Agriculture and Food

AIMS Agriculture and Food, 11(4): 996–1010.
DOI: 10.3934/agrfood.2026049
Received: 14 August 2026
Revised: 22 September 2026
Accepted: 19 October 2026
Published: 04 November 2026

https://www.aimspress.com/journal/agriculture

Research article

Unlocking the potential of china potato (Colocasia esculenta) starch: Physicochemical properties and applications in frozen bread dough formulations

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Abstract: The growing market for frozen bakery products has increased the demand for ingredients with suitable technological properties for frozen dough applications. In this context, the aim of this study was to evaluate the technological performance of native, fermented, and precooked *Colocasia esculenta* starch in frozen bread dough by characterizing its physicochemical, functional, rheological, and microstructural properties, as well as its effect on bread quality after frozen storage. Three starch treatments were evaluated: native starch (T1), fermented starch obtained using baker's yeast (*Saccharomyces cerevisiae*) (T2), and precooked starch obtained by steam treatment (T3). Starch extraction yield was highest for T1 (13.52%), followed by T3 (12.59%) and T2 (8.57%). The treatments produced differences in functional, chemical, and rheological properties. Fermented starch exhibited the highest peak viscosity (1520.01 cP), whereas precooked starch showed the lowest final viscosity (90.01 cP) and the highest degree of gelatinization. In bread prepared from frozen dough, native starch showed the highest expansion index (1.60), while fermented starch produced the highest hardness (3991.37 g) and the highest sensory scores for color (4.8), texture (4.6), and overall acceptability (4.6). These findings indicate that fermentation and steam treatment produced distinct starch profiles that were reflected in the physical, textural, and sensory characteristics of the resulting bread. The results provide evidence of the technological potential of *C. esculenta* starch treatments for frozen bread dough applications within the experimental conditions evaluated in this study.

Keywords: *Colocasia esculenta*; modified starch; frozen bread dough; breadmaking; technological properties

1. Introduction

Frozen dough technology has become one of the main strategies for optimizing the production, storage, and distribution of bakery products by providing greater flexibility to industrial processes, facilitating production planning, and extending product shelf life without substantially modifying manufacturing procedures. Its widespread adoption has been driven by the sustained growth of the convenience food market and the increasing demand for bakery products with improved stability during storage and commercialization. However, preserving the technological quality of bread after frozen storage remains one of the major challenges for the baking industry [1–3].

Despite its technological advantages, freezing induces physical and structural changes in dough as a consequence of water migration, ice crystal nucleation and recrystallization, and repeated freeze–thaw cycles. These phenomena disrupt the interactions among gluten, starch, and water, affecting the continuity of the gluten network, the structural organization of starch granules, and the dough's gas-retention capacity. As a result, dough rheological properties are altered, leading to reduced specific volume, increased crumb firmness, and lower product stability during frozen storage [1,2,4,5].

To minimize these detrimental effects, several technological strategies have been proposed to improve the stability of frozen dough, including the incorporation of functional ingredients capable of reinforcing dough structure during frozen storage. In this context, starch plays a fundamental role because of its contribution to water absorption, gelatinization, viscosity development, retrogradation, and bread texture formation. Physical, chemical, biological, and enzymatic modifications can reorganize starch molecular structure and enhance its functional properties, thereby expanding its potential application in different food systems, particularly those subjected to freezing processes [6–8].

Among alternative starch sources, *C. esculenta* Schott, commonly known as taro, has attracted increasing attention because of its high starch content, representing approximately 70%–80% of the tuber dry matter, and its small granule size, generally ranging from 1 to 5 μm. These characteristics improve digestibility and provide functional properties of considerable interest to the food industry. In addition, taro starch exhibits suitable swelling capacity and water and oil retention properties and has been successfully used as a thickener, stabilizer, emulsifier, and partial fat replacer, highlighting its potential as a functional ingredient for bakery and gluten-free products [9,10].

Although previous studies have characterized the physicochemical and functional properties of *C. esculenta* starch and described its potential applications in different food products, evidence regarding the effects of fermentation and precooked starch on its technological behavior when incorporated into frozen bread dough remains limited. This knowledge gap restricts the development of functional ingredients derived from this species for specific bakery applications, particularly in systems where dough structural and rheological stability determines the quality of the final product [6,9,10].

Therefore, the aim of this study was to evaluate the technological feasibility of native, fermented, and precooked C. esculenta starch as a functional ingredient for frozen bread dough by characterizing its physicochemical, functional, rheological, and microstructural properties, as well as its effect on dough technological performance.

2. Materials and methods

2.1. Plant material

C. esculenta tubers were cultivated and harvested at commercial maturity in the Ecuadorian Amazon region, Province of Pastaza, Puyo Canton, Fátima Parish (UTM coordinates: 166242.277 E, 9842019.098 N; Zone 18M). Tubers with an ovoid to cylindrical shape, dark brown epidermis characterized by visible concentric rings, and free of mechanical damage or deformities were selected. The flesh exhibited a uniform white to creamy-white color without internal discoloration or signs of enzymatic browning.

2.2. Starch extraction and modification

Native starch was extracted from *C. esculenta* following the wet extraction procedure described by Gupta et al. [9], complemented with drying and milling steps. Tubers were peeled, cut into small pieces, and homogenized to obtain a uniform slurry. The suspension was filtered through a sieve, and the filtrate was allowed to sediment for 2 h. The supernatant was discarded, and the recovered starch sediment was dried in a forced-air oven at 60 °C for 4 h. The dried material was milled using a Retsch ZM 200 mill fitted with a 0.5-mm screen to obtain native starch (T1).

Precooked starch (T3) was prepared by subjecting a portion of the native starch to steam treatment at 100 °C for 1 min. This short hydrothermal treatment was selected to induce controlled thermal modification of the starch while avoiding prolonged heat exposure. The treated starch was subsequently cooled, maintained in a dry state, and stored in hermetically sealed glass containers at room temperature (17 °C) until further use.

Fermented starch (T2) was obtained from a portion of the initial starch suspension, which was diluted with distilled water at a ratio of 1:3 (w/v), inoculated with *Saccharomyces cerevisiae* (1 g/L), and incubated at 17 °C for 24 h. The fermented suspension was subsequently dried at 60 °C for 4 h, and the resulting starch was stored in airtight glass containers until characterization.

Finally, extraction yield was expressed as the ratio of the recovered starch mass to the initial mass of *C. esculenta* tubers, following the procedure described by Valdés et al. [11].

2.3. Starch characterization

Functional properties were evaluated by determining water absorption capacity, solubility, and swelling power according to the method of Anderson et al. [12]. Briefly, 2.5 g of starch were dispersed in 30 mL of distilled water at 30 °C and maintained under constant agitation in a thermostatically controlled water bath for 30 min. The suspensions were then centrifuged at 5000 rpm for 20 min. The supernatant was dried at 90 °C to quantify soluble solids, whereas the sediment was used to calculate the corresponding functional parameters.

Freeze–thaw stability was evaluated using 5% (dry basis) starch suspensions previously gelatinized in a Brabender Viscoamylograph at 89 °C for 10 min. The resulting gels were stored at −20 °C and subjected every three days to one freeze–thaw cycle consisting of thawing at 60 °C for 1 h followed by centrifugation at 1000 rpm for 10 min. Water released from the gels was expressed as a percentage of the initial gel weight according to Eliasson and Kim [13]. Gel clarity was determined by measuring the transmittance of gelatinized starch dispersions following the method described by Bello-Pérez [14].

The starch microstructure was examined by scanning electron microscopy (SEM) following the procedure described by Zhang and Zhai [15]. Samples were purified by suspension in 1% sodium bisulfite solution for 24 h, followed by grinding, sieving, centrifugation, and treatment of the precipitate with 0.2% NaOH. The material was then washed repeatedly, neutralized to pH 7.0 with HCl, dried at 40 °C for 24 h, mounted on aluminum stubs using double-sided conductive carbon tape, coated with a thin carbon layer, and examined using a scanning electron microscope.

Moisture (Method 925.09) and ash (Method 942.05) contents were determined according to AOAC [16] official methods. Total starch was quantified by enzymatic hydrolysis using amyloglucosidase followed by glucose determination with the glucose oxidase–peroxidase (GOD–POD) method at 510 nm, applying a conversion factor of 0.9 as described by Goñi et al. [17]. Amylose content was determined by the iodine-binding colorimetric method with spectrophotometric measurement at 635 nm according to Villegas et al. [18]. Degree of gelatinization was determined by the iodine complexation method described by Birch and Priestley [19], which is based on the relative iodine-binding response of starch before and after alkali dispersion. The degree of gelatinization was expressed as a percentage of the response obtained for the fully gelatinized reference. The starch subjected to steam treatment at 100 °C for 1 min was therefore considered precooked and partially pregelatinized rather than completely gelatinized. Pasting properties were evaluated using a rapid visco analyzer (RVA), recording peak viscosity, hot paste viscosity, final viscosity, breakdown, setback, peak time, and pasting temperature according to Guo et al. [20].

2.4. Dough and bread preparation

Bread dough was prepared following a modified procedure based on Valqui-Pérez et al. [21]. The formulation consisted of Manabí cheese (50%), Colocasia esculenta starch (50%), 1 egg, butter, salt, and baking powder. This cheese-based formulation was selected as a model system for evaluating the technological behavior of C. esculenta starch in a traditional Ecuadorian food matrix rather than as a representation of conventional wheat-based bread dough. Baking powder was selected as the leavening agent instead of baker's yeast because the formulation was based on Manabí cheese and *C. esculenta* starch rather than wheat flour, and its use minimized the contribution of biological fermentation during bread preparation. The cheese composition was kept constant across all treatments; however, no independent cheese-composition control was included. Therefore, the effects observed in the bread should be interpreted within the specific cheese–starch formulation evaluated in this study. All ingredients were mixed and kneaded for 10 min until a homogeneous dough was obtained, followed by a resting period of 5 min. The dough was then divided into uniform portions and allowed to rest for 24 h. After the 24-h resting period, the dough portions were frozen and stored at −18 °C. Samples were evaluated after 3, 6, and 9 days of frozen storage.

2.5. Bread quality evaluation

Bread quality was assessed through physical, colorimetric, textural and sensory analyses.

Physical properties included dough weight before baking and final bread weight to calculate baking weight loss. Bread length, height, and width were measured using a digital caliper with a resolution of 0.01 mm following the procedure described by Lara [22].

Color was determined using a portable spectrophotometer (Lange Spectro-Color d/8°, Model LZM 268, Chelmsford, UK) according to the CIELAB color system. The L*, a* and b* coordinates were recorded, and chroma (C*), hue angle (H*), total color difference (ΔE), and color index were

subsequently calculated following Villacrés et al. [23].

Texture profile analysis (TPA) was performed using a double-compression test that simulates mastication. Hardness, springiness, cohesiveness, gumminess, chewiness, and adhesiveness were calculated from the force–time curves according to Padilla-Villalobos et al. [24].

Sensory acceptance was evaluated by a consumer panel of 55 participants using a hedonic scale to assess appearance, aroma, flavor, texture, and overall acceptability. The participants were university staff and students who voluntarily participated in the evaluation. Samples were randomly coded and presented in random order to minimize evaluation bias following the methodology described by Parmigiani et al. [25].

Ethical considerations: The sensory evaluation was considered a low-risk and non-invasive procedure and did not require formal ethical approval. The participants were university staff and students who voluntarily participated in the evaluation, and informed consent was obtained from all participants prior to the sensory assessment. No personal or identifiable information was collected.

2.6. Statistical analysis

All physicochemical, functional, rheological, physical, colorimetric, and textural analyses were performed in triplicate, and the results are expressed as mean ± standard deviation. Sensory evaluation results are expressed as mean ± standard deviation based on the responses of 55 consumers. Data were analyzed by one-way analysis of variance (ANOVA), and mean comparisons were performed using Tukey's honestly significant difference (HSD) test at a significance level of $p \leq 0.05$. For freeze–thaw stability, comparisons were performed separately at each storage day; therefore, no treatment × storage-time interaction was estimated. The statistical analysis was used to compare the evaluated starch treatments at each experimental condition.

3. Results

3.1. Physicochemical, functional, and rheological properties of Colocasia esculenta starch

3.1.1. Starch extraction yield

Significant differences in starch extraction yield were observed among the three treatments ($p < 0.05$; Table 1). Native starch (T1) showed the highest yield (13.52%), followed by precooked starch (T3, 12.59%). Fermented starch (T2) had the lowest yield (8.57%).

3.1.2. Chemical composition

The chemical composition differed among treatments (Table 1). Moisture content ranged from 8.305 to 8.707 g/100 g, with the lowest value in T1 and the highest in T3. Ash content was 2.30 g/100 g in T1, 1.15 g/100 g in T2, and 3.35 g/100 g in T3.

Total starch content ranged from 84.78 to 90.47 g/100 g. Amylose content ranged from 12.9 g/100 g in T1 to 15.3 and 15.6 g/100 g in T2 and T3, respectively. The degree of gelatinization was 4.70% in T1, 4.47% in T2, and 9.00% in T3.

Table 1. Physicochemical, functional, and rheological properties of *Colocasia esculenta* starch.

Parameter	Unit	Native (T1)	Fermented (T2)	Precooked (T3)
Yield	(%)	13.52	8.57	12.59
Functional properties				
Water absorption		$2.016^{a} \pm 0.3^{a}$	$2.0135^{a} \pm 0.01^{a}$	$2.129^{b} \pm 0.01^{b}$
Solubility	%	$2.90^{b} \pm 0.08^{b}$	$2.04^{a} \pm 0.1^{a}$	$5.72^{c} \pm 0.06^{c}$
Swelling power	g/g	$2.016^{a} \pm 0.3^{a}$	$2.055^{a} \pm 0.01^{a}$	$2.2585^{a} \pm 0.01^{a}$
Freezer storage day 3	g/100 g dw	$18.0^{ab} \pm 3^{ab}$	$9.667^{a} \pm 0.6^{a}$	$22.667^{b} \pm 6^{b}$
Freezer storage day 6		$36.0^{a} \pm 5^{a}$	$26.0^{a} \pm 20^{a}$	$40.0^{a} \pm 4^{a}$
Freezer storage day 9		$52.67^{a} \pm 5^{a}$	$35.33^{a} \pm 20^{a}$	$44.0^{a} \pm 5^{a}$
Clarity of starch gels		$5.833^{c} \pm 0.06^{c}$	$3.25^{a} \pm 0.05^{a}$	$5.627^{b} \pm 0.09^{b}$
Chemical composition				
Moisture	g/100 g	$8.305^{a} \pm 0.4^{a}$	$8.620^{b} \pm 0.5^{a}$	$8.707^{b} \pm 0.2^{b}$
Ash		$2.30^{b} \pm 0.01^{b}$	$1.15^{a} \pm 0.07^{a}$	$3.35^{c} \pm 0.07^{c}$
Total starch	g/100 g	$90.47^{a} \pm 2^{a}$	$89.59^{a} \pm 20^{a}$	$84.78^{a} \pm 6^{a}$
Amylose	g/100 g	$12.9^{b} \pm 0.01^{b}$	$15.3^{a} \pm 0.01^{a}$	$15.6^{a} \pm 0.01^{a}$
Degree of gelatinization	%	$4.7^{a} \pm 0.01^{a}$	$4.47^{a} \pm 0.01^{a}$	$9^{b} \pm 0.01^{b}$
Viscosity Analysis				
Peak Viscosity	cP	1294.00	1520.01	820.01
Hot Paste Viscosity		457.00	419.00	50.01
Final Viscosity (Cooling)		740.01	685.00	90.01
Gel Instability (Breakdown)		837.00	1101.00	770.01
Retrogradation (Setback)		283.00	266.00	40.01
Time to Reach Peak Viscosity	min	5.60	5.53	5.13
Gelatinization Temperature	°C	82.40	82.30	87.25
Cooking Ease	min	2.10	2.03	1.33

*Note: Means with different superscripts in the same row indicate significant differences ($p \leq 0.05$). Values are expressed as mean ± standard deviation (SD; n = 3).

3.1.3. Functional properties

Water absorption capacity and swelling power showed relatively small differences among treatments (Table 1). Water absorption values were 2.016 for T1, 2.0135 for T2, and 2.129 for T3. Swelling power was 2.016 g/g in T1, 2.055 g/g in T2, and 2.2585 g/g in T3.

Solubility differed among treatments, with values of 2.90% for T1, 2.04% for T2, and 5.72% for T3. Gel clarity was highest in T1 (5.833), followed by T3 (5.627), while T2 showed the lowest value (3.25).

During frozen storage, the measured values differed among treatments on day 3. T1, T2, and T3 showed values of 18.0, 9.667, and 22.667 g/100 g dry weight, respectively. On day 6, the corresponding values were 36.0, 26.0, and 40.0 g/100 g dry weight. On day 9, the values were 52.67, 35.33, and 44.0 g/100 g dry weight, respectively (Table 1).

3.1.4. Rheological properties

The pasting profile varied among the starch treatments (Table 1). T2 exhibited the highest peak viscosity (1520.01 cP), followed by T1 (1294.00 cP) and T3 (820.01 cP). Hot paste viscosity was

457.00 cP for T1, 419.00 cP for T2, and 50.01 cP for T3. Final viscosity was 740.01, 685.00, and 90.01 cP for T1, T2, and T3, respectively.

The breakdown values were 837.00 cP for T1, 1101.00 cP for T2, and 770.01 cP for T3. Setback values were 283.00, 266.00, and 40.01 cP, respectively. Time to peak viscosity was 5.60 min for T1, 5.53 min for T2, and 5.13 min for T3. The recorded gelatinization temperatures were 82.40 ℃, 82.30 ℃, and 87.25 ℃ for T1, T2, and T3, respectively. Cooking times were 2.10, 2.03, and 1.33 min, respectively.

3.1.5. Microstructure observed by scanning electron microscopy

SEM revealed morphological differences among the starch treatments (Figure 1). Native starch granules exhibited relatively continuous surfaces and well-defined morphology. Fermented starch showed visible surface alterations, whereas precooked starch exhibited greater deformation and partial loss of granular integrity.

The observations were qualitative. No quantitative image-based comparison was performed.

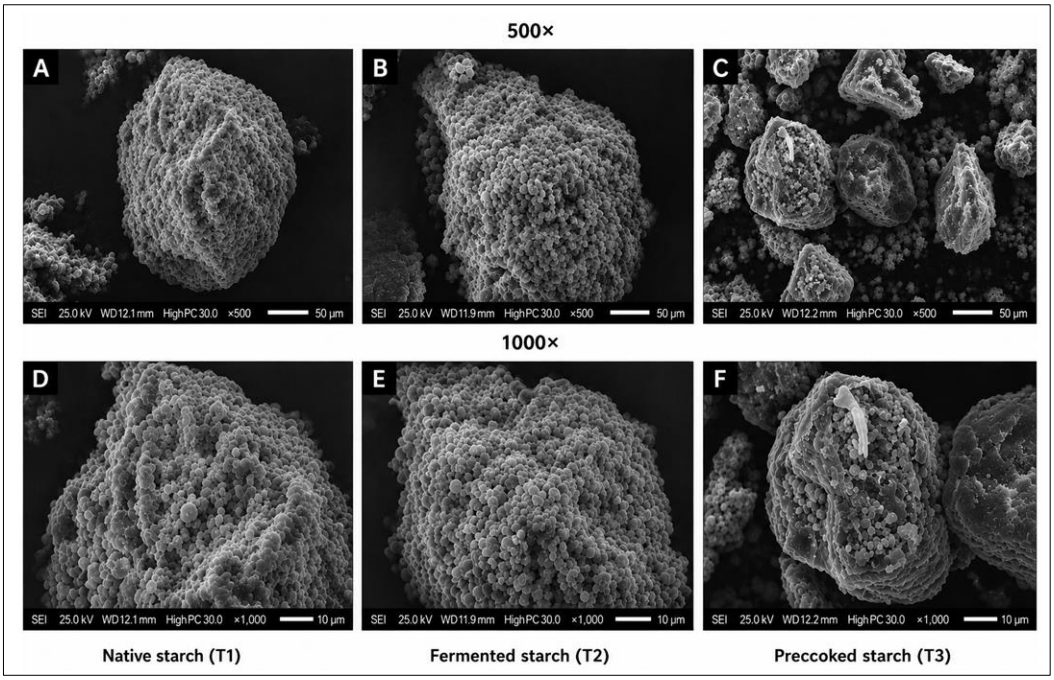


Figure 1. Scanning electron micrographs of native (T1), fermented (T2), and precooked (T3) *Colocasia esculenta* starch.

3.2. Technological quality of bread prepared with Colocasia esculenta starch

3.2.1. Physical properties

The physical properties of the bread varied among treatments (Table 2). Initial weights were 79.00 g for T1, 79.00 g for T2, and 78.00 g for T3. After baking, the corresponding weights were 68.00, 68.00, and 66.00 g. Baking weight loss was 13.92% for T1 and T2 and 15.38% for T3.

Initial volume was 122.90 mm^3 for T1, 105.66 mm^3 for T2, and 117.12 mm^3 for T3. Final volume was 196.76 mm^3 for T1, 162.90 mm^3 for T2, and 168.57 mm^3 for T3. The expansion index was highest in T1 (1.60), followed by T2 (1.54) and T3 (1.44).

3.2.2. Color properties

Instrumental color measurements are presented in Table 2. Lightness (L*) values were 45.69 for T1, 45.62 for T2, and 45.20 for T3. The a* coordinate was 15.50 for T1, 17.87 for T2, and 13.05 for T3. The b* coordinate was 48.02 for T1, 47.09 for T2, and 40.52 for T3.

Table 2. Physical properties and CIELAB color parameters of bread formulated with native, fermented, and precooked Colocasia esculenta starch.

Parameter	Unit	Native (T1)	Fermented (T2)	Precooked (T3)
Physical evaluation				
Native weight	g	79.00 ± 0.58^{a}	79.00 ± 0.58^{a}	78.00 ± 0.58^{a}
Baked weight	g	68.00 ± 0.58^{a}	68.00 ± 0.58^{a}	66.00 ± 1.00^{a}
Weight loss	%	13.92 ± 0.73^{a}	13.92 ± 0.73^{a}	15.38 ± 0.91^{b}
Initial volume	mm³	122.90 ± 3.21^{a}	105.66 ± 2.84^{b}	117.12 ± 3.05^{a}
Final volume	mm³	196.76 ± 4.82^{a}	162.90 ± 4.36^{b}	168.57 ± 3.97^{b}
Expansion index	—	1.60 ± 0.04^{a}	1.54 ± 0.03^{ab}	1.44 ± 0.04^{b}
CIELAB color parameters				
L*	—	45.69 ± 1.21^{a}	45.62 ± 1.17^{a}	45.20 ± 1.34^{a}
a*	—	15.50 ± 0.64^{ab}	17.87 ± 0.71^{b}	13.05 ± 0.58^{a}
b*	—	48.02 ± 1.35^{a}	47.09 ± 1.28^{a}	40.52 ± 1.16^{b}

*Note: Values are expressed as mean ± SD (n = 3). Means with different superscript letters in the same row indicate significant differences ($p \leq 0.05$). Volume = length × height × width. Expansion index = final volume / initial volume.

3.2.3. Texture profile analysis

TPA showed differences among the bread treatments (Table 3). Hardness was highest in T2 (3991.37 g), followed by T3 (3379.46 g) and T1 (3139.81 g). Fracturability values were 3021.06 g for T1, 3233.59 g for T2, and 2484.21 g for T3.

Adhesiveness was 4242.39 for T1, 4760.61 for T2, and 6142.00 for T3. Elasticity values were 0.8791, 0.8965, and 0.8831 for T1, T2, and T3, respectively. Cohesiveness values were 0.8804, 0.8827, and 0.8979, respectively. Gumminess was 3608.00 g for T1, 4246.49 g for T2, and 3491.35 g for T3.

Table 3. Texture profile analysis of bread prepared from frozen dough formulated with native, fermented, and precooked Colocasia esculenta starch.

Parameter	Unit	Native (T1)	Fermented (T2)	Precooked (T3)
Hardness	g	3139.81^{a} ± 643.50^{a}	3991.37^{b} ± 511.87^{b}	3379.46^{a} ± 459.55^{a}
Fracturability		3021.06^{a} ± 469.60^{a}	3233.59^{a} ± 1038.8^{a}	2484.21^{a} ± 1039.69^{a}
Adhesiveness		4242.39^{a} ± 119.70^{a}	4760.61^{a} ± 502.40^{a}	6142.00^{a} ± 1548.56^{a}
Elasticity		0.8791^{a} ± 0.15^{a}	0.8965^{a} ± 0.14^{a}	0.8831^{a} ± 0.14^{a}
Cohesiveness		0.8804^{a} ± 0.15^{a}	0.8827^{a} ± 0.13^{a}	0.8979^{a} ± 0.16^{a}
Gumminess	g	3608.00^{a} ± 655.13^{a}	4246.49^{b} ± 349.21^{b}	3491.35^{a} ± 406.95^{a}

*Note: Values are expressed as mean ± SD (n = 3). Means with different superscript letters indicate significant differences ($p \leq 0.05$).

3.2.4. Sensory evaluation

Sensory evaluation results are presented in Table 4. For color, mean scores were 3.5 for T1, 4.8 for T2, and 4.0 for T3. Aroma scores were 3.9, 4.2, and 4.5, respectively. Texture scores were 3.4 for T1, 4.6 for T2, and 4.1 for T3. Flavor scores were 4.0, 4.4, and 4.0, respectively. Overall acceptability scores were 3.9 for T1, 4.6 for T2, and 4.4 for T3.

Table 4. Sensory evaluation of bread prepared from frozen dough formulated with native, fermented, and precooked Colocasia esculenta starch.

Parameter	Native (T1)	Fermented (T2)	Precooked (T3)
Color	$3.5^{a} \pm 0.53^{a}$	$4.8^{b} \pm 0.42^{b}$	$4.0^{a} \pm 0.82^{a}$
Aroma	$3.9^{a} \pm 0.32^{a}$	$4.2^{ab} \pm 0.92^{ab}$	$4.5^{b} \pm 0.53^{b}$
Texture	$3.4^{a} \pm 0.70^{a}$	$4.6^{b} \pm 0.52^{b}$	$4.1^{b} \pm 0.88^{b}$
Flavor	$4.0^{a} \pm 0.82^{a}$	$4.4^{a} \pm 0.52^{a}$	$4.0^{a} \pm 0.82^{a}$
Acceptability	$3.9^{a} \pm 0.99^{a}$	$4.6^{b} \pm 0.52^{b}$	$4.4^{ab} \pm 0.52^{ab}$

*Note: Values are expressed as mean ± SD (n = 55). Means with different superscript letters indicate significant differences ($p \leq 0.05$).

4. Discussion

4.1. Effects of fermentation and precooking on starch properties

The extraction yield results indicate that the modification treatment was associated with differences in starch recovery. Native starch had the highest yield, whereas fermented starch had the lowest. The reduction following fermentation may reflect changes affecting starch recovery during processing. Nevertheless, extraction yield alone does not establish the technological suitability of a starch because modification can also alter functional properties relevant to food applications [9].

The chemical composition results suggest that the treatments produced different physicochemical profiles. The higher ash content in precooked starch and lower value in fermented starch should be interpreted as differences observed after processing; the present measurements do not establish the mechanisms responsible for those differences. Total starch content varied numerically among treatments. The increase in amylose content observed in T2 and T3 may be relevant to the functional behavior of the starch, but the present data do not identify the specific molecular changes underlying this variation.

The higher degree of gelatinization in T3 is consistent with the prior steam treatment. However, the measured value indicates partial rather than complete gelatinization. This distinction is important when interpreting the pasting behavior of the precooked starch. More broadly, the results support the view that physical and biological modification can produce different changes in starch structure and functionality, as discussed in previous research on starch modification [6,9,26].

4.2. Functional and rheological behavior

The functional measurements show that the treatments did not affect all starch properties in the same way. The higher solubility of T3 may be associated with thermal disruption of the granular structure, potentially facilitating the release of soluble components and interactions with water.

Conversely, the lower solubility of T2 may indicate a different modification of starch–water interactions. These explanations are plausible interpretations rather than mechanisms directly demonstrated by the present experiments [7,9].

Gel clarity was highest in native starch and lowest in fermented starch. Differences in clarity may be related to changes in molecular organization and the behavior of starch components in aqueous systems. However, the study did not directly characterize the molecular structures responsible for the observed clarity values. During frozen storage, treatment differences were apparent at the first evaluation, while the numerical differences were less pronounced at later evaluations. Because the statistical analysis compared treatments separately at each storage day and did not estimate a treatment × storage-time interaction, the results should not be interpreted as evidence of a statistically established difference in storage trajectories [6,13].

The rheological profile further distinguished the treatments. Fermented starch exhibited the highest peak viscosity and breakdown, indicating that it developed a high viscosity during heating but also experienced a substantial reduction under continued heating and shear. These observations may reflect changes in starch structure and hydration behavior during fermentation. Previous studies have reported that starch structure and processing conditions influence pasting and rheological properties [3,5,20,27].

In contrast, precooked starch showed lower peak, hot paste, and final viscosities, alongside a higher recorded gelatinization temperature and shorter cooking time. These findings are consistent with the possibility that prior steam treatment altered the granular structure and reduced the capacity for further viscosity development during subsequent heating. The SEM observations provide qualitative support for this interpretation, although they do not independently establish the mechanism.

4.3. Microstructural observations

The SEM images showed relatively well-defined granules in native starch, visible surface alterations in fermented starch, and greater deformation in precooked starch. These observations are consistent with the functional and rheological differences described above. In particular, the apparent disruption of granules in precooked starch corresponds with its higher solubility, higher degree of gelatinization, and lower peak viscosity.

Nevertheless, these findings must be interpreted cautiously. The sample preparation procedure included sodium bisulfite and NaOH treatments, which may have modified the starch surfaces before imaging. In addition, no quantitative image analysis was performed. Therefore, the micrographs provide qualitative evidence of morphological differences rather than a quantitative measurement of the extent of structural disruption [6,8,15,28].

4.4. Physical properties and color of bread

The bread prepared with native starch showed the highest expansion index, whereas bread containing precooked starch had the lowest. The greater expansion associated with native starch may reflect differences in starch–water interactions and the development of the product matrix during baking. The lower expansion of bread containing precooked starch may be associated with the prior thermal modification, which could have changed water distribution and the behavior of the starch during baking. The intermediate expansion index of fermented-starch bread suggests a different response to biological modification.

These interpretations should be considered in the context of the formulation used. The dough consisted of 50% Manab ícheese and 50% *C. esculenta* starch, rather than a conventional wheat-based

bread formulation. Consequently, the findings describe the performance of this specific cheese–starch model system and should not be generalized directly to conventional wheat dough. Although research on frozen dough highlights the importance of water distribution and starch–protein interactions, those mechanisms were not independently measured in this study [4,6].

Baking weight loss was higher in bread containing precooked starch than in the other treatments. This difference may be associated with altered water distribution or retention, but the study did not directly measure moisture migration during baking. Instrumental color differences were comparatively limited for lightness, while the a* and b* coordinates showed greater variation. The higher a* value in fermented-starch bread and lower b* value in precooked-starch bread demonstrate differences in the measured color coordinates. However, instrumental measurements alone cannot establish how consumers perceive those differences [24].

A further limitation is that no fresh-dough control was included. Dough rheology, gas retention, and structural integrity during freezing were not independently quantified. Thus, the results demonstrate bread performance after frozen storage under the experimental conditions used; they do not directly measure an improvement caused by freezing or prove preservation of dough structure during freezing.

4.5. Texture and sensory acceptance

Bread containing fermented starch exhibited the highest hardness and gumminess, whereas native-starch bread had the lowest hardness and the highest final volume and expansion index. These results suggest an association between starch treatment, product expansion, and mechanical texture. The greater hardness of fermented-starch bread may reflect differences in the structure of the baked matrix and starch–water interactions. However, the mechanisms responsible for the observed texture cannot be isolated from the measurements performed.

Adhesiveness was numerically highest in bread prepared with precooked starch. This result may be associated with the higher solubility and degree of gelatinization observed for that starch, although the study does not establish a direct causal relationship. Springiness, cohesiveness, and fracturability did not show statistically significant differences according to the table annotations and should not be described as treatment-dependent effects. Overall, the textural results indicate that the starch treatments were associated with different mechanical profiles, particularly in hardness and gumminess [5,6].

In the sensory evaluation, fermented-starch bread received the highest mean scores for color, texture, and overall acceptability. Its higher sensory texture score occurred alongside the highest instrumental hardness and gumminess. This combination shows that the panel's texture ratings should not be interpreted as a simple preference for lower instrumental hardness. Consumer perception may reflect several characteristics of the product that were not independently assessed.

The sensory color scores also differed from what might be inferred from individual instrumental color coordinates. Although fermented-starch bread received the highest mean color score, its CIELAB measurements did not show the highest value across all coordinates. Instrumental color and sensory color are related but distinct measurements, and the present data do not establish which specific visual characteristics drove panel responses. Aroma and flavor scores were comparatively similar across treatments. These findings should be interpreted within the sensory protocol used and the 55 participants who evaluated the samples [24–26].

4.6. Study limitations and implications

The experimental design included important limitations. First, the fermentation treatment did not include an uninoculated control or a pH-adjusted control. Therefore, the differences between fermented and precooked starch should be interpreted as differences between two modification approaches, not as evidence of directly comparable mechanisms. The individual contributions of fermentation-related factors cannot be isolated from the present design.

Second, the bread formulation was a cheese–starch model system containing 50% Manab ícheese and 50% *C. esculenta* starch. It was not a conventional wheat-based dough. Third, no fresh-dough control was included and dough rheology, gas retention, and structural integrity during freezing were not independently quantified. The study therefore cannot establish the direct effect of freezing or demonstrate improved frozen-dough stability.

Finally, the SEM analysis was qualitative, and the statistical approach did not estimate a treatment × storage-time interaction. Further research should include fresh-dough controls, uninoculated and pH-adjusted fermentation controls, characterization of fermentation conditions, quantitative microstructural analysis, and direct measurements of dough rheology and gas retention. Multifactorial statistical designs would also help clarify the effects of starch treatment and storage time.

Within these limitations, the results demonstrate that native, fermented, and precooked *C. esculenta* starch exhibited different physicochemical, functional, and rheological profiles and were associated with different physical, textural, and sensory characteristics in the cheese–starch formulation evaluated. These findings support further investigation of *C. esculenta* starch for specialized frozen bakery formulations, without implying that the present study has established its performance in conventional wheat-based bread systems.

5. Conclusions

The present study demonstrated that fermentation with Saccharomyces cerevisiae and steam treatment produced distinct changes in the physicochemical, functional, rheological, and microstructural properties of Colocasia esculenta starch. Native starch showed the highest extraction yield (13.52%), fermented starch exhibited the highest peak viscosity (1520.01 cP), and steam-treated starch showed the highest degree of partial gelatinization (9.0%) and the lowest final viscosity (90.01 cP).

In bread prepared from frozen dough, the starch treatments produced different technological and sensory responses. Native starch showed the highest expansion index (1.60), and fermented starch produced the highest hardness (3991.37 g) and the highest sensory scores for color (4.8), texture (4.6), and overall acceptability (4.6). These results indicate that the three starch treatments generated different performance profiles within the specific cheese–starch formulation evaluated.

The findings should be interpreted within the experimental conditions of this study. The bread formulation contained 50% Manabí cheese and 50% C. esculenta starch and therefore does not represent a conventional wheat-based bread dough. In addition, no fresh-dough control, uninoculated fermentation control, or pH-adjusted fermentation control was included. Initial pH, specific yeast strain characteristics, yeast viability, agitation, and oxygen availability were not independently characterized. Consequently, the individual contribution of these fermentation-related factors and the direct effect of freezing on dough structure cannot be isolated from the present results.

Furthermore, the SEM analysis was qualitative because the sample preparation procedure included sodium bisulfite and NaOH treatments that may have modified the observed starch surfaces and no quantitative image analysis was performed. The statistical analysis compared treatments under

each experimental condition but did not estimate a treatment × storage-time interaction. Therefore, the results provide evidence of differences among the evaluated starch treatments under frozen-storage conditions, but they should not be interpreted as direct evidence of improved frozen-dough stability or as broadly applicable to conventional wheat-based bread systems.

Overall, the results support the technological potential of C. esculenta starch as an ingredient for frozen bakery formulations under the conditions evaluated. Further studies should include fresh-dough controls, pH-adjusted and uninoculated fermentation controls, characterization of fermentation conditions, quantitative microstructural analysis, dough rheology and gas-retention measurements, and multifactorial statistical designs to clarify the mechanisms underlying starch modification and frozen-dough performance.

Use of AI tools declaration

Generative AI-assisted tools were used only to assist in arranging and combining original author-generated images into composite figures for presentation purposes. No scientific data, results, interpretations, analyses, or conclusions were generated or modified by AI. All original images, figure content, and the final manuscript were reviewed and approved by the authors.

Acknowledgments

The Technical University of Cotopaxi and the National Agricultural Research Institute INIAP supported this work, which belongs to the Project on Harvesting and Post-Harvest Management of Agricultural Products and the Study of Transformation Processes of Agricultural Waste, by providing the necessary facilities for carrying out this work.

Conflict of interest

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

Author contributions

Claudio López-Guevara: Conceptualization, methodology, investigation, writing-original draft; Elena Villacrés-Poveda: Investigation, formal analysis, data curation, writing-review and editing; Maria Monserrath Morales Padilla: Writing-original draft, writing-review and editing. All authors have read and agreed to the published version of the manuscript.

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