 3). Yam residue flour exhibited intermediate values for all three properties. The greater hydration capacity of potato residue flour is consistent with previous studies showing that the functionality of potato starch-processing residues varies with their composition and particle structure [31,32]. In the present study, potato residue flour combined the largest volume-weighted mean diameter and broadest relative particle size distribution with the lowest crude fiber content, yet exhibited the highest water retention and swelling capacities.

Conversely, cassava residue flour had the smallest mean diameter but the lowest retention and swelling capacities. These observations suggest that hydration behavior depends on the combined physical and compositional characteristics of the residues.

All residue flours showed high lightness values (L* > 85). Potato residue flour was significantly lighter than yam, whereas cassava showed an intermediate L* value that did not differ significantly from either material (Table 4). No differences were detected in a* or hue angle. Cassava presented higher b* and chroma values than potato and yam, indicating a more pronounced and saturated yellow component. Comparable variations in lightness and yellowness have been reported among tuber-derived flours as a function of botanical source, cultivar, compositional characteristics, and processing conditions [30,33,34].

Table 4. CIELAB color coordinates of starch extraction residue flours.

Residue Flour	*L**	*a**	*b**	Chroma	Hue Angle (°)
Potato	89.11 ± 1.17 ^{a}	1.30 ± 0.50 ^{a}	5.90 ± 0.60 ^{a}	6.05 ± 0.60 ^{a}	77.20 ± 4.70 ^{a}
Cassava	88.55 ± 3.81 ^{ab}	1.55 ± 0.73 ^{a}	7.00 ± 0.87 ^{b}	7.20 ± 0.90 ^{b}	77.51 ± 5.40 ^{a}
Yam	85.78 ± 1.40 ^{b}	1.11 ± 0.33 ^{a}	5.67 ± 0.87 ^{a}	5.79 ± 0.83 ^{a}	78.60 ± 4.25 ^{a}

Values are means ± standard deviations. Different superscript letters within a column indicate significant differences ($p < 0.05$).

3.2. Effect of Residue Flour Incorporation on Dough Extensibility

Residue flour incorporation affected dough extensibility differently depending on botanical source and substitution level (Table 5). At 15% substitution, cassava residue dough did not differ significantly from the wheat control, whereas potato and yam residues reduced extensibility to 75.18 and 67.74 mm, respectively. At 25% and 35%, all residue-containing doughs showed lower extensibility than their corresponding controls. Within each botanical series, no additional significant reduction occurred between 25% and 35%.

Table 5. Dough extensibility as affected by residue source and replacement level.

Replacement Level	Extensibility (mm)		
	Potato	Cassava	Yam
0%	85.34 ± 2.41 ^{a}	85.34 ± 2.41 ^{a}	85.34 ± 2.41 ^{a}
15%	75.18 ± 6.90 ^{b}	89.09 ± 3.79 ^{a}	67.74 ± 4.67 ^{b}
25%	59.11 ± 5.23 ^{c}	58.15 ± 5.25 ^{b}	54.40 ± 3.44 ^{c}
35%	59.98 ± 4.05 ^{c}	52.42 ± 3.98 ^{b}	48.58 ± 2.36 ^{c}

Values are means ± standard deviations. Different superscript letters within a botanical source column indicate significant differences ($p < 0.05$).

The reduction in extensibility at the two highest substitution levels is consistent with the combined effects of wheat flour replacement and changes in water distribution within the dough. Partial replacement with non-wheat material can dilute and interrupt the continuous gluten network [35,36], while the water-binding capacity of the added ingredients may influence water availability for gluten hydration and dough deformation [37,38].

The preservation of extensibility at 15% cassava residue substitution coincided with its smaller particle size descriptors and lower water retention and swelling capacities. Under the fixed-water formulation (Table 1), this combination may have influenced water distribution and particle interactions within the dough. At higher substitution levels, extensibility decreased within all three residue sources, consistent with the reduced proportion of wheat flour and increased incorporation of non-gluten material.

3.3. Bread Expansion and Crumb Structure

Residue flour incorporation reduced bread expansion relative to the wheat control (Table 6). For potato residue breads, expansion decreased progressively up to 25% substitution, with no additional significant change at 35%. Breads containing cassava or yam residue also showed lower expansion than the control, but no significant differences were observed among the three substitution levels.

Table 6. Bread expansion factor and crumb cell area fraction as affected by residue source and replacement level.

Replacement Level	Expansion Factor			Crumb Cell Area (%)		
	Potato	Cassava	Yam	Potato	Cassava	Yam
0%	1.55 ± 0.17 ^{a}	1.55 ± 0.17 ^{a}	1.55 ± 0.17 ^{a}	23.08 ± 1.56 ^{a}	23.08 ± 1.56 ^{a}	23.08 ± 1.56 ^{a}
15%	1.33 ± 0.06 ^{b}	1.22 ± 0.04 ^{b}	1.35 ± 0.03 ^{b}	19.57 ± 4.95 ^{a}	6.88 ± 0.77 ^{b}	16.64 ± 1.64 ^{a}
25%	1.11 ± 0.05 ^{c}	1.24 ± 0.03 ^{b}	1.34 ± 0.04 ^{b}	14.87 ± 1.00 ^{a}	7.71 ± 0.75 ^{b}	17.95 ± 2.80 ^{a}
35%	1.19 ± 0.08 ^{c}	1.23 ± 0.06 ^{b}	1.34 ± 0.07 ^{b}	4.29 ± 0.77 ^{b}	7.76 ± 1.15 ^{b}	18.16 ± 2.48 ^{a}

Values are means ± standard deviations. Different superscript letters within a botanical source column indicate significant differences ($p < 0.05$).

The lower expansion of the substituted breads is consistent with previous studies showing that partial replacement of wheat flour with tuber-derived ingredients can reduce gas retention during proofing and baking, thereby limiting bread expansion [39,40]. For cassava and yam residues, increasing the substitution level from 15% to 35% did not cause an additional reduction in expansion.

Crumb cell area provided complementary information on the internal bread structure. Within the potato residue formulations, crumb cell area did not differ significantly from the control at 15% and 25% substitution, whereas a significant reduction was observed at 35%. In contrast, within the cassava residue formulations, all substitution levels showed significantly lower crumb cell area fractions than the control, with no significant differences among the substituted formulations. Comparable changes in gas cell organization have been reported in cassava–wheat and high-fiber bakery systems [41–43]. Breads containing yam residue showed no significant differences in crumb cell area relative to the control or among substitution levels, indicating that this structural attribute was preserved throughout the evaluated range. The smaller mean particle diameter of cassava residue flour was accompanied by a reduced crumb cell area fraction at all substitution levels relative to the wheat control. In breads containing potato residue, which had a broader particle size distribution, a significant reduction occurred only at 35% substitution. These patterns suggest that crumb structure reflects the combined influence of particle size distribution, residue composition, and hydration behavior rather than particle size alone.

3.4. Bread Moisture, Water Activity, pH, and Color

Moisture content and water activity did not differ significantly from the wheat control or among substitution levels within each residue source (Table 7).

In contrast, all residue-containing breads showed significantly lower pH than the control. Breads containing cassava or yam residue had lower pH at 25% and 35% substitution than at 15%, with no significant difference between the two higher levels. For breads containing potato residue, no significant differences in pH were detected among substitution levels. This decrease was probably associated with residual citric acid from the pretreatment used to limit enzymatic browning, since the residues were dried without a neutralization step [44]. Bread quality is governed by several interacting formulation and processing factors, including ingredient source, hydration behavior, acidity, proofing, gas

retention, and crumb cell development [45]. In the present study, the pH pattern did not parallel the technological responses described above. Potato residue breads showed no significant pH differences among substitution levels, although expansion and crumb cell area changed with residue level. Conversely, cassava and yam residue breads showed lower pH at 25% and 35% than at 15%, but expansion and crumb cell area did not decrease further within each residue source. Thus, the lower pH reflects the residue flour pretreatment and formulation conditions, whereas the differences in dough extensibility, bread expansion, and crumb structure were more closely related to the source-dependent functional properties of the residues, especially water retention, swelling capacity, solubility, and their interaction with the gluten–starch matrix and gas cell development during proofing and baking.

Table 7. Moisture, water activity, and pH of breads containing starch extraction residue flours.

Residue Source	Replacement Level (%)	Moisture (%)	Water Activity (*a*w)	pH
Potato	0	34.34 ± 1.46 ^{a}	0.89 ± 0.03 ^{a}	5.48 ± 0.14 ^{a}
	15	36.19 ± 0.57 ^{a}	0.93 ± 0.01 ^{a}	5.14 ± 0.04 ^{b}
	25	35.42 ± 0.13 ^{a}	0.91 ± 0.02 ^{a}	4.34 ± 0.04 ^{b}
	35	34.35 ± 0.51 ^{a}	0.93 ± 0.08 ^{a}	4.05 ± 0.03 ^{b}
Cassava	0	34.34 ± 1.46 ^{a}	0.89 ± 0.03 ^{a}	5.48 ± 0.14 ^{a}
	15	37.09 ± 1.01 ^{a}	0.90 ± 0.07 ^{a}	5.14 ± 0.01 ^{b}
	25	35.42 ± 2.48 ^{a}	0.91 ± 0.01 ^{a}	4.64 ± 0.05 ^{c}
	35	33.77 ± 0.87 ^{a}	0.86 ± 0.02 ^{a}	4.54 ± 0.04 ^{c}
Yam	0	34.34 ± 1.46 ^{a}	0.89 ± 0.03 ^{a}	5.48 ± 0.14 ^{a}
	15	36.02 ± 0.57 ^{a}	0.83 ± 0.04 ^{a}	5.29 ± 0.08 ^{b}
	25	35.89 ± 0.69 ^{a}	0.87 ± 0.00 ^{a}	5.05 ± 0.05 ^{c}
	35	35.72 ± 0.23 ^{a}	0.87 ± 0.01 ^{a}	4.91 ± 0.02 ^{c}

Values are means ± standard deviations. Different superscript letters within a column indicate significant differences ($p < 0.05$).

In contrast, residue flour incorporation affected crust lightness and chromatic coordinates differently across substitution levels (Table 8). Potato residue breads showed lower crust L* than the control at 15% and 25% substitution, whereas no significant difference was detected at 35%. All potato residue formulations had lower b* than the control, without significant differences among substitution levels. Crust a* did not differ from the control at 15%, but was higher at 25% and lower at 35%.

The lower crust lightness at 15% and 25% substitution is consistent with observations in breads containing potato flakes, where increased browning was associated with greater availability of Maillard reaction precursors [46]. These reactions may also have contributed to the present color changes, although the absence of a significant L* difference at 35% indicates that crust darkening did not increase consistently with substitution level.

Cassava residue breads showed no significant differences in crust L* or a* relative to the control or among substitution levels. However, b* was higher in all substituted formulations, indicating a more pronounced yellow component. Yam residue breads had lower crust L* and higher a* and b* than the control at all substitution levels, with no significant differences among substituted formulations.

For the crumb, potato residue breads showed no significant differences in L* or a*, whereas b* was lower only at 35% substitution. Cassava residue breads had higher crumb L* at 25% and 35% than the control and the 15% formulation, without significant differences in a* or b*. Yam residue breads showed lower crumb L* and higher a* at 25% and 35%

than the control and the 15% formulation. Their crumb b* was lower than the control at all substitution levels, without significant differences among substituted formulations.

Table 8. CIELAB color coordinates of bread crust and crumb in formulations containing starch extraction residue flours.

Residue Source	Replacement Level (%)	Crust			Crumb		
		L*	a*	b*	L*	a*	b*
Potato	0	62.96 ± 2.32 ^{a}	0.26 ± 1.20 ^{a}	32.32 ± 4.33 ^{a}	61.65 ± 4.37 ^{a}	−1.33 ± 0.89 ^{a}	27.47 ± 4.83 ^{a}
	15	55.03 ± 3.01 ^{b}	−0.83 ± 0.26 ^{a}	24.90 ± 1.50 ^{b}	61.85 ± 3.67 ^{a}	−2.88 ± 0.61 ^{a}	25.17 ± 2.70 ^{a}
	25	53.22 ± 1.48 ^{b}	2.80 ± 1.61 ^{b}	28.23 ± 6.63 ^{b}	66.28 ± 2.78 ^{a}	−3.11 ± 0.33 ^{a}	22.18 ± 0.65 ^{a}
	35	64.51 ± 2.93 ^{a}	−3.68 ± 1.59 ^{c}	28.41 ± 1.51 ^{b}	62.91 ± 1.49 ^{a}	−2.08 ± 0.50 ^{a}	16.85 ± 2.67 ^{b}
Cassava	0	62.96 ± 2.32 ^{a}	0.26 ± 1.20 ^{a}	32.32 ± 4.33 ^{a}	61.65 ± 4.37 ^{a}	−1.33 ± 0.89 ^{a}	27.47 ± 4.83 ^{a}
	15	63.96 ± 1.50 ^{a}	−0.32 ± 0.16 ^{a}	41.31 ± 5.22 ^{b}	66.53 ± 2.85 ^{a}	−2.71 ± 0.39 ^{a}	26.67 ± 1.37 ^{a}
	25	63.96 ± 0.69 ^{a}	−0.46 ± 0.26 ^{a}	38.37 ± 1.56 ^{b}	71.14 ± 0.75 ^{b}	−3.33 ± 0.10 ^{a}	24.14 ± 0.90 ^{a}
	35	64.12 ± 1.39 ^{a}	−0.53 ± 0.30 ^{a}	38.88 ± 1.71 ^{b}	73.74 ± 0.44 ^{b}	−3.53 ± 0.15 ^{a}	26.24 ± 1.32 ^{a}
Yam	0	62.96 ± 2.32 ^{a}	0.26 ± 1.20 ^{a}	32.32 ± 4.33 ^{a}	61.65 ± 4.37 ^{a}	−1.33 ± 0.89 ^{a}	27.47 ± 4.83 ^{a}
	15	53.70 ± 1.50 ^{b}	8.03 ± 1.60 ^{b}	43.81 ± 2.39 ^{b}	63.75 ± 0.61 ^{a}	−0.62 ± 0.03 ^{a}	21.78 ± 0.44 ^{b}
	25	54.65 ± 1.70 ^{b}	9.31 ± 0.31 ^{b}	40.68 ± 0.52 ^{b}	54.01 ± 1.50 ^{b}	1.27 ± 0.17 ^{b}	23.42 ± 0.93 ^{b}
	35	54.37 ± 1.70 ^{b}	7.94 ± 0.48 ^{b}	38.64 ± 1.39 ^{b}	54.77 ± 0.73 ^{b}	1.27 ± 0.13 ^{b}	21.26 ± 0.46 ^{b}

Values are means ± standard deviations. Different superscript letters within a column indicate significant differences ($p < 0.05$).

3.5. Texture Profile

Residue flour incorporation affected the texture parameters differently across replacement levels (Table 9). For potato residue breads, fracturability, hardness, and chewiness did not differ significantly from the control at 15% substitution but increased at 25% and 35%. Hardness and gumminess were lower at 35% than at 25%, indicating that their increase was not proportional to the replacement level. Cohesiveness decreased at all substitution levels, without significant differences among them, whereas springiness showed no significant changes. Gumminess was lower than the control at 15% but higher at the two greater substitution levels. Increased crumb hardness at high potato pulp inclusion levels has also been reported by other authors [36].

Breads containing cassava residue had lower hardness, cohesiveness, gumminess, and chewiness than the control, together with higher fracturability and springiness. None of these parameters differed significantly among substitution levels. This behavior may be associated with the hydration properties of cassava residue flour, which could influence the firmness and cohesion of the bread matrix [47].

For yam residue breads, fracturability and springiness were higher than the control at all substitution levels, without significant differences among substituted formulations. Hardness differed from the control only at 35%; the 15% and 25% formulations did not differ significantly from either the control or the highest replacement level. Cohesiveness was lower than the control at 25% and 35%, while the 15% formulation did not differ significantly from the other formulations. Gumminess and chewiness showed no significant differences relative to the control or among substitution levels. The texture responses can be considered alongside the physical and compositional characteristics of the residue flours. Potato residue flour combined a larger mean particle diameter and broader size distribution with higher water retention and swelling capacities, despite its lower crude fiber content. These characteristics may have influenced water distribution under the fixed-water formulation, providing context for the increased hardness at the higher replacement levels. Conversely, the reduction in hardness observed within the cassava formulations coincided with the incorporation of a flour characterized by smaller particles and lower water retention and swelling capacities. Yam residue flour had higher crude protein and

crude fiber contents, yet gumminess and chewiness remained statistically unchanged across replacement levels.

Table 9. Texture profile of breads containing starch extraction residue flours.

Residue Flour	Replacement Level (%)	Fracturability (N)	Hardness (N)	Cohesiveness	Springiness	Gumminess (N)	Chewiness (N)
Potato	0	7.63 ± 1.09 ^{a}	18.02 ± 1.51 ^{a}	0.73 ± 0.06 ^{a}	0.67 ± 0.10 ^{a}	13.61 ± 1.19 ^{a}	9.30 ± 2.53 ^{a}
	15	8.41 ± 0.54 ^{a}	18.51 ± 0.93 ^{a}	0.55 ± 0.02 ^{b}	0.79 ± 0.08 ^{a}	10.26 ± 0.73 ^{b}	8.47 ± 0.58 ^{a}
	25	12.68 ± 1.83 ^{b}	48.35 ± 3.43 ^{b}	0.53 ± 0.04 ^{b}	0.57 ± 0.15 ^{a}	26.44 ± 0.73 ^{c}	17.03 ± 0.61 ^{b}
	35	12.11 ± 1.68 ^{b}	39.91 ± 0.08 ^{c}	0.53 ± 0.04 ^{b}	0.77 ± 0.07 ^{a}	21.71 ± 1.84 ^{d}	17.56 ± 2.55 ^{b}
Cassava	0	7.63 ± 1.09 ^{a}	18.02 ± 1.51 ^{a}	0.73 ± 0.06 ^{a}	0.67 ± 0.10 ^{a}	13.61 ± 1.19 ^{a}	9.30 ± 2.53 ^{a}
	15	10.16 ± 0.54 ^{b}	12.33 ± 1.54 ^{b}	0.54 ± 0.03 ^{b}	0.91 ± 0.03 ^{b}	6.65 ± 0.56 ^{b}	6.08 ± 0.48 ^{b}
	25	11.82 ± 0.81 ^{b}	14.62 ± 1.11 ^{b}	0.55 ± 0.05 ^{b}	0.91 ± 0.01 ^{b}	7.75 ± 0.57 ^{b}	7.03 ± 0.49 ^{b}
	35	11.77 ± 0.86 ^{b}	14.02 ± 1.96 ^{b}	0.49 ± 0.02 ^{b}	0.86 ± 0.01 ^{b}	7.53 ± 0.33 ^{b}	7.32 ± 0.47 ^{b}
Yam	0	7.63 ± 1.09 ^{a}	18.02 ± 1.51 ^{a}	0.73 ± 0.06 ^{a}	0.67 ± 0.10 ^{a}	13.61 ± 1.19 ^{a}	9.30 ± 2.53 ^{a}
	15	16.38 ± 0.55 ^{b}	18.40 ± 0.02 ^{ab}	0.68 ± 0.02 ^{ab}	0.99 ± 0.03 ^{b}	12.22 ± 0.45 ^{a}	12.11 ± 0.56 ^{a}
	25	14.16 ± 2.60 ^{b}	20.54 ± 1.77 ^{ab}	0.60 ± 0.03 ^{b}	0.96 ± 0.02 ^{b}	12.36 ± 0.90 ^{a}	11.84 ± 0.67 ^{a}
	35	13.35 ± 0.36 ^{b}	21.65 ± 0.95 ^{b}	0.54 ± 0.04 ^{b}	0.91 ± 0.04 ^{b}	11.74 ± 1.30 ^{a}	10.75 ± 1.56 ^{a}

Values are means ± standard deviations. Different superscript letters within a column indicate significant differences ($p < 0.05$).

3.6. Sensory Profile of Breads

The sensory profiles varied across the formulations evaluated (Figure 2). In breads containing potato residue flour (Figure 2a), the 15% substitution level showed the most balanced sensory profile among the substituted samples, with scores close to those of the control for overall acceptability, color, texture, and flavor. Increasing potato substitution to 25% resulted in a moderate reduction in some attributes, particularly flavor, whereas the 35% formulation showed lower overall acceptability than the control. These results indicate that, for potato, increasing substitution beyond 15% adversely affected the overall sensory profile.

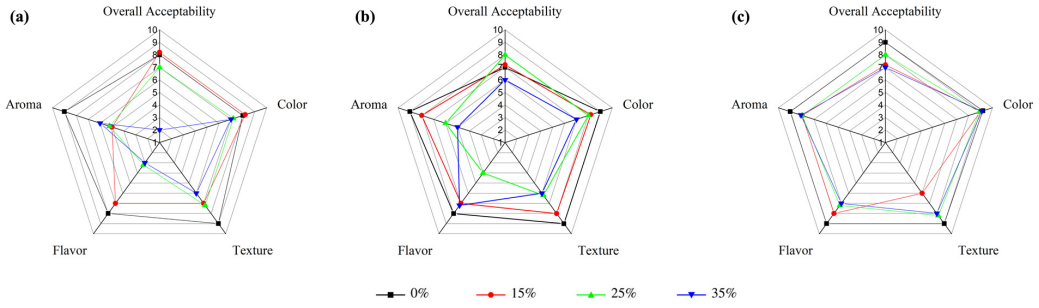


Figure 2. Radar plots of the sensory attributes of formulations containing different substitution levels (0, 15, 25, and 35%) of potato (**a**), cassava (**b**), and yam (**c**) flour.

For breads containing cassava residue flour (Figure 2b), overall acceptability remained relatively high at 15 and 25% substitution, with the latter showing the highest overall acceptability among the cassava-containing samples. However, individual attributes did not follow the same pattern. The 15% formulation maintained comparatively high scores for aroma, flavor, color, and texture, whereas the 25% formulation showed a reduction in flavor despite maintaining favorable overall acceptability and color perception.

Overall acceptability reflects the combined perception of the product and therefore does not necessarily follow the rating of any single sensory attribute. At 35% substitution, the scores for several attributes decreased relative to the control, although texture and flavor remained at intermediate-to-high levels. Thus, cassava incorporation

produced an attribute-dependent sensory response rather than a uniform decrease with increasing substitution.

Breads containing yam residue flour retained relatively high scores for overall acceptability, color, aroma, flavor, and texture at 25% and 35% substitution (Figure 2c).

The 15% formulation showed a lower mean texture score while retaining favorable ratings for the other attributes. These results indicate that the yam formulations displayed more homogeneous sensory profiles than the potato- and cassava-based formulations, particularly at the higher substitution levels.

4. Conclusions

This study shows that potato, cassava, and yam starch-processing residues exhibit distinct responses when used to partially replace wheat flour in bread, as reflected in dough extensibility, crumb structure, texture, color, and sensory acceptance. Potato residue flour showed no significant differences in hardness or chewiness relative to the control at 15% substitution, whereas higher levels increased both parameters. Cassava formulations combined lower hardness with relatively high overall acceptability at 15–25% substitution. Yam formulations showed no significant differences in crumb cell area fraction, gumminess, or chewiness relative to the control throughout the substitution range, alongside favorable sensory ratings at 25–35%. These findings identify formulation-specific opportunities for residue incorporation, although bread expansion decreased with all three residue flours. The observed responses highlight the importance of considering residue composition, particle size distribution, and hydration properties when selecting substitution levels under a fixed-water formulation. Further research should evaluate whether adjusting water addition to the hydration requirements of each residue flour improves bread quality. Dietary fiber quantification and fractionation, characterization of residual and damaged starch and gelatinization behavior, and measurements of flour pH, titratable acidity, and fermentation kinetics would help clarify the mechanisms underlying the observed responses.

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Informed Consent Statement: Informed consent was obtained from all participants before the consumer acceptance evaluation.

Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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