

Comparison of Parboiling- Induced Changes in Starch Crystallinity and Functional Properties of Brown Rice for Functional Food Applications

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Abstract. The Makan Bergizi Gratis program emphasizes the need for safe, affordable, and nutritionally complete foods that are easy to prepare and distribute. Brown rice, rich in dietary fiber and bioactive compounds with a low glycemic index, is a promising candidate for such programs. However, its functional properties can be enhanced through processing, particularly parboiling. This study investigated the effects of parboiling on the structural and functional properties of two local brown rice cultivars from East Kalimantan (SMC 279 and SMC 213). The focus was on starch crystallinity, swelling power, water absorption, oil absorption, specific gravity, and wettability to assess their suitability for biscuit production. Parboiling reduced starch crystallinity, as shown by X-ray diffraction (XRD), with weaker and broader peaks indicating a transition to more amorphous starch. Functionally, swelling power increased by approximately 7.5 times, water absorption nearly doubled (1.12–1.34% to 2.02–2.77%), and wettability improved by 2.15–9.71 times. Oil absorption (2.15–3.60%) and specific gravity (0.56–0.71 g/mL) showed minimal changes, reflecting their dependence on grain density and porosity. Cultivar-specific differences were observed, influenced by starch composition and granule architecture. In conclusion, parboiling enhances the functional and water-responsive properties of brown rice without compromising its density or oil-binding characteristics, making it a scalable, nutritious ingredient for biscuit production and other foods aligned with the Makan Bergizi Gratis initiative.

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1 Introduction

The Makan Bergizi Gratis program highlights the urgent need for safe, affordable, easy-to-transport, and nutritionally complete food solutions that can be made accessible to diverse communities. Staple-based functional ingredients are especially valuable for such programs, as they deliver both energy and essential nutrients in a cost-effective way. Brown rice is a strong candidate because, unlike polished white rice, it retains the bran layer, an important source of dietary fiber, micronutrients, and natural antioxidants such as phenolic acids, flavonoids, and anthocyanins. These bioactive compounds contribute to long-term health protection against chronic diseases including diabetes, cardiovascular disorders, and hypertension [1, 2].

With its lower glycemic index, brown rice also provides slower digestion and absorption, leading to better glycemic control and improved insulin sensitivity in individuals with type 2 diabetes [3]. At the same time, promoting local brown rice cultivars strengthens food sovereignty, supports traditional farming systems, and contributes to sustainable food security goals. Our research focuses on East Kalimantan brown rice cultivars, which combine nutritional potential with strong adaptability to tropical humid climates and iron-rich soils. These cultivars contain high levels of β -carotene and α -tocopherol, both of which are vital antioxidants. Previous work from our team successfully developed encapsulation systems for β -carotene using nanostructured lipid carriers [4,5], improving stability and bioavailability in food systems [6,7,8]. Such enrichment strategies are critical for ensuring the health benefits of lipophilic bioactives while maintaining food matrix compatibility.

Among the ten local brown rice cultivars evaluated previously [4], SMC 279 and SMC 213 clearly stood out because of their consistent grain quality, strong nutritional composition, and promising functional performance after parboiling. Unlike other cultivars that showed more broken or unevenly colored grains, both SMC 279 and SMC 213 had uniform grain appearance, making them reliable for flour processing and standardization. Beyond appearance, they also carry elevated levels of β -carotene and α -tocopherol, two key antioxidants that enhance the nutritional profile of the flour. Their combination of stable grain quality, improved hydration-related traits, and high bioactive content makes them strong candidates for producing scalable, nutrient-rich food products.

The functional and physical properties of brown rice are strongly influenced by processing. Parboiling, a hydrothermal treatment, reduces starch crystallinity while increasing swelling power, water absorption, and wettability, thereby improving flour functionality for food processing [9,10]. Our recent SEM and XRD analyses confirmed that parboiling disrupts starch granule order and enhances hydration behavior in local cultivars such as SMC 279 and SMC 213. These changes are particularly relevant for biscuit applications, where hydration capacity and dough handling directly affect product quality and processing efficiency. By combining parboiling with bioactive enrichment, this study aims to position East Kalimantan brown rice as a Food for Special Purposes (PTT) or food for particular purposes. To our knowledge, this is the first evaluation of local East Kalimantan brown rice cultivars for biscuit applications, highlighting both their improved functional flour properties and their nutritional potential as scalable ingredients for programs like Makan Bergizi Gratis.

This research aims to evaluate how parboiling alters the structural and functional properties of brown rice particularly its starch crystallinity, hydration behavior, oil absorption, specific gravity, and wettability and to establish cultivar-dependent differences that determine its potential as a functional ingredient in food applications such as biscuits.

2 Method

2.1. Material

The material used in this study was brown rice grains, which were processed through parboiling, milling, and flouring. Additional materials included distilled water and commercial cooking palm oil. The equipment utilized consisted of a parboiling unit (soaking container, steamer, dryer), X-ray diffractometer (XRD), water bath, centrifuge (3500 rpm), vortex mixer, measuring cylinders (100 mL), analytical balance (± 0.001 g), stopwatch, milling machine, and standard laboratory glassware such as centrifuge tubes and beakers.

2.2. Experimental Design

The experiment was conducted using a Completely Randomized Design (CRD) with two factors: cultivar (SMC 279 and SMC 213) and treatment (unparboiled and parboiled). Each treatment combination was replicated three times. The measured response variables included swelling power, water absorption, oil absorption, specific gravity, and wettability.

2.2.1. Parboiling Rice

The parboiling process of rice consists of several interrelated stages. The first step is cleaning, where impurities such as stones, dust, and straw residues are removed to ensure that only sound paddy grains proceed to the next stage. The cleaned paddy is then soaked in clean water at room temperature or slightly elevated temperatures (about 25–70 °C) for 3 to 24 hours, which raises the grain moisture content to around 30–35% and makes starch gelatinization possible. After soaking, the paddy undergoes steaming, where it is exposed to steam at 100–120 °C for a few minutes up to half an hour. This process gelatinizes the starch and transfers nutrients from the outer layers into the endosperm. The steamed paddy is then dried in stages initial drying, tempering, and final drying until the moisture content reaches 12–14%, ensuring stability during storage. Drying can be done by sun drying or mechanical methods such as hot air dryers or fluidized bed dryers, with careful control to prevent grain cracking. The final step is milling, which removes the husk and polishes the grains. Parboiled rice has several advantages, including a higher head rice yield, improved nutritional quality due to better retention of vitamins and minerals, and longer shelf life with reduced susceptibility to insect infestation. However, parboiled rice typically appears darker, has a stronger aroma, and requires a longer cooking time compared to raw rice [10].

2.2.2. XRD Analysis

XRD measurements were performed using a Bruker Endeavour diffractometer (model D4/max-B, Germany) with Cu K α radiation (40 kV, 20 mA). The diffraction patterns were recorded over a 2θ range from 4° to 50°, with a step size of 0.02° and a scan rate of 0.02°/s to ensure high resolution and accuracy. The resolution was set at 0.02° for precise peak identification, allowing for reliable quantification of starch crystallinity and providing clear

insights into the impact of parboiling on the starch structure [11]. The degree of crystallinity was determined by analyzing the XRD patterns using the Brückner and Frost methods. The crystalline peaks were isolated from the amorphous scattering region of the XRD data, and the relative crystallinity was calculated as the ratio of crystalline area to total area under the diffractogram. These values are expressed as % relative crystallinity.

2.2.3 Swelling Power

The flour sample was weighed at 0.5 g and was placed into a pre-weighed centrifuge tube. Ten milliliters of distilled water to the tube, followed by homogenization using a vortex. Subsequently, the sample underwent a 30-minute heating process in a water bath at 60°C with occasional stirring, followed by rapid cooling in ice water for 1 minute. After allowing the mixture to stand at room temperature for 5 minutes, the brown rice sample was centrifuged at 3500 rpm for 15 minutes. The resulting gel was then weighed and expressed as swelling power (g/g dry basis) [12].

2.2.4. Water Absorption

The flour sample was weighed at 1g and placed into a centrifuge tube, followed by the addition of 10 mL of distilled water. The mixture was stirred using a vortex mixer for 30 seconds. Afterward, the sample was left at room temperature for 30 minutes and then subjected to centrifugation at 3500 rpm for 30 minutes. The supernatant was carefully decanted, and the water absorption capacity was quantified as the weight percentage of water absorbed by 1 g of the flour sample [13].

2.2.5. Oil absorption

The flour sample was weighed at 1g and placed into a centrifuge tube, followed by the addition of 10 mL of commercial cook palm oil, followed by vortexing for 30 seconds. Subsequently, the sample was let at room temperature for 30 minutes and was then centrifuged at 3500 rpm for 30 minutes. After centrifugation, the supernatant was carefully decanted, and the oil absorption capacity was quantified as the weight percentage of oil absorbed by 1 g of the flour sample.

2.2.6. Bulk Density and Wettability

Bulk density and wettability measurements were carried out employing method from and [15]. The brown rice flour was weighed at 10 grams, then put into a pre-weighted 100 ml sized measuring glass. The bottom of the measuring cup is tapped several times to obtain a constant volume. The bulk density (g/mL) was measured as weight of sample (g) divided by volume (mL). Wet time refers to the duration it took for brown rice flour to become completely wet after it was introduced with water. In this test, brown rice sample was weighted at 0.4 g and was introduced into 40 milliliters of distilled water within a measuring cup. The dispersion process was conducted at room temperature, and no stirring was applied. The time it took for a complete wetting was then recorded using a stopwatch (in seconds).

2.2.7. Statistical Analysis

Data were analyzed using one-way ANOVA to determine the effect of parboiling within each cultivar, followed by Duncan's Multiple Range Test (DMRT) at $p < 0.05$ to separate means. All statistical analyses were performed using Microsoft Excel 2019. Results are expressed as mean \pm standard deviation (SD). To evaluate the relationship between the functional properties and structural properties of brown rice, Pearson correlation analysis was performed. The functional properties analyzed include swelling power, water absorption, oil absorption, and wettability, while the structural properties include crystallinity values derived from XRD analysis. The Pearson correlation coefficient (r) was calculated to determine the strength and direction of the linear relationship between the functional and structural properties. A significance level of $p < 0.05$ was used to determine statistically significant correlations.

3 Result and Discussion

3.1 Physical observation

The two cultivars of brown rice, SMC 279 (left) and SMC 213 (right), exhibit subtle yet significant visual differences. SMC 279 grains are generally slimmer with slight variations in reddish-brown hues, while SMC 213 grains are plumper, broader, and more uniform in color (Figure 1). These physical differences are not merely cosmetic; they often reflect variations in starch composition, granule size, and bran thickness, which can influence how the rice behaves during processing. For example, slimmer grains may gelatinize and absorb water differently than bulkier grains, affecting the texture when used as an ingredient. Both cultivars will undergo parboiling before being milled into flour for biscuit production. Parboiling improves hydration, swelling power, and wettability by reducing starch crystallinity, enhancing the flour's functionality in baked goods. This is particularly important for biscuits, where texture and moisture control are essential. Research indicates that parboiled brown rice flour not only improves baking performance but also enhances the nutritional quality of the final product by preserving dietary fiber and bioactive compounds from the bran [16,17].

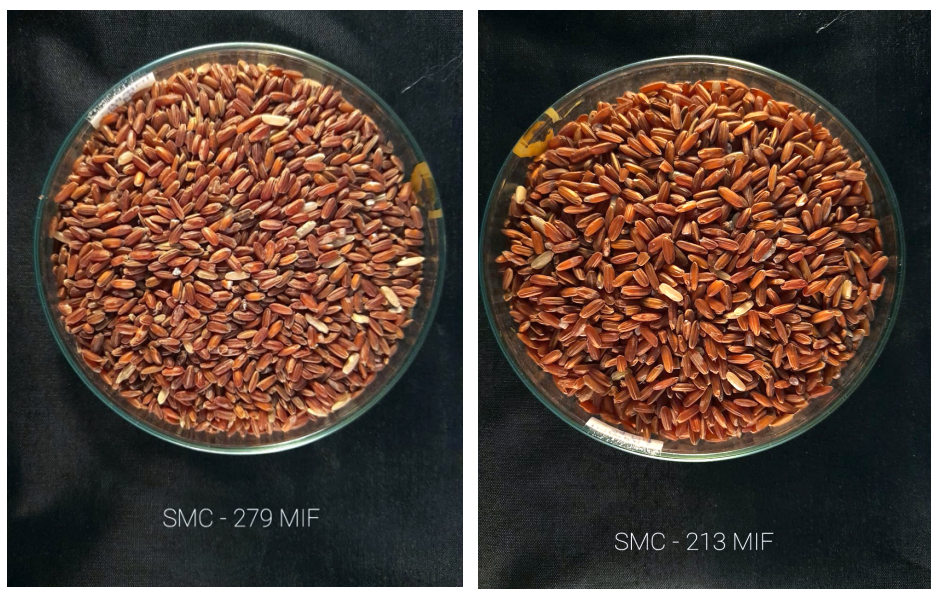


Fig 1. SMC 279 and 213 as two cultivars of locally produced brown rice.

3.2 XRD profiles of the selected unparboiled and parboiled brown rice cultivars

The XRD profiles (Figure 2) show that parboiling disrupts the crystalline structure of brown rice starch. In the untreated state, sharp diffraction peaks at $2\theta \approx 15-17^\circ$ and $22-24^\circ$ indicate the presence of ordered crystalline regions, typical of A-type cereal starch [18]. After parboiling, these peaks weaken and broaden, while the baseline between $18-30^\circ$ rises, indicating an increase in amorphous material. Although the peaks do not completely

disappear, this suggests that the polymorph type remains unchanged, but the overall crystalline order is significantly reduced [19, 20]. This reduction in crystallinity reflects a shift from crystalline to amorphous domains. In untreated starch, the crystalline fraction dominates, producing sharp peaks. After parboiling, the peaks flatten, and the amorphous contribution increases, indicating disruption of crystalline lamellae. The heating process, in the presence of water, breaks down the granule's compact structure: double helices and lamellae unravel, crystalline regions partially melt, and amylopectin chains become more randomized [21, 22].

The extent of this transformation varies by cultivar. Differences in the amylose-to-amylopectin ratio, lipid content, granule size, and initial moisture influence how strongly the crystalline regions resist disruption. For example, starch with higher amylose content retains more crystallinity, while higher amylopectin levels favor amorphization [23, 24]. This is supported by our quantitative crystallinity data (Table 1), where SMC-213 Unparboiled exhibited 36.10% relative crystallinity, and SMC-213 parboiled showed a slight reduction to 36.04%. Similarly, SMC-279 Unparboiled had 34.50% relative crystallinity, which further decreased to 33.90% after parboiling. These structural changes directly affect the functional properties of rice flour. Reduced crystallinity correlates with higher swelling power, water absorption, and wettability, as the granules become more open to hydration [25, 26]. In contrast, oil absorption and specific gravity remain relatively unaffected, as these traits are more influenced by grain density and porosity than crystalline order. Overall, the XRD data, along with the quantitative crystallinity values in Table 1, confirm that parboiling shifts rice starch from a highly ordered to a more amorphous state, with the degree of change depending on the cultivar's starch chemistry and granule structure.

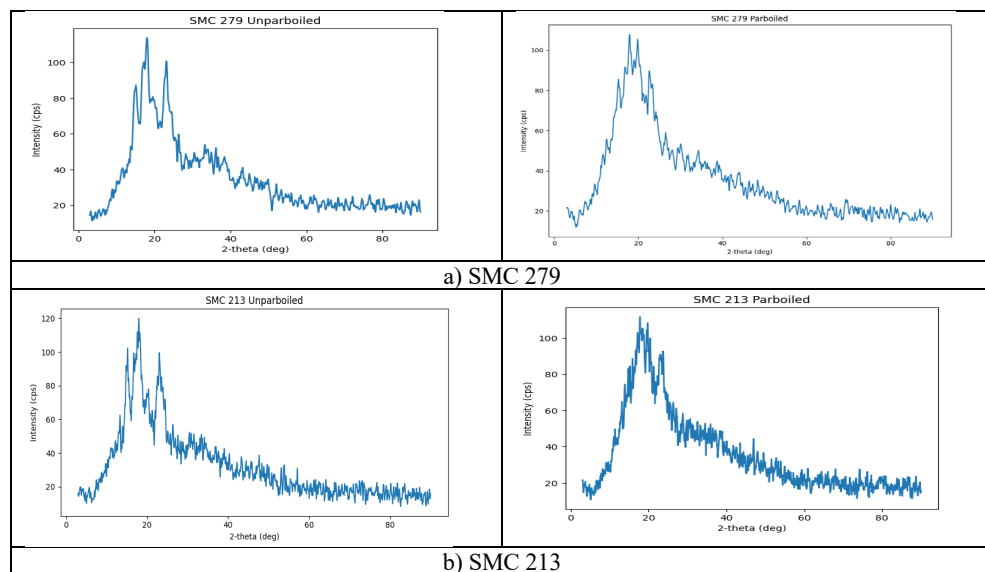


Fig 2. XRD profiles of unparboiled and parboiled brown rice cultivars of SMC 279 and 213.

Table 1. Quantitative Crystallinity of Parboiled and Unparboiled Brown Rice Cultivars

| Sample | Relative Crystallinity (%) |
|---------------------|----------------------------|
| SMC-213 Unparboiled | 36.10 |
| SMC-213 Parboiled | 36.04 |
| SMC-279 Unparboiled | 34.50 |
| SMC-279 Parboiled | 33.90 |

3.3 Swelling power

Parboiling significantly enhances the swelling power of brown rice by promoting starch gelatinization and structural disruption (Table 1). The swelling power of the unparboiled brown rice cultivars ranged from 0.41 to 0.53 g/g (Table 1), consistently showing low values. In contrast, parboiled samples exhibited a dramatic increase, reaching values between 2.99 and 4.53 g/g, approximately 7.5 times higher than non-parboiled rice. This stark difference underscores the strong effect of parboiling on starch granule functionality. By applying heat and moisture, parboiling gelatinizes starch granules and disrupts their crystalline structure, allowing them to absorb and retain more water during hydration [21].

Statistical analysis using ANOVA confirmed that there were significant differences ($p < 0.05$) in swelling power between parboiled and unparboiled samples. This significant increase is directly linked to the reduction in starch crystallinity observed in the XRD analysis. The weakened and broadened diffraction peaks at $2\theta \approx 15\text{--}17^\circ$ and $22\text{--}24^\circ$ suggest partial melting of crystalline lamellae, leaving a more amorphous matrix that facilitates more effective hydration and swelling of the granules [18,20]. This shift from ordered to disordered starch explains why parboiled cultivars show higher swelling capacities compared to their unparboiled counterparts.

Swelling power is also influenced by factors such as moisture content, particle size, and amylose content. For example, increasing moisture content from 12% to 18% raises swelling power from 7.89 g/g to 8.77 g/g, while reducing particle size from $>710 \mu\text{m}$ to $<250 \mu\text{m}$ increases swelling from 5.5 g/g to 9.2 g/g [27]. Similarly, rice with higher amylose content ($>20\%$) exhibits greater swelling capacity (8.28 g/g) compared to low-amylose rice ($<10\%$), which has a swelling power of 4.72 g/g, due to the stronger gel network formed during hydration [28]. This study supports these trends, as higher water absorption in parboiled samples (2.02–2.77%) complements the increase in swelling power, and higher wettability values (2.15–9.71 times greater) reinforce improved water–starch interactions [21]. In summary, the significant increase in swelling power after parboiling is directly linked to starch gelatinization, reduced crystallinity, and enhanced water interactions in brown rice, as similarly observed in previous research [21,19].

3.4 Water Absorption

Parboiling significantly increases the water absorption capacity of brown rice through starch gelatinization and structural modification (Table 2). The water absorption of unparboiled brown rice ranged from 1.12% to 1.34%, while parboiled samples absorbed between 2.02% and 2.77% (Table 3), representing nearly a twofold increase. This rise in water uptake can be attributed to starch gelatinization, which weakens the crystalline regions of starch granules

and creates more amorphous zones that readily bind water. ANOVA results showed significant differences ($p < 0.05$) in water absorption between parboiled and unparboiled samples, confirming the substantial enhancement in hydration. These findings are consistent with previous studies, which reported varying degrees of water absorption in rice based on cultivar and processing conditions. For instance, water absorption in steamed fragrant rice ranged from 1.53 to 1.94 times the grain weight [29], and up to 1.81 times the grain weight in glutinous rice soaked for 12 hours [30].

The increase in water absorption also aligns with the XRD profiles of the parboiled samples, which showed reduced peak sharpness and higher background intensity in the 2θ region of $15\text{--}30^\circ$, indicating a loss of crystallinity. This structural transition from crystalline to amorphous starch enhances the accessibility of hydroxyl groups, promoting hydrogen bonding with water molecules [21]. Additionally, water absorption trends parallel those observed for swelling power, which increased 7.5-fold in parboiled rice (Table 3). Together, these findings confirm that parboiling enhances hydration at both the granule and bulk levels, resulting in greater water uptake capacity.

Other factors, such as rice variety, amylose content, and particle size, also influence water absorption. For example, soaking treatments (6–12 hours) significantly increase water uptake by enhancing the permeability of starch granules [30,31]. Variations among cultivars also explain differences in absorption, as rice with higher amylose content typically shows stronger water-binding capacity [28]. These factors suggest that the improvements in water absorption observed in parboiled brown rice are a combined effect of structural disruption by gelatinization and inherent varietal composition. In conclusion, the higher water absorption in parboiled brown rice results from starch gelatinization, reduced crystallinity, and improved water accessibility within starch granules.

3.5 Oil Absorption

Parboiling has a minimal effect on the oil absorption capacity of brown rice, with grain density playing a greater role (Table 2). The oil absorption capacity of unparboiled brown rice ranged from 2.65% to 3.60%, while parboiled samples showed values between 2.15% and 3.23% (Table 2). Unlike swelling power and water absorption, which increased significantly after parboiling, oil absorption remained within a narrow and overlapping range. This suggests that parboiling does not substantially alter the rice's affinity for oil. Although ANOVA detected statistical differences ($p < 0.05$), the practical impact is minor, as the overall capacity for oil retention remained largely unchanged.

This stability in oil absorption can be better understood by considering the XRD and specific gravity results. Although XRD analysis confirmed reduced crystallinity and increased amorphous content after parboiling, these structural changes primarily favor water interactions rather than lipid uptake [21]. The specific gravity values (ranging from 0.56 to 0.71 g/mL across samples, Table 2) suggest that denser grains, particularly those with higher compactness after parboiling, may resist oil penetration. Therefore, parboiling enhances hydration (as indicated by higher swelling power and water absorption) but has minimal impact on oil absorption because density and porosity, not crystallinity alone, govern lipid retention.

Beyond parboiling, other factors such as cooking temperature, duration, moisture levels, and particle size strongly influence oil absorption. For instance, higher cooking temperatures and longer durations increase porosity, promoting oil uptake [32]. Similarly, higher moisture levels facilitate oil penetration by expanding the grain structure [33]. Smaller particle sizes with greater surface area are also more prone to oil absorption [34]. These findings suggest that grain density, particle size, and processing conditions are more decisive factors than parboiling in determining the oil absorption capacity of brown rice. In conclusion, parboiling does not significantly alter oil absorption in brown rice, as grain density and porosity exert stronger control over lipid uptake than starch gelatinization or changes in crystallinity.

3.6 Specific Gravity

The specific gravity of brown rice remains relatively stable after parboiling, with minor variations driven by grain size, moisture content, and impurities. The specific gravity of the brown rice samples ranged from 0.56 to 0.71 g/mL across both unparboiled and parboiled treatments (Table 2). Unlike swelling power and water absorption, which showed large increases following parboiling, specific gravity remained stable, suggesting that parboiling does not substantially alter the grain density. The narrow range of values indicates only small shifts in the mass-to-volume ratio, with denser samples reflecting a more compact grain structure, while lighter ones likely contained higher internal porosity.

This trend can be partially explained by the XRD results, which showed that parboiling reduced starch crystallinity and increased amorphous regions. While this structural transition enhanced water uptake and swelling, it did not significantly change the overall bulk density of the rice grains. Instead, specific gravity appears to be more sensitive to grain morphology and composition. For instance, larger and more voluminous grains tend to have a higher bulk density [35], while hydration decreases density by expanding internal voids [24]. These findings align with the relatively unchanged oil absorption values (2.15–3.60%), as higher-density grains with lower porosity naturally resist lipid penetration.

Foreign elements such as broken grains, dust, or stones also influence specific gravity by increasing empty space and lowering the density of the bulk mixture [36]. In the present samples, the stability of specific gravity across treatments suggests that the effect of parboiling was minor compared to these external factors. Taken together, these data indicate that while parboiling alters starch functionality, its impact on bulk density is minimal. Specific gravity is primarily governed by grain integrity, moisture balance, and impurity content. In summary, specific gravity in brown rice remains largely unaffected by parboiling, being more strongly influenced by grain morphology, hydration, and foreign elements than by starch structural changes.

3.7 Wettability

Parboiling significantly enhances the wettability of brown rice by improving surface hydrophilicity and reducing crystalline order. Wettability values increased markedly after parboiling, rising between 2.15 and 9.71 times compared to the unparboiled samples (Table 2). This substantial increase highlights the effect of parboiling on the rice's interaction with water. In untreated rice, lower wettability reflects limited surface hydrophilicity and

restricted water penetration. After parboiling, starch gelatinization and granule disruption promote greater water accessibility at the grain surface, resulting in faster wetting.

ANOVA results showed significant differences ($p < 0.05$) in wettability between parboiled and unparboiled rice, confirming the substantial enhancement in wettability due to parboiling. These findings align with the XRD data, which showed reduced crystallinity and increased amorphous content in parboiled rice. A more amorphous starch structure facilitates water binding at the molecular level, complementing the enhanced wettability observed macroscopically [21]. Moreover, the increase in wettability corresponds with higher swelling power (7.5-fold increase) and water absorption (up to 2.77%), all pointing toward improved hydration properties in parboiled grains. These properties suggest that structural loosening from gelatinization creates a synergistic effect: not only do the grains absorb more water, but they also wet more rapidly.

Beyond parboiling, external factors such as moisture content, surface roughness, and storage conditions also affect wettability. For instance, wettability is highest at moisture contents of 8–12%, due to the formation of a thin water film on grain surfaces [37]. Conversely, storing rice under high humidity reduces wettability by altering grain surface texture [38], while dust, oil, or starch residues can form hydrophobic coatings that hinder water contact [39]. In this study, the strong effect of parboiling appears to override these external influences, reinforcing the role of starch structural modification as the dominant factor. In conclusion, parboiling significantly improves the wettability of brown rice by reducing starch crystallinity and enhancing surface-water interactions.

Table 2. Swelling power, water absorption, oil absorption, specific gravity, and wettability of unparboiled vs parboiled brown rice

| Sample | Physical properties | | | | |
|------------------|----------------------|----------------------|--------------------|-------------------------|-----------------|
| | Swelling Power (g/g) | Water absorption (%) | Oil absorption (%) | Specific Gravity (g/mL) | Wettability (s) |
| Non-PG SMC-223 | 0.43 ± 0.03a | 1.13 ± 0.12a | 3.20 ± 0.10a | 0.56 ± 0.00a | 42.00 ± 10.00a |
| PG SMC-223 | 3.32 ± 0.94b | 2.53 ± 0.37b | 3.05 ± 0.42a | 0.71 ± 0.00b | 93.33 ± 27.47b |
| Non-PG SMC-59 | 0.51 ± 0.04a | 1.28 ± 0.07a | 2.65 ± 0.50a | 0.56 ± 0.00a | 17.67 ± 4.73a |
| PG SMC-59 | 4.53 ± 0.70c | 2.09 ± 0.08c | 2.15 ± 0.93a | 0.68 ± 0.03b | 37.67 ± 11.50b |
| Non-PG SMC-279 | 0.41 ± 0.03a | 1.12 ± 0.04a | 3.00 ± 0.26a | 0.56 ± 0.00a | 36.33 ± 11.55a |
| PG SMC-279 | 3.85 ± 0.31d | 2.26 ± 0.22d | 3.13 ± 0.45a | 0.71 ± 0.00b | 62.67 ± 33.08b |
| Non-PG SMC-213 | 0.53 ± 0.09a | 1.32 ± 0.08a | 3.11 ± 0.15a | 0.53 ± 0.00a | 60.00 ± 15.52a |
| PG SMC-213 | 3.57 ± 0.55e | 2.02 ± 0.13d | 3.23 ± 0.72a | 0.70 ± 0.03b | 163.33 ± 44.47c |
| Non-PG SMC-251 | 0.51 ± 0.07a | 1.34 ± 0.11a | 3.17 ± 0.11a | 0.56 ± 0.00a | 87.33 ± 10.79b |
| PG SMC-251 | 4.44 ± 0.83f | 2.03 ± 0.15e | 3.18 ± 0.27a | 0.67 ± 0.00b | 134.33 ± 32.72c |
| Non-PG SMC-295 | 0.49 ± 0.18a | 1.19 ± 0.16a | 3.32 ± 0.04a | 0.59 ± 0.00a | 14.67 ± 5.08a |
| PG SMC-295 | 4.50 ± 0.39g | 2.04 ± 0.12f | 2.91 ± 0.21a | 0.68 ± 0.03b | 136.33 ± 26.63c |
| Non-PG SMC-222 | 0.47 ± 0.01a | 1.26 ± 0.08a | 3.60 ± 0.15a | 0.56 ± 0.00a | 142.67 ± 28.29c |
| PG SMC-222 | 3.98 ± 0.11h | 2.20 ± 0.23g | 2.80 ± 0.16a | 0.70 ± 0.03b | 219.67 ± 60.99d |
| Non-PG IMPARA-7 | 0.45 ± 0.07a | 1.19 ± 0.08a | 2.86 ± 0.22a | 0.59 ± 0.00a | 11.33 ± 4.04a |
| PG IMPARA-7 | 2.99 ± 0.96i | 2.53 ± 0.20h | 3.09 ± 0.22a | 0.70 ± 0.03b | 21.33 ± 2.08b |
| Non-PG IMPARI-24 | 0.44 ± 0.02a | 1.15 ± 0.10a | 3.17 ± 0.18ac | 0.56 ± 0.00a | 11.00 ± 2.65a |
| PG IMPARI-24 | 3.13 ± 0.89j | 2.77 ± 0.27i | 2.77 ± 0.11a | 0.71 ± 0.00b | 89.00 ± 24.33c |

Note: Values are means ± SD (n = 3). Different superscript letters indicate significant differences at p < 0.05 (Duncan's test).

3.8 Physical properties of Unparboiled vs Parboiled Brown Rice

Parboiling significantly improves the physical properties of brown rice, particularly in how the grain interacts with water and other components. The most notable change is in swelling power, where values increase by nearly 7.5 times compared to the non-parboiled samples (Table 3). This improvement is directly linked to starch gelatinization: when the crystalline structure of starch granules is disrupted by heat and moisture, more amorphous regions are created, allowing water to penetrate and expand the granules more effectively [9,21]. These findings are consistent with the XRD profiles, which showed weakened and broadened peaks after parboiling, confirming that the ordered crystalline regions of starch were broken down into a more disordered, water-accessible state [40].

A similar trend was observed in water absorption. While unparboiled rice absorbed only 1.12–1.34% water, parboiled rice absorbed nearly double that amount (2.02–2.77%) (Table 2). This increase reflects how parboiling enhances porosity and surface area, making it easier for water to permeate the grain [41]. Wettability data further support this: parboiled rice wetted between 2.15 and 9.71 times faster than raw rice, indicating that the grain surface became more hydrophilic, facilitating faster water interaction [42]. Together, these hydration-related improvements make parboiled rice easier to cook and potentially more digestible, providing both nutritional benefits and advantages in food processing.

In contrast, oil absorption showed a different pattern. Unlike swelling power and water absorption, oil absorption values remained relatively stable, ranging between 2.15 and 3.60% across both treatments (Table 2). This stability suggests that oil retention is more dependent on particle size, porosity, and density than on the crystalline-to-amorphous transitions observed in the XRD analysis [34]. Similarly, specific gravity values remained within a narrow range of 0.56–0.71 g/mL, showing little difference between parboiled and non-parboiled samples. This indicates that, while parboiling significantly alters starch functionality, it does not substantially affect the overall bulk density of the grains [10].

In summary, these results demonstrate a clear pattern. Parboiling primarily enhances the hydration-related properties of brown rice swelling power, water absorption, and wettability by reducing starch crystallinity and increasing water accessibility (Table 2). However, properties tied more closely to density and lipid interaction, such as oil absorption and specific gravity, remain largely unchanged. Thus, parboiling transforms brown rice into a grain that is more responsive to water without fundamentally altering its density or oil-binding behavior, which enhances its functional value for both cooking and food processing.

Table 3. Summary of Brown Rice Properties (Unparboiled vs Parboiled)

| Parameter | Unparboiled | Parboiled | Key Effect |
|-----------------------------|---------------|------------------------------|--|
| Swelling Power (g/g) | 0.41 – 0.53 | 2.99 – 4.53 (~7.5x higher) | Large increase due to starch gelatinization |
| Water Absorption (%) | 1.12 – 1.34 | 2.02 – 2.77 (~2x higher) | Increased porosity and hydration |
| Oil Absorption (%) | 2.65 – 3.60 | 2.15 – 3.23 (minimal change) | Minimal effect, depends on grain porosity |
| Specific Gravity (g/mL) | 0.56 – 0.71 | 0.56 – 0.71 (stable) | Stable, mainly influenced by grain size/impurities |
| Wettability (fold increase) | Baseline (1x) | 2.15 – 9.71x higher | Large increase, improved surface hydrophilicity |

3.9 Pearson Correlation Analysis between Functional and Structural Properties

The Pearson correlation analysis revealed several significant relationships between the functional and structural properties of brown rice (Table 4). A strong positive correlation was observed between swelling power and water absorption ($r = 0.85$), suggesting that increased swelling power enhances water absorption. Similarly, swelling power was positively correlated with specific gravity ($r = 0.92$), indicating that denser rice grains tend to have higher swelling power. A moderate positive correlation was found between swelling power and wettability ($r = 0.53$), suggesting that grains with higher swelling power also wet more quickly. Water absorption was strongly correlated with specific gravity ($r = 0.94$), implying that denser rice grains absorb more water. A weaker, negative correlation was found between oil absorption and both swelling power ($r = -0.38$) and specific gravity ($r = -0.29$), indicating that rice with higher swelling power and density tends to absorb less oil. Wettability showed moderate positive correlations with specific gravity ($r = 0.44$) and water absorption ($r = 0.40$), highlighting that denser and more water-absorbing rice varieties tend to wet faster. These findings suggest that swelling power and water absorption are closely linked and influenced by structural properties such as specific gravity, while oil absorption appears to be less influenced by these factors.

Table 4. Pearson Correlation Matrix

| | Swelling Power (g/g) | Water Absorption (%) | Oil Absorption (%) | Specific Gravity (g/mL) | Wettability (s) |
|-------------------------|----------------------|----------------------|--------------------|-------------------------|-----------------|
| Swelling Power (g/g) | 1.00 | 0.85 | -0.38 | 0.92 | 0.53 |
| Water Absorption (%) | 0.85 | 1.0 | -0.30 | 0.94 | 0.40 |
| Oil Absorption (%) | -0.38 | -0.30 | 1.0 | -0.29 | 0.16 |
| Specific Gravity (g/mL) | 0.92 | 0.94 | -0.29 | 1.0 | 0.44 |
| Wettability (s) | 0.53 | 0.40 | 0.16 | 0.44 | 1.0 |

3.10 Nutritional and Sensory Implication

Previous research has shown that the use of parboiled rice in food products can provide benefits in terms of texture quality, moisture content, and lower glycemic index in the final product. For example, studies [43] demonstrated that the parboiling process improves water absorption and enhances starch structure, contributing to better texture and moisture retention in products like bread and cakes. Another study [19] concluded that parboiling could lower the glycemic index of rice-based products due to changes in starch structure, which results in slower carbohydrate absorption. This study highlights the potential advantages of using parboiled rice in biscuit production, offering both healthier and sensory-appealing options for consumers.

Although this study does not directly involve biscuit production, the findings regarding the functional properties of parboiled rice such as swelling power, water absorption, and wettability have important nutritional and sensory implications for future biscuit manufacturing. Parboiling causes structural modifications in rice starch that significantly impact both the texture and moisture content of the rice, which can translate into desirable outcomes for biscuit production.

3.10.1. Nutritional Implications

One of the primary nutritional benefits of using parboiled rice in biscuits is the potential reduction in the glycemic index (GI) of the final product. The swelling power and water absorption of parboiled rice (Table 3) are significantly higher than non-parboiled rice, indicating that parboiling enhances starch gelatinization. This structural change makes the starch more digestible, which could lead to a lower glycemic response compared to biscuits made from non-parboiled rice. Research suggests that parboiled rice results in a slower carbohydrate absorption, which is beneficial for managing blood sugar levels, making parboiled rice a healthier alternative for individuals with diabetes or those aiming to control their glycemic index [44]. Furthermore, oil absorption in parboiled rice remained stable, suggesting that the fat content in the biscuits would remain similar to biscuits made from non-parboiled rice, without compromising on the desired crispy texture. Additionally, the increased swelling power (Table 3) reflects an improved starch structure that could enhance the digestibility of the biscuits, making them easier to break down during digestion. This could make biscuits with parboiled rice a more nutritionally accessible option for consumers looking for easily digestible foods.

3.10.2. Sensory Implications

From a sensory perspective, the structural modifications due to parboiling significantly improve the texture and moisture retention of biscuits. The higher water absorption (2.02–2.77%) in parboiled rice indicates that parboiled rice granules can hold more water during baking, which leads to biscuits with a softer texture and improved moisture content [45]. This could make the biscuits more appealing to consumers who prefer a soft and moist product, rather than a dry or overly crumbly biscuit. Moreover, the enhanced wettability of parboiled rice (Table 3) means that the rice will integrate more evenly with other ingredients during mixing, resulting in a smoother dough and a uniform texture in the final product. As

wettability is linked to water interaction, the improved texture in the biscuit may provide a more pleasant mouthfeel during consumption.

In terms of crispness, the oil absorption data (2.15–3.32%) suggests that the parboiled rice does not significantly alter the crispness of the biscuit compared to non-parboiled rice. The crispy texture, often a desirable characteristic of biscuits, is maintained, ensuring that the sensory profile remains balanced between moisture and crispness. In conclusion, the use of parboiled rice in biscuit production offers several nutritional and sensory advantages. The improved hydration properties such as swelling power, water absorption, and wettability lead to softer, moister biscuits with better texture and mouthfeel. Additionally, the lower glycemic index and enhanced digestibility of parboiled rice make it a healthier choice for consumers, while still preserving the desired sensory attributes like crispness and moisture retention. These factors make parboiled rice a promising ingredient in nutritious, consumer-friendly biscuits.

4 Conclusion

This study demonstrates that parboiling induces significant structural and functional changes in brown rice, enhancing its suitability for food processing applications. XRD analysis revealed that parboiling reduces starch crystallinity, shifting the starch from a highly ordered to a more amorphous form. This transformation enhances the rice's water-responsive properties, with swelling power increasing by over seven times, water absorption nearly doubling, and wettability improving substantially. These improvements in hydration directly support the use of parboiled brown rice flour in biscuit production, where proper water interaction and dough handling are essential for achieving optimal texture and quality. However, properties such as oil absorption and specific gravity showed minimal changes, indicating that these characteristics are more influenced by grain density and morphology than by starch order. Furthermore, cultivar-dependent differences were observed: SMC 279 exhibited greater resilience in retaining starch order, while SMC 213 showed more significant improvements in hydration properties. In conclusion, parboiling is a practical and effective method to enhance the functional properties of local brown rice, making it a versatile and scalable ingredient for food products. The improvements in processing functionality and nutritional value position parboiled brown rice as a promising solution to support initiatives like the Makan Bergizi Gratis program, aimed at providing affordable and nutritious food to diverse communities.

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