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Physicochemical Characteristics of Pre-gelatinized Purple Sweet Potato (*Ipomoea batatas* var. Ayamurasaki) Flour and Their Effects on Analog Rice

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ABSTRACT

Purple sweet potato (*Ipomoea batatas* var. Ayamurasaki), a crop widely cultivated in West Java, is notable for its high anthocyanin content and antioxidant potential. This study examined the effect of pre-gelatinization, via steaming or boiling, on the physicochemical, functional, and bioactive characteristics of purple sweet potato flour, as well as its application in analog rice. Flour samples were prepared in non-pre-gelatinized and pre-gelatinized (steamed or boiled) forms, then dried, milled, and analyzed for color, pasting profile, proximate composition, total phenolic, anthocyanin, and antioxidant activity. The flours were subsequently used to produce analog rice, which was evaluated for cooking and sensory qualities. Pre-gelatinization significantly increased color intensity, with a* values ranging from 13.76 (boiled) to 17.67 (steamed), while non-pre-gelatinized flour exhibited a higher L* value (49.19). Non-pre-gelatinized flour demonstrated a pasting onset temperature of 80.9 °C and the highest final viscosity (1,769 cP), whereas pre-gelatinized flours showed no detectable pasting onset and reduced setback viscosity, decreasing from 668 cP (non-pre-gelatinized) to 611 cP (boiled) and 350 cP (steamed). Total phenolic content increased from 73.41 to 92.73–114.20 mg GAE/100 g, as well as anthocyanin rising from 0.48 to 0.63–0.77 mg CyE/g. In addition, DPPH scavenging activities rose from 74.71% to 84.05–97.70%. Analog rice produced from pre-gelatinized flour exhibited a deeper purple color, shorter cooking time (3.3–3.4 min vs. 4.3 min), and more pronounced sticky, soft, and chewy textures. Steaming was identified as the most effective pre-gelatinization method for improving flour functionality and enhancing bioactive compound retention.

Keywords: analog rice, anthocyanin, phenolic content, pre-gelatinization, purple sweet potato

INTRODUCTION

Purple sweet potato (*Ipomoea batatas* var. Ayamurasaki) is widely cultivated in West Java and is recognized for its intense purple color derived from anthocyanin pigments, with reported contents ranging from 69.7 to 174 mg/100 g fresh weight (Bennett *et al.,* 2021; Kusnandar *et al.,* 2024a). These anthocyanins are primarily mono- or diacylated derivatives of peonidin and cyanidin, which exhibit strong antioxidant activity and are associated with potential protective effects against oxidative stress-related degenerative diseases (Im *et al.,* 2021; Rosell *et al.,* 2024; Sun *et al.,* 2018). Beyond its traditional use in conventional foods, recent studies have demonstrated the expanding utilization of purple sweet potato as a functional ingredient in formulated products such as biscuits, nuggets, and composite foods, driven by its contributions of dietary fiber, minerals, amino acids, and bioactive compounds, as well as its suitability for processing into flour as a food ingredient (Bakara *et al.,* 2025; Pusparani and Yuwono, 2014).

The functional quality of purple sweet potato flour is significantly influenced by processing conditions, particularly pre-gelatinization, a physical starch modification involving wet heating above the gelatinization temperature followed by drying. Pre-gelatinized flours altered starch structure, improved cold-water solubility, and modified pasting behavior, which are advantageous for food applications (Compart *et al.,* 2023; Ma *et al.,* 2022; Ye and Baik, 2023). Pre-gelatinization can be achieved through several methods, including boiling and steaming, which differ in heat transfer mechanisms and the extent of starch–water interaction and consequently result in distinct physicochemical and functional properties (Kusnandar *et al.,* 2024b). These two methods are particularly relevant because they are widely applied in traditional and small-to-medium-scale starch and flour processing, require minimal equipment, and are considered cost-effective and scalable. Previous studies have shown that pre-

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gelatinization of purple sweet potato stabilized anthocyanins, suppressed enzymatic browning, and modified viscosity and water interaction properties, enabling its use in beverages, instant porridge, ice cream, and analog rice (Fahrullah *et al.,* 2022; Mahmudatussa'adah *et al.,* 2019, 2020; Marta and Tensiska, 2016; Ticoalu *et al.,* 2016). However, no prior study directly compares these two common pre-gelatinization techniques in analog rice application, highlighting a gap in understanding their specific effects on flour properties and product qualities.

Analog rice is typically produced from non-rice flours, such as tubers and legumes, through extrusion processing, with additives such as glycerol monostearate (GMS) used to enhance granule integrity and textural properties (Budijanto *et al.,* 2016). High-quality analog rice is characterized by compact, intact granules that retain structural stability during drying and cooking. However, incorporation of purple sweet potato flour often results in a darker product color, which is generally less preferred by consumers and may limit market acceptance despite its nutritional advantages (Kusnandar *et al.,* 2024b). Pre-gelatinization has been reported to improve color stability and functional performance of purple sweet potato flour; however, systematic comparative studies evaluating the effects of different pre-gelatinization methods—particularly steaming versus boiling—on flour physicochemical properties and their subsequent performance in analog rice formulations remain limited.

Accordingly, this study compares the physicochemical characteristics of non-pre-gelatinized and pre-gelatinized purple sweet potato flours produced by steaming and boiling, and evaluates their effects on the physical, chemical, and sensory qualities of analog rice. The novelty of this research lies in the direct comparison of two practical, industry-relevant pre-gelatinization methods and in elucidating how these modification approaches influence the functional properties of purple sweet potato flour in analog rice formulations. This study addresses a knowledge gap in the development of functional flour and in analog rice processing.

MATERIALS AND METHOD

Materials

Purple sweet potato (*Ipomoea batatas* var. Ayamurasaki) used for flour production was obtained from a local farmer in Dramaga, Bogor, Indonesia, at an elevation of approximately 250 m above sea level. Corn flour (CV Garuda Mas Lestari, Indonesia), sago starch (Javara Sago Starch Flour, Indonesia), and food-grade glycerol monostearate (GMS; PT Samiraschem, Indonesia) used for analog rice formulation were purchased from local markets in Bogor. Chemicals used for analysis included 85% and 80% ethanol (Merck, Germany), potassium chloride buffer (pH 1.0) and sodium acetate buffer (pH 4.5) (Merck), gallic acid standard (Sigma-Aldrich, St. Louis, MO, USA), sodium carbonate (Na_2CO_3) solution (Merck), Folin–Ciocalteu reagent (Sigma-Aldrich), Whatman No. 1 filter paper (GE Healthcare, UK), phosphate buffer solution (pH 6.0) (Merck), Termamyl enzyme (Novozymes, Denmark), and sodium hydroxide (NaOH) solution (Merck).

Preparation of purple sweet potato flour

Three types of purple sweet potato flour were prepared: non-pre-gelatinized flour and pre-gelatinized flours produced by steaming or boiling treatment. Non-pre-gelatinized flour was prepared from 8 kg of selected tubers meeting quality criteria—physiologically mature roots with uniform purple flesh coloration, free from mechanical injury, sprouting, pest infestation, and visible microbial spoilage. The tubers were washed, abrasively peeled, and sliced to approximately 2–3 mm thick to facilitate uniform moisture removal. The slices were arranged in a single layer on perforated stainless-steel trays to ensure uniform airflow and dried in a cabinet dryer (Terada Sesakusho, Japan) at 60 °C for 6 h. Dried slices were cooled to ambient temperature, milled in a pin-disc mill (Hosokawa Micron Corporation, Osaka, Japan), and sieved to obtain flour with an 80-mesh particle size.

Pre-gelatinized flours were produced using the same procedure, with an additional steaming or boiling step applied prior to drying. The processing conditions were selected based on the literature, which indicates that heating tuber flours at atmospheric pressure for 20–30 min effectively induces starch gelatinization while minimizing anthocyanin degradation and structural damage (Sun *et al.,* 2023; Tsakama *et al.,* 2011). For steaming, sliced tubers were arranged in a single layer on a perforated tray above boiling water, without direct contact, and heated at approximately 100 °C for 30 min. For boiling, the slices were cooked in boiling water (100 °C) at a material-to-water ratio of 1:5 (w/v) for 30 min with gentle stirring to ensure uniform heat transfer.

After pre-gelatinization, the samples were drained, spread in a single layer on perforated trays, and dried at 60 °C for 14 h. The longer drying time required for pre-gelatinized samples (6 h) is attributed to their substantially higher moisture content and water-binding capacity following gelatinization, as starch swelling and disruption of the granular structure increase water retention and reduce drying rate. Drying was continued until a comparable final moisture content suitable for milling was achieved before further processing.

All flour samples were subsequently analyzed for physical properties (color and pasting profile) and chemical characteristics, including proximate composition, crude fiber, total phenolics, anthocyanin content, and antioxidant activity.

Preparation of analog rice

Analog rice was prepared following Kusnandar *et al.* (2024b) using a total of 6,120 g of raw materials. The formulation included purple sweet potato flour (2,700 g), corn flour (2,700 g), sago flour (600 g), and glycerol monostearate (GMS, 120 g). The dry ingredients were thoroughly mixed, after which 3,000 mL of water was added and kneaded with a dough mixer until a homogeneous dough was obtained. The dough was then extruded using a twin-screw extruder (Berto Industries, Indonesia) with temperature settings of 87 °C (thermocontrol 1), 85 °C (thermocontrol 2), and 83 °C (thermocontrol 3), a screw speed of 40 Hz, an auger speed of 40 Hz, and a cutter speed of 30 Hz, producing rice-like granules. The wet granules were evenly distributed on drying trays, dried in a cabinet dryer at 60 °C for 30 min, and then cooled to ambient temperature. The dried analog rice was subsequently analyzed for cooking time, chemical composition (anthocyanin content, total phenolics, and antioxidant activity), and sensory qualities.

Color measurement

Color of the flour samples was measured using a chromameter (CR-400, Konica Minolta, Japan) and expressed in the CIE Lab color space, where L represents lightness on a scale from 0 (black/dark) to 100 (white/light), a* indicates the red–green axis (positive values denote redness and negative values denote greenness), and b* represents the yellow–blue axis (positive values denote yellowness and negative values denote blueness). The instrument was calibrated prior to analysis using a standard white reference plate under D65 illuminant conditions with a 2° standard observer. Flour samples were placed in a sample holder to obtain a flat and uniform surface, and color measurements were taken by positioning the measuring head perpendicular to the sample surface. Each sample was measured at three different points, and the results were reported as mean values **.

Pasting profile analysis

The pasting profile of the flour samples was analyzed using a rapid visco analyzer (RVA) (Newport Scientific, Australia) following the procedure described by Balet *et al.* (2019). A 3 g portion of the sample (dry basis) was dispersed in 25 g of water, with adjustments made for moisture content. The suspension was loaded into the RVA, programmed to begin at 50 °C, heat to 95 °C at 12 °C/min, hold at 95 °C for 5 min, then cool back to 50 °C at 12 °C/min, followed by a 2 min hold. The instrument automatically recorded viscosity parameters, including pasting temperature, peak viscosity, hold viscosity, breakdown viscosity, setback viscosity, and final viscosity.

Proximate analysis

Proximate analysis included the determination of moisture content using the oven method (AOAC 925.10, 2016), ash content using the furnace method (AOAC 923.03, 2016), protein content using the Kjeldahl method (AOAC 2001.11, 2016), fat content using the Soxhlet method (AOAC 920.39C, 2016), and carbohydrate by difference. All measurements were performed in triplicate as analytical replicates for each sample. The results were expressed on a wet weight basis.

Crude fiber analysis

Crude fiber analysis was performed according to the AOAC method 978.10 (AOAC, 2016). Each sample was analyzed in triplicate (analytical replicates). The samples were finely milled, and 2 g portions were defatted with hexane. The defatted material was placed in a 600 mL Erlenmeyer flask along with 0.5 g of pre-ignited asbestos and a few drops of antifoaming agent. Using a reflux condenser, the mixture was boiled for 30 min with occasional shaking. After heating, the contents were filtered through a pre-weighed filter paper, and the residue was rinsed with hot distilled water until the reaction was neutral, as confirmed by litmus paper. The residue was then transferred back to the flask, treated with 200 mL of 1.25% (w/v) NaOH solution, and boiled for another 30 min. Filtration was repeated using the same pre-weighed filter paper, followed by sequential washing with 10% K_2SO_4 solution (Sigma-Aldrich, USA), hot distilled water, and 95% ethanol (Sigma-Aldrich, USA). The final residue was dried in an oven at 110 °C until constant weight was achieved. Crude fiber content was reported on a wet weight basis.

Total phenolic content

Total phenolic content was determined using the Folin-Ciocalteu colorimetric assay, a widely accepted standard method for phenolic quantification in food matrices, as described by Martins *et al.* (2021). All extractions and absorbance measurements were carried out in triplicate as analytical replicates. A 0.5 g sample was extracted at room temperature with 10 mL of 80% (v/v) ethanol and vortexed until homogeneous. The extract was centrifuged at 3,000 rpm for 10 min. An aliquot of 0.4 mL supernatant was mixed with 0.2 mL of 50% Folin–Ciocalteu reagent and 4 mL of sodium carbonate solution. After incubation for 30 min at room temperature, absorbance was measured at 750 nm using a UV-Vis spectrophotometer (Shimadzu, Japan). Total phenolic content was expressed as mg gallic acid equivalents (GAE) per 100 g sample, calculated as follows (Equation 1).

$$\text{Total Phenolic Content (mg GAE/100 g)}= \frac{C\times V\times DF}{m}\times 100 \quad (1)$$

C= phenolic concentration obtained from the gallic acid calibration curve (mg GAE/mL), V= total volume of extract (mL), DF= dilution factor, m= mass of sample (g), 100= conversion factor to express results per 100 g sample

Total anthocyanin content

Total anthocyanin content was analyzed using the pH-differential method, an AOAC Official Method 2005.02. Each sample was extracted and analyzed in triplicate (analytical replicates). Sample extraction was performed by mixing 1 g of flour with 10 mL of 85% ethanol (Sigma-Aldrich, St. Louis, MO, USA), then centrifuged at 3,000 rpm for 10 min. An aliquot of 1 mL extract was diluted separately with potassium chloride buffer (pH 1.0) and sodium acetate buffer (pH 4.5). Absorbance was measured at 510 nm using a UV–Vis spectrophotometer. Total anthocyanin content was calculated and expressed as mg cyanidin-3-glucoside equivalents (CyE) per g of sample using the following formula (Equation 2).

$$A= (A_{510}-A_{700})_{pH\ 1.0} - (A_{510}-A_{700})_{pH\ 4.5} \quad (2)$$

Total anthocyanin content was then calculated using the following equation (Equation 3).

$$\text{Total Anthocyanins (mg GAE/100 g)}= \frac{A\times MW\times DF\times V}{\varepsilon\times l\times m} \quad (3)$$

A= absorbance difference between pH 1.0 and pH 4.5, MW= molecular weight of cyanidin-3-glucoside (449.2 g/mol), DF= dilution factor, V= total extract volume (mL), ε= molar absorptivity of cyanidin-3-glucoside (26,900 $L\cdot mol^{-1}\cdot cm^{-1}$), l= path length of the cuvette (1 cm), m= sample mass (g).

Antioxidant capacity

Antioxidant capacity was evaluated using the 1,1-diphenyl-2-picryl-hydrazyl (DPPH) radical scavenging assay following the method of Baba and Malik (2015). All measurements were performed in triplicate. A 0.1 g sample was extracted with 10 mL of methanol, then centrifuged at 3,000 rpm for 10 min. An aliquot of 200 µL extract was mixed with 3.8 mL of 25 ppm DPPH solution, while ascorbic acid served as the positive control. The mixture was incubated in the dark for 1 h, and absorbance was measured at 517 nm using a UV-Vis spectrophotometer. The ability of the sample to scavenge DPPH radical was determined from Equation 4.

$$\text{DPPH Scavenging Effect (\%)}= \frac{OD_{control}-OD_{sample}}{OD_{control}}\times 100 \quad (4)$$

$OD_{control}$= the absorbance of the DPPH solution without sample, OD_{sample}= the absorbance of the sample extract

Cooking time analysis

Cooking time of the analog rice was evaluated using a household rice cooker following the method of Noviasari *et al.* (2013) with modifications by Chaturvedi and Manickavasagan (2024). Each cooking treatment was conducted in triplicate. A water-to-rice ratio of 1:2 was used, with 80 mL of water preheated for 4–5 min until boiling, then added to the rice. Cooking continued until the rice cooker indicator switched from “Cook” to “Off.” Cooking time was recorded from the moment the “Cook” indicator was activated until it turned off.

Sensory analysis

Sensory analysis was conducted using the Rate-All-That-Apply (RATA) method and hedonic rating (Adawiyah *et al.,* 2020) to capture both descriptive sensory characteristics and consumer-oriented responses. The evaluation consisted of three stages: focus group discussion, panelist selection, and sensory test. A trained sensory panel consisting of 15 members (8 males and 7 females) was first engaged in a focus group discussion to systematically generate and refine relevant sensory attributes of analog rice, ensuring accurate terminology, consistency, and relevance of descriptors across samples. During this process, commercial rice samples were used as reference to establish a baseline for attribute description. This inclusion reinforced descriptor consistency and provided concrete anchors for subsequent analysis. The identified attributes were grouped into four categories: color, aroma, taste, and texture, comprising purple color; sweet potato and corn aromas; sweet, bitter, and corn flavors; and sweet and bitter aftertastes.

These attributes were subsequently evaluated using the RATA method by a panel of untrained consumer panelists (50 individuals, 25 males and 25 females) to capture consumer perceptions and variability, as RATA is well-suited for use with non-expert assessors while still providing semi-quantitative intensity data. This combined approach allows trained panelists to establish a robust and product-relevant sensory lexicon, while untrained panelists provide insight into perceived intensity and acceptability from a consumer perspective. Three samples, each coded with a unique three-digit number, were evaluated, and attribute intensities were rated on a 7-point scale.

Data analysis

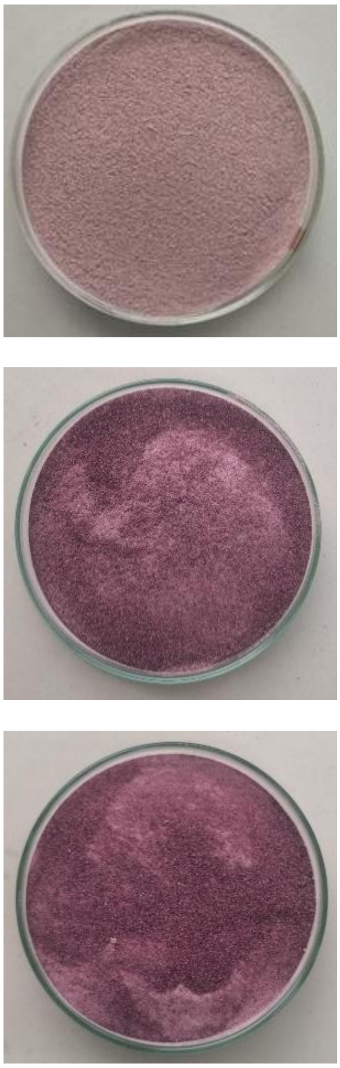
The experiment was designed using a completely randomized design (CRD) as described by Moraes *et al.* (2021). Data were analyzed using analysis of variance (ANOVA) in XLSTAT to evaluate differences among samples for each sensory attribute. The results were verified in IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA, 2017). Mean values and standard deviations were calculated with Microsoft Excel 2019.

RESULTS AND DISCUSSION

Color

Purple sweet potato flour showed significant differences in color depending on the pre-gelatinization treatment (Figure 1). Flour without pre-gelatinization appeared paler, whereas both steaming and boiling produced a more intense purple color, with steaming yielding the most vivid and stable hue. The improved color stability after wet pre-gelatinization is associated with the thermal inactivation of oxidative enzymes and reduced pigment degradation, leading to greater anthocyanin retention. These findings are consistent with previous studies showing that blanching or steaming prior to drying effectively preserves anthocyanins and improves color quality in purple sweet potato flour (Cipriano *et al.,* 2015; Mahmudatussa'adah *et al.,* 2019).

Table 1 shows that pre-gelatinization significantly altered the color of purple sweet potato flour ($p<0.05$). Lightness (L*) decreased from 49.19±0.04 in non-pre-gelatinized flour to 36.69±0.05 and 35.13±0.09 in steamed and boiled flours, respectively, indicating a darker appearance after thermal treatment. Redness (a*) increased significantly with steaming (17.67±0.00) compared with non-pre-gelatinized (11.58±0.06) and boiled flours (13.76±0.18), while boiling resulted in a lower a* value than steaming ($p<0.05$), suggesting greater pigment loss due to direct water contact. The b* value also differed significantly among treatments ($p<0.05$), shifting from positive in non-pre-gelatinized flour (7.22±0.03) to near-neutral or negative in steamed flour (−0.16±0.01), indicating enhanced bluish-purple tones, with boiled flour showing an intermediate value (1.34±0.03). Overall, steaming more effectively intensified purple coloration than boiling by improving anthocyanin expression and stability. This increase in the a* value correlates with consumer preferences for more intense purple, as revealed in the RATA sensory scores for analog rice, where steamed purple sweet potato flour incorporation was favored for its vibrant color.



A

B

C

Figure 1. Purple sweet potato flour without pre-gelatinization (A), pre-gelatinization (steaming) (B), and pre-gelatinization (boiling) (C)

Pasting profile

The pasting profiles of purple sweet potato flour are summarized in Table 2. The pasting onset temperature was relatively high for non-pre-gelatinized flour (80.9 °C), which can be attributed to its amylose content (commonly reported at 8–23% in sweet potato starch). Higher amylose levels require more energy to disrupt hydrogen bonding and initiate gelatinization (Ambarsari *et al.,* 2020).

Table 1. Color attributes of purple sweet potato flour (with and without pre-gelatinization treatment)

Purple Sweet Potato Flour	Color Attributes		
	L*	a*	b*
Without pre-gelatinization	49.19±0.04[a]	11.58±0.06[b]	7.22±0.03[a]
With pre-gelatinization (steaming)	36.69±0.05[b]	17.67±0.00[c]	-0.16±0.01[b]
With pre-gelatinization (boilding)	35.13±0.09[c]	13.76±0.18[a]	1.34±0.03[c]

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

Table 2. Pasting profile of purple sweet potato flour (with and without pre-gelatization treatment)

Pasting Profile	Purple Sweet Potato Flour		
	Without Pre-Gelatinization	Pre-Gelatinization (Steaming)	Pre-Gelatinization (Boiling)
Heating phase			
Pasting onset temperature (°C)	80.9	–	–
Peak viscosity (cP)	1304.0	660	874
Breakdown viscosity (cP)	203.0	–	–
Viscosity at 95 °C (cP)	1101.0	661	874
Cooling phase			
Setback viscosity (cP)	668.0	350	611
Final viscosity (cP)	1769.0	1011	1485

In contrast, the pasting onset temperature of pre-gelatinized flours, whether steamed or boiled, could not be determined because the starch had already gelatinized prior to drying. Overall, non-pre-gelatinized flour exhibited the highest pasting profile, with the greatest final viscosity (1,769 cP), while pre-gelatinized flours showed lower pasting values. During heating, non-pre-gelatinized flour displayed an initial viscosity increase, followed by breakdown and a subsequent setback during cooling. Conversely, both pre-gelatinized flours (steamed and boiled) showed no viscosity breakdown during heating, and viscosity increased gradually during cooling. Among the samples, steaming treatment produced the lowest setback value (350 cP) compared with boiling treatment (611 cP) and non-pre-gelatinized flour (668 cP), indicating that steaming is more effective in reducing retrogradation and syneresis.

These findings are consistent with the results of Nurdjanah *et al.* (2021), who reported that preheating treatments decreased the pasting properties of purple sweet potato flour. Their study showed that native flour exhibited higher peak, breakdown, and setback viscosities compared with preheated samples. The reduction in peak viscosity was attributed to a lower degree of gelatinization, while prolonged preheating further reduced breakdown viscosity, reflecting decreased granule disintegration.

Chemical composition

Table 3 presents the proximate composition of purple sweet potato flour, both untreated and pre-gelatinized by steaming or boiling, including moisture, ash, fat, protein, carbohydrate, and crude fiber contents. Moisture contents ranged from 6.71 to 7.29% (wb), with the boiled treatment showing slightly higher values, likely due to greater water absorption during pre-gelatinization. These values are somewhat higher than those reported by Widhasari and Putri (2014), who found 6.44–6.66%. The discrepancy may stem from differences in steaming time (5 min compared with 20 min in the present study) and variations in drying conditions. Comparable findings have been reported by Truong *et al.* (2012), who also observed that pre-treatment and drying processes significantly affect the residual moisture of purple-fleshed sweet potato flour.

Ash content, reflecting mineral levels, was 2.24% wb in non-pre-gelatinized flour, 2.28% wb in steamed flour, and 1.57% wb in boiled flour. The steamed sample aligns with previous reports (Husna *et al*., 2013; Widhasari and Putri, 2014). Differences may be influenced by harvest maturity, as later harvests enhance mineral uptake (Yaningsih *et al*., 2013), and by moisture content, with higher moisture levels correlating with lower ash content. Statistical analysis showed that pre-gelatinization significantly affected ash content (p<0.05).

Fat content was 0.99% wb in non-pre-gelatinized flour, 0.62% wb in steamed flour, and 0.95% wb in boiled flour. The reduction in fat content observed in the steamed flour can be attributed to the combined effects of thermal treatment and moisture exposure, which may promote lipid leaching, oxidation, or complex formation with gelatinized starch during heating. Steaming, which involves prolonged exposure to high temperature and water vapor, likely facilitated partial lipid migration or degradation, whereas boiling showed a smaller reduction, possibly due to shorter effective interaction between lipids and water following subsequent drainage and drying.

Protein content ranged from 3.22 to 3.91% wb, with the highest value observed in boiled flour and the lowest in non-pre-gelatinized flour. The apparent increase in protein content after boiling may result from concentration effects associated with starch gelatinization and partial solubilization or leaching of low-molecular-weight carbohydrates during boiling, thereby increasing the relative proportion of protein in the dry matter. Thermal processing may also induce protein denaturation, exposing hydrophobic and hydrophilic groups, thereby improving protein retention during drying and milling rather than causing significant protein loss. Carbohydrate content, calculated by difference, ranged from 86.28% to 87.06% wb. Crude fiber was 4.73% wb in non-pre-gelatinized flour, 5.78% wb in steamed flour, and 5.81% wb in boiled flour, higher than the 3.34% wb reported by Husna *et al.* (2013) for pre-gelatinized flour.

Total phenolic content, anthocyanin, and anti-oxidant capacity

Phenolic compounds, classified as secondary metabolites in plants, are well known for their antioxidant capacity, which largely stems from the ability of their hydroxyl groups to donate hydrogen atoms and stabilize free radicals. Total phenolic content is commonly used as an indicator of antioxidant capacity in plant-based materials (Handayani *et al.,* 2017). In this study, total phenolic content of purple sweet potato flour—both non-pre-gelatinized and pre-gelatinized—ranged from 78.69 to 122.50 mg GAE/100 g (Table 4). Non-pre-gelatinized flour had the lowest phenolic content (78.69 mg GAE/100 g), while pre-gelatinized flours exhibited higher values, from 100 to 122.5 mg GAE/100 g.

Pre-gelatinization prior to drying enhances total phenolics by altering the plant matrix and facilitating the release of phenolic compounds (Phomkaivon *et al.,* 2018). Thermal treatment can degrade heat-sensitive phenolics, but in some cases, it increases extractable phenolic content by breaking down complex polyphenols into smaller molecules (Ruttarattanamongkol *et al.,* 2016; Tokusoglu and Yildirim, 2012). Pre-gelatinization also enhances anthocyanin content, the primary pigments in purple sweet potato, predominantly acylated 3,5-diglucosides of cyanidin and peonidin, which are more stable after heat treatment. Steaming, in particular, improved color intensity and pasting profile, making flour more suitable for food applications.

Anthocyanin is sensitive to heat and pH changes, exhibiting color shifts across pH values (red at pH 1, purple at pH 7, blue at pH 10). Heat can degrade this pigment, causing color loss; steaming preserves brightness, whereas baking may result in fading (Mahmudatussa'adah *et al.,* 2019). In this study, steaming treatment yielded the highest anthocyanin concentration (0.77 mg CyE/g), followed by boiling (0.63 mg CyE/g) and non-pre-gelatinized flour (0.48 mg CyE/g), with statistical analysis confirming significant effects of both treatments ($p<0.05$). These values align with those of Phomkaivon *et al.* (2018) but are lower than those of Mahmudatussa'adah *et al.* (2019), likely due to differences in steaming duration (20 min vs. 7 min).

Table 3. Chemical composition of purple sweet potato flour without and with pre-gelatinization treatments

Chemical Composition	Purple Sweet Potato Flour		
	Non-pre-gelatinized	Pre-gelatinized (Steaming)	Pre-gelatinized (Boiling)
Moisture (% wb)	6.71±0.02[c]	6.81±0.01[b]	7.29±0.02[a]
Ash (% wb)	2.24±0.00[b]	2.28±0.01[a]	1.57±0.00[c]
Fat (% wb)	0.99±0.00[b]	0.62±0.01[c]	0.95±0.00[a]
Protein (% wb, N=6.25)	3.55±0.02[b]	3.22±0.03[c]	3.91±0.01[a]
Carbohydrate (% wb)	86.52±0.00[b]	87.06±0.04[a]	86.28±0.02[c]
Crude fiber (% wb)	4.73±0.00[b]	5.78±0.02[a]	5.81±0.01[a]

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

Table 4. Total phenolic content, anthocyanin concentration, and antioxidant capacity of purple sweet potato flour without and with pre-gelatinization

Sample	Total Phenolic (mg GAE/100 g, db)	Anthocyanins (mg CyE/g)	Free Radical Scavenging Activity (% inhibition)
Non-pre-gelatinized	78.69±0.86[c]	0.48±0.00[c]	74.71±0.17[c]
Pre-gelatinized (steaming)	122.50±0.69[a]	0.77±0.00[a]	84.05±0.08[b]
Pre-gelatinized (boiling)	100.02±0.87[b]	0.63±0.01[b]	97.70±0.14[a]

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

The DPPH assay is commonly employed to evaluate free radical scavenging capacity. In this study, the scavenging activity was 74.71% for non-pre-gelatinized flour, increased to 84.05% after steaming, and reached 97.70% following boiling. Pre-gelatinization significantly increased both total phenolics and antioxidant activity (p<0.05). Boiling led to higher antioxidant activity than steaming, likely due to enhanced release of bioactive compounds from disrupted plant tissue (Musilová *et al.*, 2020). Nurdjanah *et al.* (2017) reported that pre-heating purple sweet potato at 90 °C for increasing durations (15–75 min) enhanced the retention of total phenolic content and anthocyanin compared with untreated flour. The longer pre-heating times resulted in higher levels of both bioactive compounds, suggesting that heat treatment improved extractability and stability by disrupting cell structures. In addition, pre-heated flours exhibited greater antioxidant activity, consistent with higher phenolic and anthocyanin retention, indicating that controlled pre-heating can preserve, and even improve, the functional properties of purple sweet potato flour.

Color

Three analog rice formulations were prepared using purple sweet potato flour subjected to different pre-gelatinization treatments: non-pre-gelatinized flour, steam-pre-gelatinized flour, and boil-pre-gelatinized flour (Figure 2). Pre-gelatinization significantly affected the color characteristics of the resulting analog rice (p<0.05). Rice prepared from non-pre-gelatinized flour exhibited the highest lightness (L*= 37.42±0.49), indicating a paler purple appearance. In contrast, rice produced from steamed pre-gelatinized flour showed a significantly lower L* value (24.33±0.02), reflecting a darker and more intense purple color. Rice from boiled pre-gelatinized flour displayed an intermediate L* value (34.11±0.02), suggesting partial pigment loss during boiling.

Redness (a*) differed significantly among treatments (p<0.05), with boiled flour producing rice with the highest a* value (8.27±0.07), followed by non-pre-gelatinized (7.69±0.01) and steamed flours (6.35±0.02). Similarly, b* values varied significantly (p<0.05), decreasing from 7.87±0.04 in non-pre-gelatinized rice to 3.00±0.01 in steamed rice, indicating a stronger bluish-purple hue, while boiled rice showed an intermediate b* value (4.87±0.05). These trends are consistent with the color characteristics of the corresponding flours (Table 5), confirming that steaming more effectively preserves anthocyanin stability and produces a deeper, more desirable purple color in analog rice, whereas boiling results in partial pigment leaching.

A B C

Figure 2. Appearance of analog rice made from purple sweet potato flour without pre-gelatinization (A), pre-gelatinization (steaming) (B), and pre-gelatinization (boiling) (C)

Table 5. Physical characteristics of purple sweet potato-based analog rice (color parameters and cooking time)

Physical Characteristics of Analog Rice	Purple Sweet Potato Flour		
	Without Pre-Gelatinization	Pre-Gelatinization (Steaming)	Pre-Gelatinization (Boiling)
Color			
L*	37.42±0.49[a]	24.33±0.02[c]	34.11±0.02[b]
a*	7.69±0.01[b]	6.35±0.02[c]	8.27±0.07[a]
b*	7.87±0.04[a]	3.00±0.01[c]	4.87±0.05[b]
Cooking time (min)	4.33±0.06[a]	3.33±0.04[b]	3.42±0.03[b]

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

Cooking time

Cooking time is a critical parameter of analog rice quality, as it influences texture and sensory acceptability of the final product. As shown in Table 5, analog rice produced from pre-gelatinized purple sweet potato flour exhibited shorter cooking times (3.4 min for steamed flour and 3.3 min for boiled flour) compared with 4.3 min for rice produced from non-pre-gelatinized flour. Thus, the observed reduction in cooking time should be interpreted as a relative improvement due to pre-gelatinization rather than as an absolute comparison across all samples. The shorter cooking time is attributed to structural modifications in starch induced by pre-gelatinization, which partially gelatinizes the starch and forms a softer matrix with more open pores. These pores facilitate faster water penetration and heat transfer during cooking, thereby accelerating gelatinization. In contrast, non-pre-gelatinized flour retains native starch granules, which require longer hydration and swelling. These findings are consistent with Ulfa *et al.* (2021), who reported that pre-gelatinization enhances water absorption and reduces cooking time in starch-based products.

Total phenolic content, anthocyanin, and antioxidant capacity

Table 6 presents the total phenolic content, anthocyanin concentration, and antioxidant properties of analog rice produced from purple sweet potato flour with and without pre-gelatinization. Analog rice made from pre-gelatinized flour exhibited higher total phenolic content, anthocyanin concentration, and antioxidant activity compared to rice from non-pre-gelatinized flour, consistent with the trends observed in the corresponding flours (Table 4). As explained previously, this improvement can be attributed to the inactivation of polyphenol oxidase during the pre-gelatinization step, which reduces oxidative degradation of phenolic compounds and anthocyanins, thereby enhancing their retention in the flour and, consequently, in the analog rice (Cipriano *et al.,* 2015; Mahmudatussa'adah *et al*., 2019).

Nevertheless, the absolute values of total phenolics and anthocyanins in analog rice were lower than those in the flours, largely due to dilution by other ingredients used in the formulation. Similar reductions in bioactive compound concentration after product formulation have been reported in composite or analog food systems, where carrier ingredients decrease the relative proportion of phenolic-rich components (Handayani *et al.,* 2017). Despite this dilution effect, the incorporation of purple sweet potato flour still conferred a measurable antioxidant advantage compared to rice made from non-pigmented or refined flours.

Sensory quality

The analog rice samples evaluated in this study were prepared from purple sweet potato flour without pre-gelatinization, with pre-gelatinization by steaming, and with pre-gelatinization by boiling, as shown in Figure 2. Their sensory attribute profiles and interrelationships are presented in the PCA biplot (Figure 3), which integrates sensory responses with processing-induced functional changes. Samples produced from pre-gelatinized flour (B and C) were located in Quadrant IV, indicating a sensory profile distinct from that of the non-pre-gelatinized sample (A).

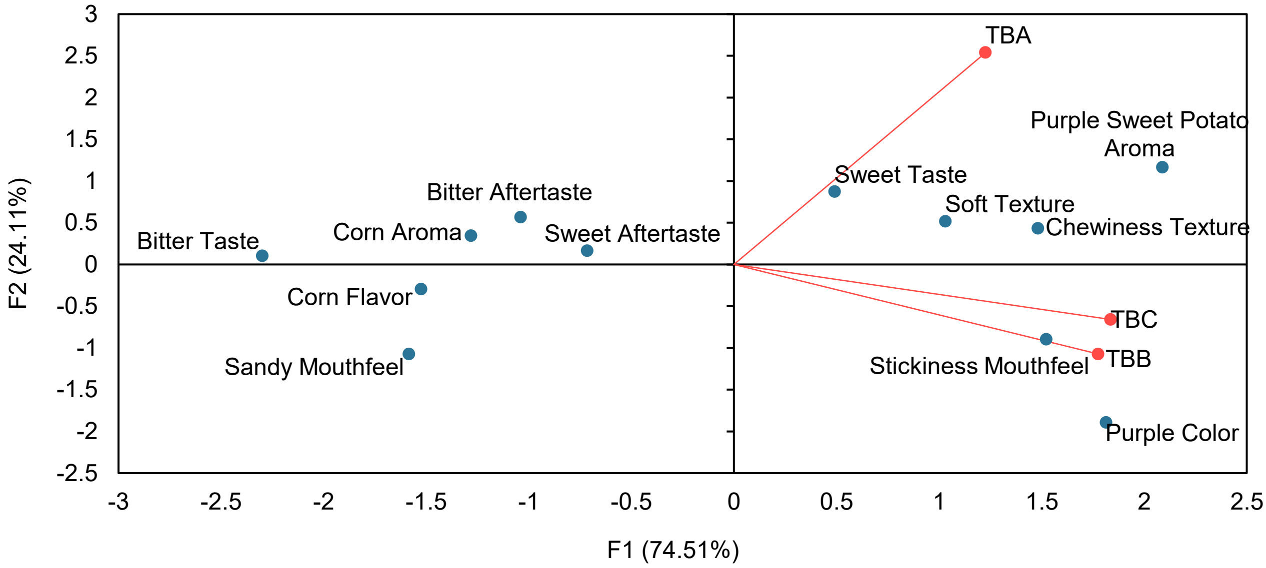
In contrast, samples from non-pre-gelatinized flour were positioned in Quadrant I, indicating clear sensory differentiation driven by flour treatment. Correlations among sensory attributes can be inferred from their relative positions: attributes located opposite each other indicate negative correlations, while those positioned close together at angles <90° indicate positive correlations (Sarwar *et al.,* 2022). Accordingly, a positive correlation reflects a concurrent increase in attributes, whereas a negative correlation indicates an inverse relationship.

Bitter taste showed a negative correlation with sweet taste, suggesting that enhanced sweetness effectively masked bitterness perception, a sensory interaction generally associated with improved consumer acceptability. The purple color attribute correlated positively with stickiness, indicating that greater pigment retention was associated with a more cohesive mouthfeel. Similarly, sweet taste was positively associated with soft and chewy textures and a more pronounced purple sweet potato aroma. These sensory associations are consistent with instrumental observations: pre-gelatinization promoted starch gelatinization and pigment stability, thereby influencing both color intensity and textural properties. Analog rice produced from pre-gelatinized flour (steamed and boiled) clustered with dominant attributes of purple color and stickiness, reflecting the role of pre-gelatinization in modifying starch structure and enhancing sensory cohesiveness.

Table 6. Moisture content, total phenolics, anthocyanin and antioxidant capacity of purple sweet potato-based analog rice (without and with pre-gelatinization)

Purple Sweet Potato Flour	Moisture Content (% wb)	Total Phenolics (mg GAE/100 g, db)	Anthocyanin Content (mg CyE/g)	Free Radical Scavenging Activity (% inhibition)
Non-pre-gelatinized	8.44±0.13^{ab}	73.47±0.88^{b}	0.22±0.01^{b}	35.87±0.16^{b}
Pre-gelatinized (steaming)	8.66±0.02^{ab}	89.20±1.41^{a}	0.37±0.01^{a}	65.81±0.41^{a}
Pre-gelatinized (boiling)	8.83±0.03^{a}	85.50±1.88^{a}	0.40±0.02^{a}	64.08±0.07^{a}

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



Note: TBA= analog rice (non-pre-gelatinized purple sweet potato flour), TBB = analog rice (steamed pre-gelatinized flour), TBC= analog rice (boiled pre-gelatinized flour)

Figure 3. PCA biplot (98.62%) based on panelists' evaluation using the RATA method (n= 50)

The RATA sensory data are further illustrated in the spider web chart (Figure 4), which highlights distinct attribute intensities across samples. Analog rice made from non-pre-gelatinized flour exhibited the highest intensities for corn aroma (2.37), bitter taste (2.09), and bitter aftertaste (2.54), consistent with its higher final and setback viscosities, which contributed to a firmer and less cohesive texture. Such firmness, coupled with bitterness, may negatively influence consumer acceptance, particularly for staple foods expected to be mildly flavored. In contrast, rice from steamed pre-gelatinized flour showed the highest scores for purple color (4.56), purple sweet potato aroma (3.63), sweet taste (3.17), sweet aftertaste (2.61), sticky mouthfeel (4.22), soft texture (3.37), and chewy texture (3.61). Rice from boiled pre-gelatinized flour exhibited the highest corn flavor intensity (2.20). The dominance of sticky, soft, and chewy textures in steamed analog rice corresponds closely with its pasting profile, characterized by reduced final and setback viscosity. Lower viscosity values in pre-gelatinized flours, particularly those subjected to steaming, facilitate the formation of cohesive yet elastic gels, which are perceived sensorially as sticky and chewy while reducing firmness compared with non-pre-gelatinized samples. In West Java, where rice is a staple, the cultural preference leans towards moderately sticky. This is especially true for traditional dishes, which often enhance the overall dining experience with such textures. While moderate stickiness is considered desirable in several rice-consuming cultures for enhancing cohesiveness and palatability, excessive stickiness may deviate from the textural benchmark of conventional rice and reduce acceptance among consumers accustomed to firmer, more discrete grains. Therefore, although pre-gelatinization improves color stability and softens texture, optimization of stickiness is critical to align sensory properties with consumer expectations for analog rice products.

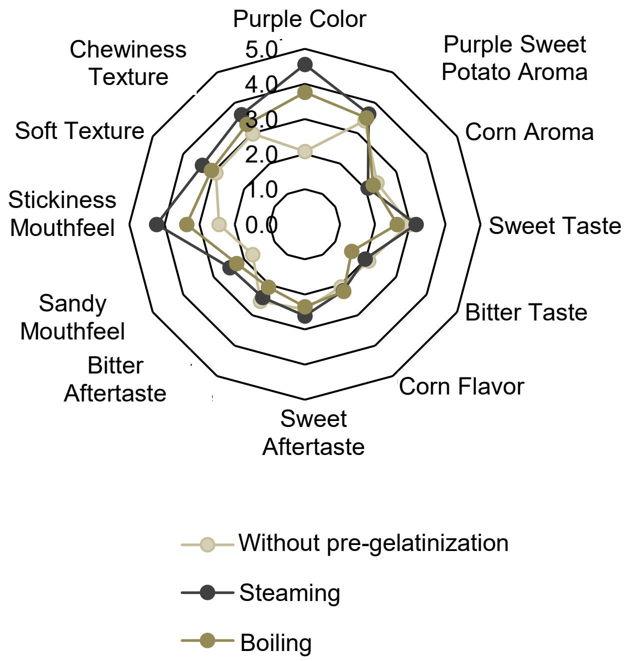


Figure 4. Spider web chart of the combined sensory profiles of three purple sweet potato-based analog rice products based on RATA evaluation by untrained panelists

Overall, this study demonstrates that improvements in color retention and functional stability achieved through flour pre-gelatinization are directly reflected in measurable sensory attributes of the final analog rice product, confirming the relationship between processing, structure, and sensory acceptability. From a practical standpoint, the findings indicate that steaming is a technically simple, energy-efficient, and scalable pre-gelatinization method suitable for adoption by small- and medium-scale sweet potato flour processors without specialized equipment. The resulting flour possesses functional properties appropriate for analog rice extrusion, yielding products with enhanced color stability, cohesiveness, and acceptable textural characteristics. However, careful control of processing parameters is necessary to prevent excessive stickiness and ensure that textural properties remain within consumer-acceptable ranges comparable to those of conventional rice.

Despite these promising results, it is important to acknowledge the limitations of this study. One key caveat is the transition from laboratory-scale extrusion to industrial-scale throughput, which could introduce variability in product quality and consistency. Additionally, while steaming has been identified as the most effective pre-gelatinization method in this context, its scalability at an industrial level requires further investigation to ensure the process remains cost-effective and practical. These limitations underline the need for continued research to optimize processing parameters and validate findings in commercial settings.

These findings suggest that pre-gelatinization of purple sweet potato flour is a practical and scalable strategy for small- and medium-scale analog rice production. The observed improvements in cooking time, extrusion behavior, texture, and sensory attributes contribute to enhanced process efficiency and product consistency, particularly important for processors with limited energy resources and limited process control. Furthermore, the retention of antioxidant activity, combined with acceptable sensory quality, underscores the potential to develop value-added, health-oriented analog rice products utilizing locally available raw materials.

CONCLUSION

Pre-gelatinization of purple sweet potato (*Ipomoea batatas* var. Ayamurasaki) flour by steaming or boiling enhanced functional properties without affecting proximate composition. Steaming showed superior performance, resulting in higher color brightness, greater retention of phenolic and anthocyanin, and stronger antioxidant activity, likely due to reduced leaching of water-soluble compounds compared with boiling. Both treatments reduced pasting viscosity relative to untreated flour, with steamed flour exhibiting the greatest decreases in final and setback viscosity, indicating improved starch stability and a lower retrogradation potential. When applied to analog rice, steamed pre-gelatinized flour produced grains with a softer, more cohesive, and characteristically sticky texture, whereas boiling yielded moderately softened grains with lower stickiness and less cohesive structure. Steaming represents the most promising pre-gelatinization method for enhancing color retention, antioxidant functionality, and textural cohesiveness, while further optimization of formulation and processing is needed to balance stickiness and flavor and to improve consumer acceptance of purple sweet potato-based analog rice.

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