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Pre-Hydration Degree of Oat Bran Modulates Water Competition, Cooking Quality, Texture, and Starch Digestibility of Noodles

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ABSTRACT

Oat bran improves the nutritional profile of noodles but disrupts gluten network formation through intense water competition, which compromises textural quality. This study investigated a tunable pre-hydration strategy designed to convert this competition into a controlled interaction. Oat bran was pre-hydrated to different degrees, corresponding to water activity (a_w) levels from 0.9908 to 0.9973, and then used to prepare noodles. The noodle formula was oat bran powder: oat flour: wheat flour = 20:10:70 (w/w/w). When pre-hydration approached the saturation point of oat bran ($a_w = 0.9970$), the noodles showed optimal cooking quality, with a breakage rate of 3.5% and a cooking loss of 10.4%. Texture profile analysis showed no significant differences ($p > 0.05$) in hardness, cohesiveness, springiness, and chewiness between these noodles and wheat noodles. This treatment also maximized the retention of β-glucan, polyphenols, and dietary fiber while reducing the darkening typically caused by bran. Compared with noodles containing untreated bran, noodles prepared with pre-saturated bran showed a 53.1% increase in resistant starch (RS) content and a 15.6% decrease in estimated glycemic index (eGI). These findings indicate that precise hydration of fibrous ingredients is a key design parameter for simultaneously improving processing performance and nutritional quality. This approach offers a practical strategy for making staple foods healthier without sacrificing cooking quality. Overall, this study supports the high-value utilization of oat bran and the development of low-GI functional foods.

1 | Introduction

Oat bran is the outer layer of the oat groat and is obtained during milling. It is a nutrient-dense by-product that is especially rich in dietary fiber. The main fiber component is mixed-linkage (1→3)(1→4)-β-D-glucan, which accounts for at least 5.5% of its dry weight (Butt et al. 2008; Rasane et al. 2015). Oat bran also provides appreciable amounts of protein (approximately 24% of its weight), unsaturated fatty acids, B vitamins, and minerals such as iron, magnesium, phosphorus, and zinc (Butt et al. 2008; Rasane et al. 2015). Uniquely among cereals, it contains avenanthramides, phenolic alkaloids with well-documented antioxidant, anti-inflammatory, and vasodilatory activities (L.-W. Wang et al. 2025; Yang et al. 2014), as well as a range of phenolic acids and flavonoids (Perrelli et al. 2018; Sang and Chu 2017). This distinctive composition makes oat bran an appealing functional ingredient for staple foods. Its regular consumption has been consistently associated with improvements in glycemic control, lipid metabolism, oxidative status, and cardiovascular health (Noronha et al. 2023). Enriching widely consumed

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wheat-based products, such as noodles with oat bran is therefore a promising strategy for increasing dietary fiber intake in the general population.

Despite these nutritional benefits, incorporating oat bran directly into noodle formulations introduces considerable technical challenges. Dough handling becomes more difficult, cooking loss increases, and the noodles develop a coarse, gritty mouthfeel and a darker color. Bitter or off-flavors also develop. Together, these changes reduce consumer acceptability (Peng 2023; Wardhana and Banawi 2020). The underlying causes can be grouped into three categories: physical, chemical, and water-related. Physically, rigid bran particles act as inert obstacles that disrupt the continuity of the gluten network, thereby diluting and mechanically weakening the starch-gluten matrix (M. Li et al. 2024; M. Li, Zheng, et al. 2025). Chemically, ferulic acid and other hydroxycinnamic acids, which are abundant in oat bran, can mediate cross-linking between polysaccharide chains or between polysaccharides and proteins. This alters gluten aggregation and promotes the formation of compact, poorly extensible complexes that further compromise the protein phase (He et al. 2023; C.-C. Wang et al. 2022). Most critically, oat bran has an exceptionally high water-binding capacity. This property is driven mainly by its insoluble fiber fraction, whereas soluble β-glucan contributes to high viscosity. During dough mixing, the bran creates intense competition for the limited water available. The insoluble fiber physically traps water, restricting gluten hydration and starch gelatinization. It also partially dehydrates the gluten matrix, thereby destabilizing the polymeric gluten network (Jacobs et al. 2016; R. Li et al. 2023). At the same time, hydrated β-glucan forms viscous gels that coat gluten strands and prevent them from coalescing into a continuous network (Bock and Damodaran 2013), and effect also reported in more recent studies (Gao et al. 2024; Hu et al. 2025). The resulting increase in the viscosity of the aqueous phase reduces its plasticizing efficiency, impairing the development of the viscoelastic properties essential for noodle dough.

To address these problems, several bran pretreatment methods have been explored, including fractionation, extrusion, autoclaving, enzymatic hydrolysis, and hydrothermal pretreatments such as steaming and baking (Coda et al. 2014; Onipe et al. 2021). Some of these approaches have led to partial improvements in quality, but they often increase production costs or require specialized equipment. Others rely on chemical additives, an approach that conflicts with the growing consumer demand for clean-label, minimally processed foods (Tebben et al. 2018). Pre-hydrating bran before dough mixing has received far less attention, yet it is a conceptually simple, low-cost strategy based on a clear thermodynamic principle. When dry, native bran is added directly, it absorbs water rapidly and competes with gluten for the limited available water, thereby impairing gluten network formation. Pre-saturating bran to its water-binding capacity before mixing could, in principle, minimize this competition and allow gluten to hydrate and develop without interference. Wu et al. recently showed that pre-saturating oat bran before breadmaking effectively reduced the adverse effects of bran on dough rheology and bread texture (Wu et al. 2025a, 2025b). This finding highlights the critical role of bran hydration in ensuring compatibility with gluten-based food matrices. However, this strategy has not yet been explored in noodle systems, where a continuous gluten network is even more essential for product quality. Extending the pre-hydration concept to noodles therefore represents a logical next step.

The effects of bran incorporation extend beyond dough handling and texture. The physical state of the bran matrix strongly influences the release, distribution, and retention of bioactive compounds, including β-glucan, polyphenols, and dietary fiber fractions, as well as the susceptibility of starch to digestive enzymes. Soluble dietary fiber released from bran has been shown to significantly inhibit starch and protein digestion in noodles by increasing the viscosity of the digestive chyme, In oat-fortified noodles, β-glucan also interacts with protein, modifying the noodle microstructure and reducing starch digestion rates (Nguyen et al. 2022). To date, the influence of bran hydration level on these nutritional and digestive outcomes in noodle systems has remained largely unexplored.

The specific role of pre-hydration in modulating water competition between oat bran and the gluten network remains poorly understood. In this study, oat bran was pre-hydrated to different levels, defined by moisture content and water activity (a_w), and then incorporated into noodles at a fixed level of 20% (w/w) in the flour blend. The resulting effects on cooking quality, texture properties, color difference, retention of bioactive compounds, and in vitro starch digestibility were systematically evaluated. The findings will provide a theoretical basis for more targeted improvement of oat bran noodle quality and for expanding the application of raw material pretreatment in noodle production.

2 | Materials and Methods

2.1 | Materials and Chemicals

Oat bran (8.6% moisture, 7.4% fat, and 22.5% total dietary fiber) was obtained from Shanxi Xinfei Agricultural Science and Technology Co. LTD (Shuozhou, China). The bran was ground to a mean particle size of 180 μm using a laboratory disc mill (Brabender Company, Germany).

Common wheat flour (71.4% total carbohydrate, 15% protein, 1.5% total fat) was purchased from Yihaijiali Golden Dragon Food Group Co. LTD (Shanghai, China). Wheat gluten (moisture, protein, and fat contents were 7.11%, 75%, and 2%, respectively) was obtained from Xinxiang Liangrun Whole Grain Food Co. LTD (Xinxiang, China). The α-amylase (A4551, from *Bacillus licheniformis*, 50 U/mg), pepsin (P7012, from porcine gastric mucosa, ≥ 250 U/mg), and pancreatin (P7545, from porcine pancreas, 8 × USP) were purchased from Sigma-Aldrich Chemical Co. (St. Louis, MO, USA). A Total Dietary Fiber kit and β-Glucan Assay Kit (Mixed Linkage) were purchased from Megazyme International Ireland Ltd. (Bray, Ireland). All other chemical reagents were of analytical grade.

2.2 | Pre-Hydration of Oat Bran and Determination of Water Activity

Pre-hydrated oat bran samples were prepared by mixing oat bran with deionized water at 25°C at predetermined water-to-dry-bran

ratios of 0.8, 1.2, 1.3, 1.5, 1.6, 1.7, 1.8, and 1.9 (w/w). After hydration, the samples were sealed and allowed to equilibrate for 2 h. An equilibration period of 2 h was used because preliminary water activity measurements showed that the system stabilized after 2 h, consistent with previous bran hydration studies (Renzetti et al. 2021; Robertson et al. 2000). The actual moisture content of each pre-hydrated sample was determined by the direct drying method specified in the Chinese National Food Safety Standard GB 5009.3-2016 (Determination of Moisture in Foods). A 3–5 g portion of each moistened bran samples was weighed accurately into a pre-dried weighing dish and dried in an air oven at 105°C to constant weight. The corresponding moisture contents were 40.33%, 45.81%, 54.52%, 56.56%, 60.47%, 62.03%, 63.29%, and 64.87%, respectively, confirming the hydration levels achieved at each water-to-dry-bran ratio. These ratios were selected based on preliminary trials that examining the relationship between water activity (a_w) and moisture content, with the aim of identifying the saturation point of bran. Water activity was then measured according to National Food Safety Standard of the People's Republic of China, Determination of Water Activity in Foods (GB 5009.238-2016). The moisture content at saturation was identified from the resulting curve of water activity versus moisture content.

2.3 | Preparation of Noodles

Noodle dough was prepared by mixing flour with salt (3 g) and water (45 g). The control was prepared from 100 g of wheat flour. The experimental groups comprised two types of noodles. One type was prepared with unhydrated oat bran and designated as UN. The other type was prepared with oat bran pre-hydrated to four different water activity levels (a_w = 0.9908, 0.9954, 0.9970, and 0.9973) and designated as TN-1, TN-2, TN-3, and TN-4; these were collectively referred to as pre-hydrated bran noodles (PBN). As shown in Figure 1, the pre-hydration degree of the bran increased progressively from TN-1 to TN-4. Specifically, TN-1 and TN-2 had relatively low pre-hydration levels, and the bran remained unsaturated; TN-3 bran reached an essentially saturated state; and with a further increase in water content, TN-4 bran became supersaturated. All experimental noodles were formulated at a fixed mass ratio of oat bran powder:oat flour:wheat flour = 20:10:70, and wheat gluten (5 g) was added to strengthen the gluten network. Preliminary trials showed that dough became unmanageable when the bran level exceeded 20%. Because the oat bran had been pre-conditioned with water, the amount of water added during mixing was reduced by an equivalent weight to maintain the target overall hydration. All ingredients were first combined in a dough mixer (JMHZ-200, Beijing, China) and blended for 5 min until homogeneous. The dough was then sealed in a plastic bag and rested at 30°C and 75% relative humidity to allow moisture equilibration. After resting, the dough was sheeted on a laboratory semi-automatic noodle machine (JCXZ-95, Beijing, China), with the roll gap gradually reduced from 20.0 to 2.0 mm in steps of 2.0 mm; at each gap setting, the dough sheet was folded and passed through three times. The sheet was then cut into 5.0 mm wide strips

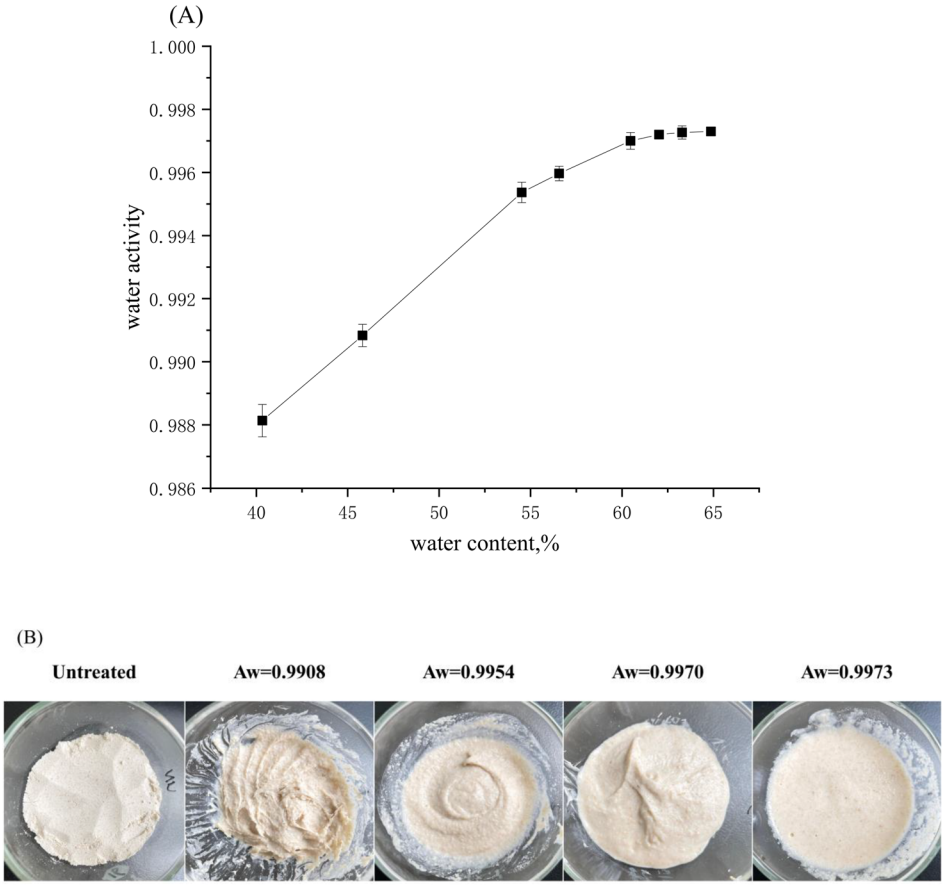


FIGURE 1 | (A) Water activity of pre-hydrated oat bran sample as a function of water content; (B) Photographs of pre-hydrated oat bran at key water activity levels.

using a pasta machine (PASTA FRESCA, MARCATO S.p.A., Campodarsego (PD), Italy). The freshly prepared noodles were immediately evaluated for cooking performance and texture properties. The remaining noodles were lyophilized and stored at −20°C for subsequent analysis.

2.4 | Cooking Quality Analysis of Noodles

Cooking quality attributes, including noodle breakage rate, cooking loss, and water absorption were evaluated according to the procedure described by Guo et al. (2020). Noodle samples (30 g W_1) were boiled in 500 mL of water. After surface moisture was removed with filter paper, the cooked noodles were weighed, and the mass was recorded as W_2. The cooking water was collected, transferred to a 500 mL volumetric flask, and made up to volume. The diluted cooking water was then poured into a beaker that had been pre-dried to constant weight, and dried at 105°C to constant weight. The total weight of dry impurities in the cooking water was W_3 Water absorption (%) and cooking loss (%) was calculated as follows:

$$\text{Water absorption}\,(\%) = \frac{W_2 - W_1}{W_1} \times 100\,\% \quad (1)$$

$$\text{Cooking loss}\,(\%) = \frac{W_3}{W_1 \times (1 - w)} \times 100\,\% \quad (2)$$

where W is the moisture content of uncooked noodles (%).

The breakage rate was calculated as follows. After cooking a fixed number of noodle strands (20 strands) for the optimal time, the noodles were immediately transferred to cold water, spread flat on a plate, and the number of broken strands (defined as strands fractured into two or more pieces) was counted. The breakage rate was calculated as the percentage of broken strands relative to the total number of cooked strands.

2.5 | Texture Profile Analysis of Noodles

Texture profile analysis (TPA) was performed according to the procedure described by S. Zou et al. (2021) using a TA-XT plus Texture Analyzer (Stable Micro Systems, Surrey, UK). Deionized water (500 mL) was poured into a stainless steel pot and brought to a rolling boil on an induction cooker set at 2200 W. Fresh noodles (50 g) were then added and cooked for the predetermined optimal cooking time, after cooking, the noodles were removed and immediately cooled in cold water for 1 min. Three cooked noodle strands were placed on the platform and compressed using a P/36R cylindrical probe. The samples were compressed to 75% strain with a trigger force of 5.0 g, and the crosshead speed was kept constant at 1.0 mm/s during the pre-test, test, and post-test phases.

2.6 | Color Analysis of Noodles

Lyophilized noodle powders were analyzed for color parameters (L*, a*, and b* values) using a NW-1 Whiteness Checker (Nippon Denshoku Industries Co. Ltd., Japan). Color was quantified using the CIE L*a*b* system, in which L* denotes lightness (0 for black and 100 for white), a* represents the red–green chromatic component (positive a* indicates redness, negative a* indicates greenness), and b* represents the yellow–blue chromatic component (positive b* indicates yellowness, negative b* indicates blueness).

2.7 | Bioactive Compound Contents of Noodles

2.7.1 | β-Glucan Content

β-Glucan content in lyophilized noodle powders was quantified enzymatically using a mixed-linkage β-glucan assay (Megazyme Ltd., Bray, Ireland), according to AOAC Method 995.16 (Latimer 2023b). Absorbance at 510 nm was recorded using a microplate reader (Spectrophotometer, Thermo Fisher Scientific Inc., Finland), and each sample was analyzed in quadruplicate.

2.7.2 | Total Phenolic Content

The total phenolic content (TPC) was measured according to the method of Dulf et al. (2016). The Folin–Ciocalteu reagent was first diluted 10-fold with water. A 2.5 mL portion of the diluted reagent was transferred into a centrifuge tube, followed by 0.5 mL of the sample supernatant. The mixture was allowed to react for 6 min. Then, 2 mL of a 7.5% Na_2CO_3 solution was added, and the tube was incubated at 25°C for 1 h. Absorbance at 760 nm was measured using a microplate spectrophotometer (Thermo Fisher Scientific Inc.). A calibration curve was prepared using gallic acid, and TPC values were expressed as milligrams of gallic acid equivalents per gram of dry weight (mg GAE/g DW).

2.7.3 | Dietary Fiber Content

Total, insoluble, and soluble dietary fiber (TDF, IDF, and SDF, respectively) in the noodles were determined by an enzymatic-gravimetric procedure. Measurements were performed using a Megazyme Total Dietary Fiber Assay kit according to AOAC method 991.43 (Latimer 2023a).

2.8 | In Vitro Starch Digestibility of Noodles

In vitro starch digestibility was determined according to the method of Englyst and Hudson (1996) with slight modifications. Cooked, freeze-dried noodle powders containing 2.0 g of starch were weighed, ground, and transferred to a conical flask; white wheat noodles was used as the control. Then, 20 mL of 0.3 mol/L HCl–NaCl buffer (pH 2) was added. The mixture was boiled for 5 min and then pre-incubated at 40°C in a shaking water bath for an additional 5 min. Subsequently, 0.4 mL of pepsin solution (0.1 g/mL) was added, and the homogenized suspension was shaken at 40°C for 30 min. Incubation was performed at 40°C, as previously described for

cooked noodle samples (Hu et al. 2025; Keran et al. 2022), because this temperature better mimics the thermal conditions encountered after ingestion of hot starchy foods. The pH was then adjusted with 5 mL of 0.01 M NaOH, and 25 mL of phosphate buffer (pH 6.9) was added to bring the total volume to 50 mL. Subsequently, 1 mL of amyloglucosidase (5000 U/mL), 4 mL of α-amylase (3000 U/mL), and 1 mL of pancreatin were added to the mixture, which was then incubated under shaking at 150 rpm. At predetermined time points (0, 5, 10, 20, 30, 45, 60, 90, 120, and 180 min), 1 mL aliquots were withdrawn. Each aliquot was immediately mixed with absolute ethanol to stop the reaction and then centrifuged at 5000×g for 10 min. The supernatant was collected and analyzed at 510 nm using GOPOD reagent. Starch hydrolysis rates and the corresponding starch fractions were calculated using the equations provided below.

$$C = C_{\infty} \times \left(1 - e^{-kt}\right) \tag{3}$$

$$\mathrm{RDS}\,(\%) = 90 \times (\mathrm{G20} - \mathrm{FG}) / \mathrm{TS} \tag{4}$$

$$\mathrm{SDS}\,(\%) = 90 \times (\mathrm{G120} - \mathrm{G20}) / \mathrm{TS} \tag{5}$$

$$\mathrm{RS}\,(\%) = 100 - \mathrm{RDS} - \mathrm{SDS} \tag{6}$$

TS denotes total starch, and GF denotes the initial glucose content. G20 and G120 represent the amounts of glucose released at 20 and 120 min of hydrolysis, respectively. C_{∞} (%) is the equilibrium hydrolysis percentage, and k ($\times 10^{-2}\,\mathrm{min}^{-1}$) is the kinetic rate constant. RDS, SDS, and RS denote rapidly digestible starch, slowly digestible starch, and resistant starch, respectively.

The hydrolysis index (HI) was calculated from the area under the hydrolysis curve. Specifically, HI is the area under the hydrolysis curve for the test food, expressed as a percentage of that for the reference food (white wheat noodles). The estimated glycemic index (eGI) was then calculated from HI using the equation reported by Goñi et al. (1997). For the cooked noodles, HI and eGI were determined as follows:

$$\mathrm{HI} = \frac{\mathrm{S}}{\mathrm{SW}} \times 100 \tag{7}$$

$$\mathrm{eGI} = 39.71 + 0.549 \times \mathrm{HI} \tag{8}$$

In this equation, S denotes the area under the hydrolysis curve of the test food, and SW represents the corresponding area for the standard food.

2.9 | Statistical Analysis

One-way analysis of variance (ANOVA) was performed using SPSS Version 25.0 (IBM, Chicago, IL, USA). When significant effects were detected, means were separated using Duncan's multiple range test at $p < 0.05$. All figures were generated in Origin 2024 (OriginLab Corporation, Northampton, MA, USA).

3 | Results and Discussion

3.1 | Relationship Between Water Activity and Water Content of Pre-Hydrated Oat Bran

As water is gradually added, oat bran undergoes a clear and continuous change in appearance. In its dry, native state, the bran is a loose, free-flowing powder composed of pale beige to light tan flakes that feel airy and slightly coarse. With the first addition of water, the material darkens almost immediately to a medium brown, and the previously separate particles begin to cling together into small, soft clumps. As more water is taken up, these clumps merge into a cohesive, dough-like mass that becomes visibly moist and noticeably sticky, with a slight surface gloss but no sign of free water yet. Approaching full saturation, the bran softens further and gradually shifts from a pliable paste into a thick, viscous slurry of a uniform dark brown color. Once the fiber matrix can hold no more water, the system becomes a semi-fluid, porridge-like suspension. A thin film of unabsorbed water may appear around the edges of the mass, indicating full saturation, at which point water activity approaches unity and no additional water can be immobilized within the particle structure. Representative images of oat bran at key water activity levels during pre-hydration are shown in Figure 1.

Water activity (a_w) is an intensive thermodynamic quantity, formally defined as the ratio of the fugacity of water in a given material to the fugacity of pure water at the same temperature; under low-pressure conditions, this reduces to the ratio of equilibrium partial vapor pressures. By definition, pure water has an a_w of exactly 1.0000. Inside a food matrix, water molecules engage in diverse molecular associations with proteins, carbohydrates, and minerals, these include hydrogen bonding, ion-dipole interactions, and entropically driven structuring of water adjacent to nonpolar surfaces. Such associations lower the chemical potential of water, restrict its translational mobility and reduce its effective availability as a solvent or its ablility to participate in chemical and biochemical reactions relative to bulk pure water. Consequently, even when the moisture content of a food approaches its saturation limit, water activity can only approach 1.0000 asymptotically. It can never reach that value because a residual water-matrix affinity invariably persists and cannot be completely eliminated (Bhagwat 2019).

The relationship between water activity (a_w) and water content for pre-hydrated oat bran samples is shown in Figure 1. A sharp increase in a_w was observed as the moisture content increased from 40.33% to 60.47%. Once the critical hydration point was exceeded (60.47% water content, $a_w = 0.9970$), further water addition produced only negligible changes in a_w, indicating that the bran had effectively reached its saturation limit. The appearance of free water in samples beyond this point confirmed that the bran had reached its maximum water-binding capacity. In terms of experimental design, initial scoping trials were performed to narrow the water content range in which saturation would occur. Subsequent measurements at small incremental water additions were used to resolve the narrow moisture interval containing the saturation point; this interval was then designated as the saturated water content. In principle, a finer sampling density, whether of water content or water activity, would allow more accurate determination of the saturation point.

When native (dry) oat flour or bran is incorporated, its abundant fiber and arabinoxylan fractions exhibit a strong affinity for water, rapidly sequestering a large proportion of the available moisture (Renzetti et al. 2021). This competitive hydration restricts the amount of water accessible to wheat gluten proteins, leading to incomplete plasticization of gliadin and glutenin. The resulting gluten network is poorly developed and structurally discontinuous, and it cannot effectively encase the starch granules. As a result, the noodles show greater cooking loss and develop a softer, less elastic texture. In contrast, pre-hydrating oat bran to near saturation (water activity approaching unity) raises the chemical potential of its internal water to a level close to that of free water. When this fully hydrated bran is used in place of untreated bran, it no longer competes for water during mixing. The aqueous phase therefore remains fully available for gluten development. The wheat proteins then hydrate properly and build a continuous, cohesive viscoelastic matrix around the oat particles. This well-formed network not only improves cooked noodle firmness and extensibility but also physically restricts starch granule swelling and rupture. Cooking loss decreases sharply, and the overall cooking and textural quality improves.

3.2 | Effects of Pre-Hydration Degree on the Quality of Oat Bran Noodles

3.2.1 | Appearance of Dough and Noodles

Figure 2 presents images of the manufacturing process, dough, fresh noodles, and cooked noodles. All formulations formed a cohesive dough after 10 min of kneading. Partial replacement of wheat flour with oat bran did not impair dough workability during processing. The UN samples had a noticeably darker appearance.

3.2.2 | Cooking Quality

The cooking properties of noodles prepared with oat bran at different pre-hydration degrees and the control are presented in Table 1. Pre-hydration significantly influenced water absorption, cooking loss, and breakage rate. As the degree of pre-hydration increased, the water absorption and cooking loss of TN-3 decreased markedly by 27.39% and 48.74%, respectively, compared with UN. No significant differences were observed between TN-3 and the white wheat noodle control for any of these three parameters. In contrast, UN exhibited the highest water absorption, cooking loss, and breakage rate among all samples, indicating poor cooking quality. The breakage rate of TN-3 was 84.30% lower than that of UN. Both the white wheat noodle control and TN-3 exhibited strong resistance to breakage and had a compact structure, whereas UN was noticeably fragile and crumbly. Overall, TN-3 achieved a desirable balance of moderate water absorption, low cooking loss, and good mechanical integrity, making it the best-performing formulation in terms of processing quality.

Water absorption, cooking loss, and breakage rate are key indicators of noodle cooking quality. Water absorption reflects the ability of the noodle matrix to hold water and is influenced by the composition of starch, fiber, and protein, as well as by the integrity of the protein–starch network. Compared with the white wheat noodle control, TN-1 and TN-2 showed significantly higher water absorption ($p < 0.05$). In these samples, unsaturated oat bran competitively absorbed water during dough

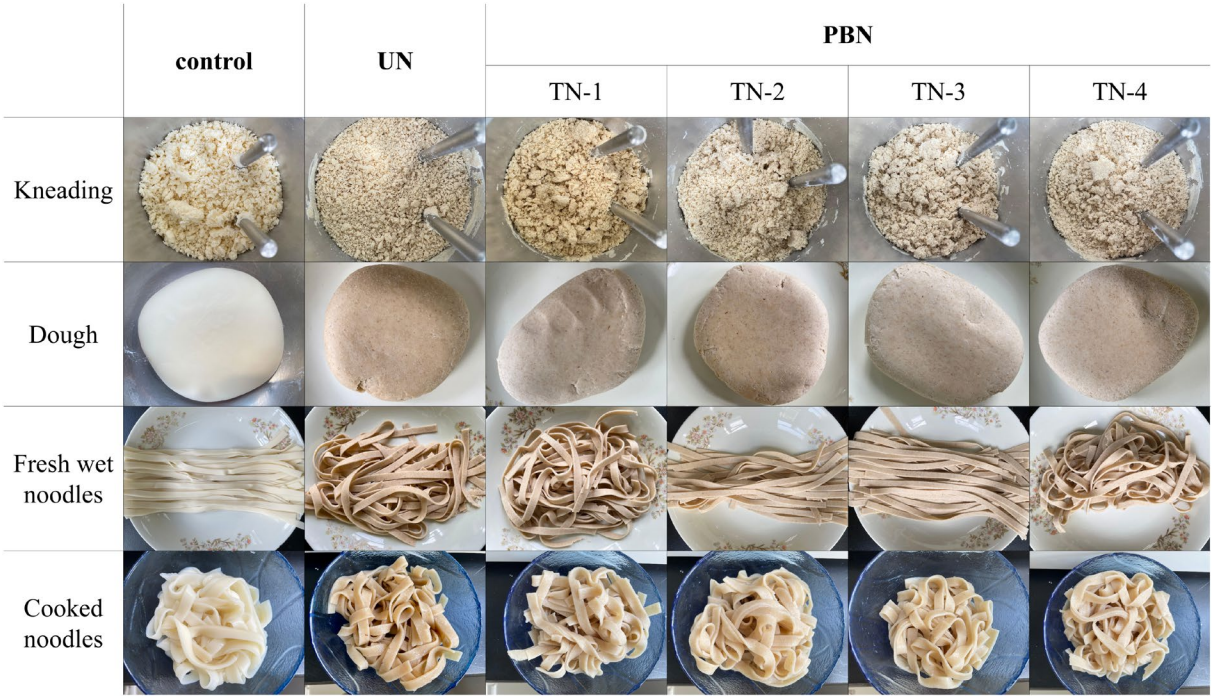


FIGURE 2 | Effects of pre-hydration degree of oat bran on the formation of dough and noodles. TN1 to TN4 are noodles prepared with pre-hydrated bran; the pre-hydration degree increases from TN1 to TN4, with TN-3 reaching saturation and TN-4 being over-hydrated. UN refers to noodles prepared with untreated dry bran.

development, resulting in incomplete gluten network formation, a weakened structure, and greater susceptibility to breakage. During cooking, the abundant dietary fiber and β-glucan in the unsaturated bran further absorbed water, increasing water absorption. In TN-3, the bran reached a saturated state and did not compete for water; the resulting starch-protein network was denser and more cohesive, thereby restricting water binding to proteins and starch. With respect to cooking loss, TN-3 exhibited the lowest value and was statistically comparable to the white wheat noodle control. In contrast, insufficient or excessive pre-hydration significantly increased cooking loss ($p < 0.05$). When bran was unsaturated, the increased solubility and hydration capacity of its dietary fiber during cooking promoted the leaching of starch and other solids and hindered the formation of a continuous starch gel network (Feng et al. 2023). As cooking proceeds, starch is partially degraded into smaller molecules, which accelerates the leaching of starch granules and enhances water penetration, thereby increasing the transfer of soluble solids from the noodle to the cooking water (Q. Wang et al. 2020). This mechanism contributes to a higher breakage rate and a cloudier, more viscous cooking broth, consistent with previous reports (Fan et al. 2022; Tsurunaga et al. 2025). Additionally, boiling disrupts the gluten network and solubilizes proteins, and it increases the level of damaged starch, further exacerbating cooking loss (Kim and Kweon 2024). Similarly, pretreating cereal bran can help offset the quality losses that typically accompany bran incorporation. It has been reported that enzymatic wheat bran (EWB) reduces cooking loss in noodles because the treatment exposes more functional groups that can interact with gluten proteins (W. Li, Xu, et al. 2025). These interactions improve dough structure and help limit the loss of solid components during cooking. The addition of cereal bran can alter cooking behavior and other quality attributes through interactions with the other noodle components (Ahmed et al. 2024; Fan et al. 2022). In summary, saturating oat bran prior to dough mixing minimized structural disruption and solid leaching, yielding noodles with cooking characteristics comparable to those of the white wheat noodle control.

TABLE 1 | Cooking quality of noodles.

Sample	Water absorption (%)	Cooking loss (%)	Breakage rate (%)
TN-1	86.51 ± 1.18d	16.92 ± 0.24c	10.87 ± 0.33c
TN-2	77.70 ± 0.65c	13.13 ± 0.61b	7.97 ± 0.43b
TN-3	67.32 ± 1.08a	10.39 ± 1.18a	3.50 ± 0.47a
TN-4	72.50 ± 1.08b	15.38 ± 0.45bc	12.11 ± 0.66cd
UN	92.72 ± 0.73e	20.27 ± 0.78d	22.30 ± 1.47e
Control	69.46 ± 1.42ab	9.22 ± 0.85a	2.13 ± 0.39a

Note: Means with different lowercase letters within the same column are significantly different at $p < 0.05$.

3.2.3 | Textural Profile Analysis

The white wheat noodle control, untreated oat bran noodles (UN), and noodles prepared with oat bran at four pre-hydration levels (TN-1 through TN-4) were analyzed by texture profile analysis (TPA). Five parameters were evaluated: hardness, springiness, cohesiveness, chewiness, and resilience. The results are summarized in Table 2.

As shown in Table 2, the addition of oat bran and the degree of bran pre-hydration significantly affected all five TPA parameters ($p < 0.05$). UN exhibited the highest hardness (4948 g), which was significantly greater than that of the white wheat noodle control (3407 g) and all pre-hydrated samples. However, UN also displayed relatively low springiness (0.856), cohesiveness (0.617), chewiness (2442 g), and resilience (0.341), indicating that despite their strong resistance to compression, the UN noodles lacked internal structural continuity and elastic recovery. As the degree of pre-hydration increased, hardness decreased progressively from 4759 g (TN-1) to 3572 g (TN-3), whereas springiness, cohesiveness, and resilience first increased and then declined, reaching their optimal values among the bran-containing samples at TN-3. Although the textural attributes of TN-4 were slightly lower than those of TN-3, they remained significantly better than those of UN and TN-1. This systematic shift indicates that pre-hydration does not affect noodle texture in a simple, monotonic way. Instead, an optimal hydration window exists in which the physical state of the bran particles and the gluten network achieve the greatest mechanical compatibility.

TABLE 2 | Texture profile of noodles.

Sample	Hardness (g)	Cohesiveness	Springiness	Chewiness	Resilience
TN-1	4758 ± 54b	0.530 ± 0.011d	0.820 ± 0.006d	2610 ± 22bc	0.438 ± 0.021d
TN-2	4334 ± 35c	0.575 ± 0.009cd	0.832 ± 0.003cd	2688 ± 58ab	0.534 ± 0.013c
TN-3	3572 ± 38e	0.645 ± 0.036ab	0.876 ± 0.011ab	2736 ± 47ab	0.675 ± 0.009b
TN-4	3928 ± 42d	0.568 ± 0.013cd	0.863 ± 0.010ab	2704 ± 77ab	0.582 ± 0.014c
UN	4948 ± 21a	0.617 ± 0.019bc	0.856 ± 0.012bc	2442 ± 39c	0.341 ± 0.039e
Control	3407 ± 34e	0.683 ± 0.009a	0.883 ± 0.012a	2823 ± 60a	0.782 ± 0.009a

Note: Means with different lowercase letters within the same column are significantly different at $p < 0.05$.

Hardness measures a noodle's resistance to compression. In this study, the UN sample was markedly harder than the control ($p < 0.05$), a result closely tied to the physical nature of the insoluble dietary fiber abundant in oat bran. Without pre-hydration, the rigid, compact bran particles remained as stiff fillers inside the gluten–starch matrix. They not only resisted deformation but also competed for the limited water, restricting starch gelatinization and the full expansion of the gluten network. As a result, the cooked noodles developed an overall dense and rigid structure. Such behavior has been widely reported in fiber-enriched noodle products. Izydorczyk et al. (2005) found that partially replacing wheat flour with β-glucan-rich barley markedly increased the firmness of fresh yellow alkaline noodles. They attributed this hardening to a semi-solid, three-dimensional network formed by the viscoelastic and matrix-building constituents of the barley. The physical filling effect of insoluble fiber particles and the water-competition mechanism are recognized as the two main causes of elevated hardness in whole-grain noodles (Fan et al. 2024; Kong et al. 2026; W. Li, Xu, et al. 2025). Earlier work on oat-fortified noodles has shown that hardness is positively associated with β-glucan content (3.1%–5.2%) and with specific starch fine structures: longer amylopectin chains (DP ≥ 26) and a higher proportion of long amylose chains (DP ≥ 1000) (Nguyen et al. 2020). These same molecular features govern the pasting viscosities of wholemeal oat flour, which in turn correlate with noodle hardness. Such findings confirm that both starch architecture and β-glucan level are key determinants of texture.

Following pre-hydration, hardness decreased progressively with increasing hydration level, and the TN-3 did not differ significantly from the control in hardness ($p > 0.05$). This reduction can be explained by the fact that pre-hydration allowed the bran fiber to absorb water, swell, and soften beforehand, weakening its role as a rigid stress concentrator. At the same time, the softened bran particles were able to deform in harmony with the extensional flow of the gluten network during subsequent mixing and sheeting, thereby alleviating physical disruption of network continuity. In the TN-4 sample, hardness rebounded slightly to 3928 g. This is likely because, under the oversaturated condition, a portion of the soluble β-glucan was extensively leached out during the pre-hydration step itself, leading to a collapse of the internal structure of the bran particles and a decrease in their water-binding capacity, which ultimately resulted in a firmer structure after cooking (Wu et al. 2025a, 2025b).

Resilience was the TPA parameter most sensitive to pre-hydration and showed the greatest discriminatory ability among the five attributes. The UN sample had a resilience of only 0.341, representing a 56.4% decrease compared with the control (0.782), a reduction far exceeding those observed for the other four parameters. Resilience measures the instantaneous recovery of a noodle strand after the first compression and before the second, it primarily captures the immediate viscoelastic response of the gluten network and is therefore more sensitive to micro-defects and stress concentrations within the matrix. Consequently, the micro-cracks and interfacial discontinuities created by unhydrated bran particles were most clearly reflected in this parameter. Pre-hydration significantly improved resilience: values increased progressively from TN-1 to TN-3, reaching 0.675 in TN-3. Although this value was still lower than that of the control ($p < 0.05$), it was nearly double that of UN. This marked improvement provides compelling evidence that the primary effect of pre-hydration is to restore the continuity of the gluten network. The subsequent decline in resilience to 0.582 in TN-4 further confirms the detrimental consequence of excessive hydration. Previous research has shown that an increase in insoluble dietary fiber from bran promotes a shift in gluten protein secondary structure toward β-sheet conformations, leading to a more rigid and less extensible protein network that, in turn, increases hardness and reduces springiness (Huang et al. 2017). The data obtained for the UN sample provide strong textural evidence in support of this mechanism.

When the changes across all five TPA parameters are considered together, a clear pattern emerges: the influence of pre-hydrated bran on noodle texture can be understood through the formation and structural integration of a β-glucan gel network. When pre-hydration is insufficient (TN-1, TN-2), the β-glucan chains cannot fully extend, leaving a patchy, discontinuous gel. When pre-hydration is excessive (TN-4), the surplus free water dilutes the effective gel concentration and reduces the density of network junctions. Both extremes limit the textural improvement. This mechanism is consistent with findings from a study on fermented wheat bran noodles, which demonstrated that pretreated bran promotes the migration of water from the bran to the protein and starch matrix and improves the overall uniformity of water distribution in the dough (Fan et al. 2022).

3.3 | Color Parameters

To ensure measurement accuracy, color was determined using powders obtained by grinding lyophilized noodle samples. The color parameters of noodles prepared with oat bran at different pre-hydration levels are presented in Table 3. Consistent with earlier reports (Feng et al. 2023; Kong et al. 2026), bran addition darkened both dough and noodles and increased their yellowness. UN recorded an L* value of only 52.49, an a* value as high as 4.13, and a b* value of 19.09, all of which differed significantly ($p < 0.05$) from those of the white wheat noodle control (L* = 70.93, a* = 2.40, b* = 17.88). This sharp decrease in lightness and marked increase in redness and yellowness are consistent with the dull, yellowish color and the dark-brown bran specks visible on the noodle surface. As the pre-hydration degree increased, L* increased steadily, whereas a* and b* decreased progressively, reaching the most favorable values at TN-3 (L* = 65.40, a* = 3.02, b* = 18.29). Beyond this point, a* and

TABLE 3 | Color measurement of noodles.

Sample	L*	a*	b*
TN-1	60.87 ± 0.68c	3.46 ± 0.10bc	18.45 ± 0.11bc
TN-2	65.27 ± 0.89c	3.95 ± 0.08d	18.65 ± 0.08bc
TN-3	65.40 ± 0.44b	3.02 ± 0.12b	18.29 ± 0.15b
TN-4	65.36 ± 1.07b	3.72 ± 0.13cd	18.73 ± 0.11cd
UN	52.49 ± 1.05d	4.13 ± 0.25d	19.09 ± 0.21d
Control	70.93 ± 0.67a	2.40 ± 0.25a	17.88 ± 0.17a

Note: Means with different lowercase letters within the same column are significantly different at $p < 0.05$.

b* for TN-4 rebounded slightly to 3.72 and 18.73, respectively, indicating an initial improvement followed by mild deterioration.

The mechanisms underlying these color changes involve both physical optics and biochemical browning. Physically, the hard, sharp-edged particles of untreated bran created numerous optical interfaces when embedded in the gluten network. This caused strong scattering of incident light, which lowered lightness and produced visible specks where dark particles were concentrated. Pre-hydration allowed the bran fiber to absorb water, swell, and soften. During sheeting, these swollen particles were more easily and uniformly wrapped by the gluten matrix, markedly reducing interfacial light scattering and increasing light penetration, which in turn elevated L* and reduced the appearance of specks. Chemically, oat bran is rich in polyphenol oxidase (PPO) and its phenolic substrates. Cell disruption during noodle processing brings the enzyme into contact with its substrates, catalyzing the oxidative polymerization of phenolics into brown pigments, which are the main source of the elevated a* and b* values. The pre-hydration process may partially reduce PPO activity by limiting enzyme-substrate contact, and it probably solubilized and uniformly dispersed some soluble pigments and phenolics, preventing localized concentration and thereby significantly lowering the redness and yellowness of TN-3. Taken together, the color data demonstrate that judiciously controlled pre-hydration not only physically masks the negative visual impact of bran particles but also suppresses browning at a biochemical level, shifting the color of bran-enriched noodles toward that of pure wheat noodles. This shift is critical for improving the visual quality of bran-enriched noodles.

3.4 | Effects of Pre-Hydration Degree on Bioactive Compound Content of Oat Bran Noodles

Pre-hydration of oat bran strongly influenced the retention of bioactive compounds and dietary fiber in the noodles (Figure 3). The β-glucan content of the UN was the lowest (3.42%), and it increased progressively as the bran was hydrated from an unsaturated state (TN-1: 3.82%; TN-2: 4.13%) to near saturation (TN-3), where it peaked at 4.79%. When the bran was over-hydrated (TN-4), the β-glucan content decreased slightly to 4.34%, but this value remained significantly higher than those of the unsaturated and untreated counterparts. Total polyphenol content (TPC) showed a similar trend. The UN sample contained 7.31 ± 0.12 mg GAE/100 g, and TPC increased steadily with hydration, rising from 7.65 GAE/100 g in TN-1 to 8.53 and 8.54 mg GAE/100 g in TN-3 and TN-4, respectively, with no meaningful difference between the saturated and

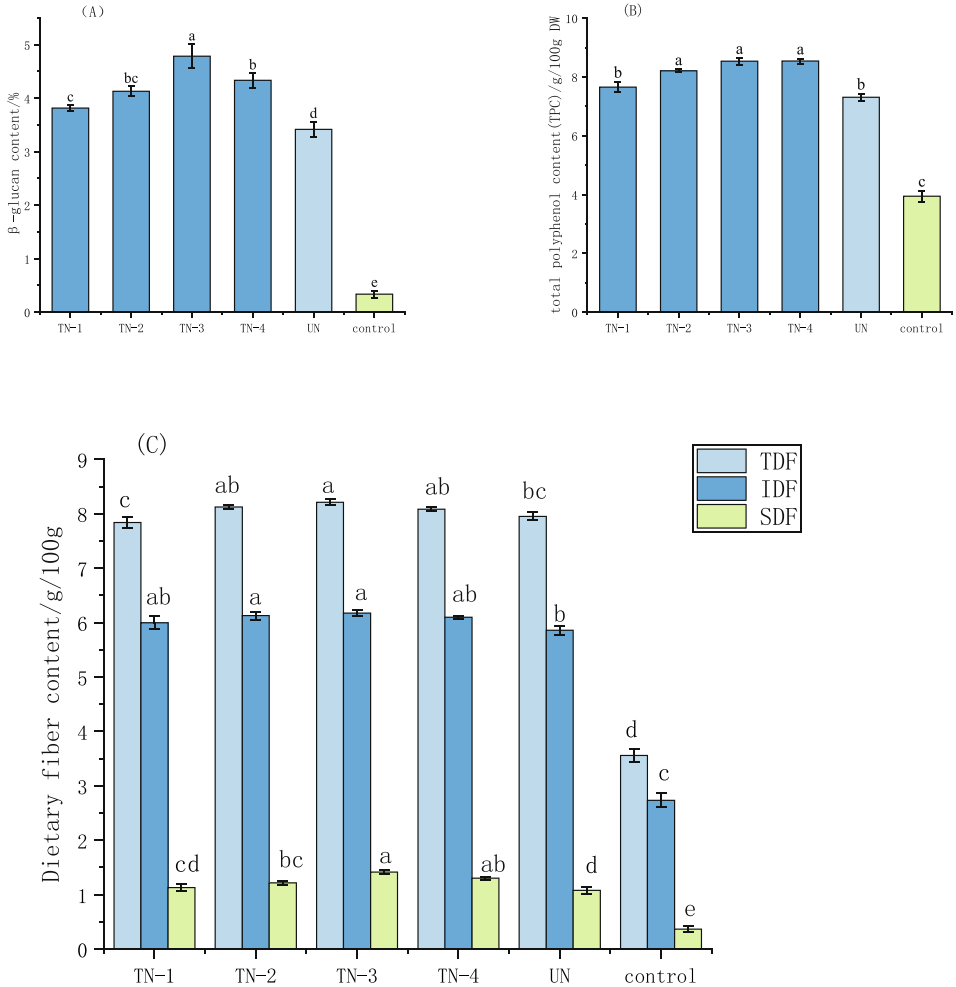


FIGURE 3 | Effects of pre-hydration degrees on (A) β-glucan content; (B) total polyphenol content; and (C) dietary fiber content of noodles. Different lowercase letters above bars of the same series (i.e., bars of the same color/legend category) indicate significant differences among treatment groups ($p < 0.05$); bars sharing the same letter are not significantly different. Each series was analyzed separately.

over-hydrated samples. Xue et al. reported that the TPC of raw noodles increased significantly ($p < 0.05$), from 5.86 in the control to 12.32 in noodles with 35% Tartary buckwheat bran flour substitution (TBBF-35) (Xue et al. 2022).

The dietary fiber profile showed a similar trend. With increasing pre-hydration, total dietary fiber (TDF) reached a maximum of 8.21 g/100 g in TN-3 before decreasing to 8.08 g/100 g in TN-4. Insoluble dietary fiber (IDF) peaked at 6.18 g/100 g (TN-3) and then decreased to 6.10 g/100 g, whereas soluble dietary fiber (SDF) showed the largest relative increase, from 1.08 g/100 g in UN to 1.42 g/100 g in TN-3, before decreasing to 1.30 g/100 g in TN-4. The control sample, which contained no oat bran, had only 3.56 g/100 g TDF, confirming that the bran was the main source of fiber.

These parallel trends can be explained by the physical and biochemical changes that water induces in the bran matrix. As hydration approaches saturation, water gradually plasticizes and swells the rigid cell walls. Soluble β-glucan and bound polyphenols are therefore released more easily and become evenly dispersed during dough mixing. This effect is most pronounced near saturation (TN-3), where cell wall relaxation and matrix integration are optimized, yielding the highest values for β-glucan, TPC, TDF, IDF, and SDF. In the over-hydrated state (TN-4), excess free water begins to act as a solvent, leaching a portion of the solubilized β-glucan and other soluble fibers out of the noodle matrix during sheeting and cooking. This leaching accounts for the decreases observed in SDF and TDF. Polyphenols, in contrast, remained largely unaffected by this slight increase in free water, because the bran structure has already been sufficiently disrupted to release the accessible phenolics, and oxidative losses appeared negligible under the processing conditions used. Overall, pre-hydrating oat bran precisely to its water-binding capacity represents the most effective strategy for simultaneously maximizing the retention of β-glucan, polyphenols, and dietary fiber fractions in oat bran noodles.

3.5 | Effects of Pre-Hydration Degree on In Vitro Starch Digestibility of Oat Bran Noodles

To determine whether bran pre-hydration affects noodle digestibility, the in vitro starch digestibility of PBN was

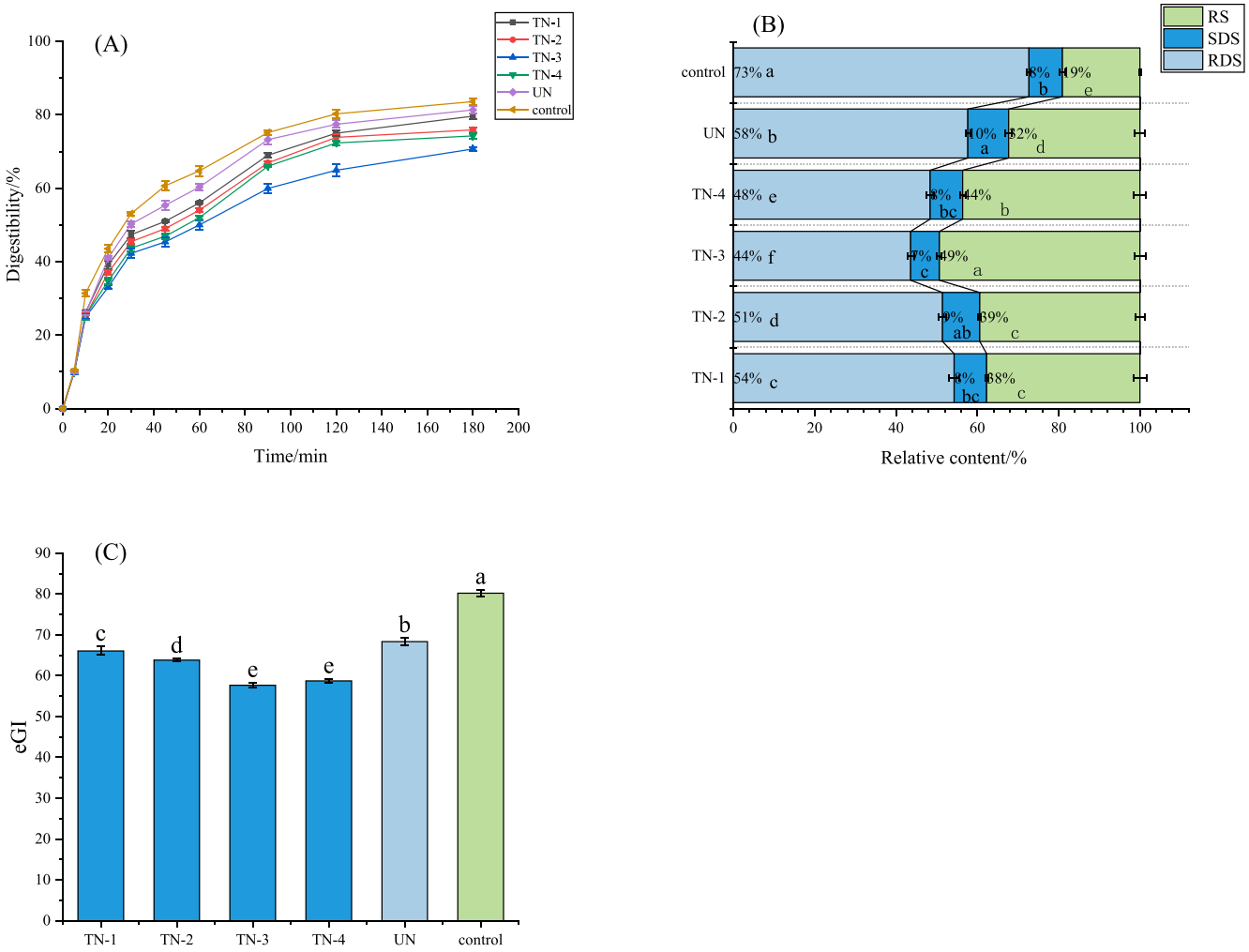


FIGURE 4 | Starch digestion properties of cooked noodles. (A) In vitro digestion curve; (B) content of RDS, SDS, and RS. Different lowercase letters within the same segment (RDS, SDS, or RS) across different treatment groups indicate significant differences ($p < 0.05$); values sharing the same letter are not significantly different. Each component was analyzed separately; (C) estimated glycemic index (eGI) values. Different lowercase letters above bars indicate significant differences among treatment groups ($p < 0.05$); bars sharing the same letter are not significantly different.

examined. The digestion profiles of cooked noodles (Figure 4) showed that the oat bran markedly suppressed starch digestibility, and pre-hydrating the bran further reduced it significantly. The lowest starch digestibility was observed when the bran was hydrated to saturation, whereas neither insufficient nor excessive pre-hydration produced the same effect. PBN had a substantially higher resistant starch (RS) fraction and a much lower rapidly digestible starch (RDS) fraction than untreated bran noodles (UN) or the white wheat noodle control. This can be attributed to the abundant polyphenols, lipids, β-glucan, and proteins in oat bran, which have been shown to enhance the resistance of starch to digestion by inhibiting amylase activity, promoting resistant starch formation, and increasing matrix viscosity (Romero Hernández et al. 2022). Compared with TN-1 (54% RDS, 8% SDS, 38% RS) and TN-2 (51% RDS, 9% SDS, 39% RS), TN-3 had a notably higher RS content (49%) and lower RDS content (44%), indicating that pre-hydrating oat bran can convert part of the RDS and SDS fractions into RS in cooked noodles. Furthermore, the estimated glycemic index (eGI) of PBN was significantly lower than that of UN, with TN-3 exhibiting the lowest eGI value. Compared with UN, TN-3 showed a 53.1% increase in RS content and a 15.6% decrease in eGI. The complete data on the changes in starch digestion over time are provided in Supplementary Table S1.

The results showed that a stepwise increase in bran pre-hydration gradually increased the resistant starch (RS) content and decreased the hydrolysis rate of the oat bran noodles. This trend is consistent with an emerging consensus that controlled hydrothermal conditioning of oat materials reconfigures their macromolecular architecture into a digestion-resistant state. In a previous study, oat groats were pre-baked and steamed and then combined with untreated buckwheat to make noodles; the cooked product contained as much as 41% RS (X. Zou et al. 2023). The authors attributed this to two structural changes. First, the pretreatment created an extended, thermally stable protein network by rearranging gluten and oat globulins. Second, it enhanced the short-range molecular order of gelatinized starch through newly formed double helices and binary/ternary complexes (starch–lipid, starch–protein, and starch–lipid–protein). A strikingly similar structural reinforcement was reported for brown rice flour after combined heat-moisture treatment and extrusion (Zhang et al. 2023). In that study, the synergy of moisture and mechanical energy drove starch to reorganize from an amorphous to a crystalline state and induced starch–lipid complex formation. The result was a significantly lower estimated glycemic index than that obtained with either treatment alone. The central role of moisture in ordering starch was further demonstrated in a model roasting system designed for oat starch–lipid mixtures. An initial moisture content of 20% dramatically increased the amount of Type I amylose–lipid crystallites, increasing RS to 88.3% (Ma et al. 2026). Multivariate analysis confirmed that digestion resistance was predominantly governed by long-range molecular order and lamellar structural features, both of which were formed under moist conditions.

In addition, the physical barrier provided by oat cell-wall polysaccharides also warrants attention. When β-glucan from wholemeal oat flour was tested with isolated oat starch, it did not alter the digestion rate. However, incorporating that same β-glucan into white salted wheat noodles significantly slowed starch hydrolysis (Nguyen et al. 2022). Confocal microscopy revealed that β-glucan interacted with the protein phase and reinforced the starch–protein matrix, thereby altering the noodle microstructure. In addition, pre-hydrated bran releases β-glucan into the noodle matrix in a partially solubilized form. This β-glucan is dispersed within the protein–starch continuum, creating a denser microstructure that restricts enzyme access. Therefore, the gradual reduction in starch digestibility observed with increasing bran pre-hydration (TN-1 to TN-3) most likely reflects the cumulative effect of three intertwined factors: a tighter protein scaffold, a greater proportion of ordered starch domains and starch–lipid complexes, and a more uniformly distributed β-glucan barrier. Together, these factors slow enzyme diffusion and catalysis. Our findings reinforce the view that careful moisture management, whether applied to whole oat groats, oat flour, or bran fractions, is a mechanistically sound and broadly applicable strategy for designing slowly digestible oat-based staples.

4 | Conclusions

Oat bran was pre-hydrated to different water activity levels ($a_w = 0.9908–0.9973$) and then used to prepare noodles. The degree of oat bran pre-hydration was decisive for both the processing quality and nutritional functionality of the enriched noodles. Hydrating oat bran to its water saturation point ($a_w = 0.9970$) largely eliminated the competitive water absorption that occurs when dry bran is added, thereby allowing the gluten network to develop properly. Noodles prepared with pre-saturated bran showed optimal cooking quality, with a breakage rate of 3.5% and a cooking loss of 10.4%. Under this condition, hardness (3572 g), cohesiveness (0.645), springiness (0.876), and chewiness (2736) did not differ significantly ($p > 0.05$) from those of the white wheat noodle control. This pre-saturation treatment also resulted in the highest retention of β-glucan (4.79%), polyphenols (8.54 mg GAE/100 g), and dietary fiber (6.18 g/100 g), while reducing the darkening typically caused by bran incorporation. In addition, starch digestion was markedly slower in noodles made with pre-saturated bran, and their estimated glycemic index (eGI) was 15.6% lower than that of noodles containing untreated bran. In summary, pre-hydration of oat bran facilitated water migration and the formation of a compact β-glucan–starch–protein network in PBN, thereby improving noodle quality and digestive resistance. Overall, pre-saturating oat bran before dough mixing offers a straightforward, low-cost, and effective strategy for simultaneously improving the cooking quality and nutritional profile of fiber-enriched noodles. Further work is still needed to provide additional microstructural insights using techniques such as scanning electron microscopy and low-field nuclear magnetic resonance. The findings of this study establish a precise hydration design methodology for the pretreatment of oat bran, and provide a theoretical basis for the development of low-GI foods.

Author Contributions

Xin Lu: conceptualization, writing – original draft, funding acquisition. **Tingting Meng:** writing – review and editing, investigation.

Yongji He: project administration, resources. **Chao Liu:** validation, methodology. **Xuefen Li:** software, data curation.

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Disclosure

Manuscript approval and data integrity statement: All authors have read and approved the final version of the manuscript. The corresponding author, Tingting Meng, had full access to all of the data in this study and takes complete responsibility for the integrity of the data and the accuracy of the data analysis.

Transparency statement: Xin Lu affirms that this manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned have been explained.

Ethics Statement

The authors have nothing to report.

Consent

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The authors confirm that the data supporting the findings of this study are available within the article and its Supplementary Materials.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Supplementary Table S1:** In vitro digestion data.