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Micronization of wheat bran: influence on the quality and starch digestibility of dietary fiber-enriched steamed sponge cake

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ABSTRACT

Exploring an ideal carrier for superfine wheat bran dietary fiber is important for maximizing its health benefits. This study evaluated the batter rheology, texture, gel network structure, and starch digestibility of steamed sponge cake (SPC) enriched with wheat bran of different particle sizes at 10%, 20%, and 30% addition. The results indicated that to maintain the quality (appearance, texture, and sensory attributes) of SPC without significant compromise, the addition of coarse bran (84–110 μm) should not exceed 10%. However, for superfine wheat bran (19 μm), increasing the addition from 10% to 30% did not impair the hardness, springiness, overall acceptability, gas cell structure, and relatively intact starch gel network of SPC. Moreover, the starch digestibility of SPC with 30% superfine wheat bran decreased from 90.1% (control) to 81.6%, and resistant starch content increased by 85.9%. This study suggests that products not requiring gluten development could be ideal carriers for high levels of micronized dietary fiber.

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1. Introduction

Epidemiological studies link the regular consumption of whole grains to a reduced risk of various chronic diseases such as type 2 diabetes, inflammation, and cardiovascular disease^[1]. Whole grain foods can be included in the human diet as they are rich in dietary fiber, antioxidants, vitamins, and other nutrients, mainly concentrated in bran^[2]. Concurrently, bran poses some unique challenges for whole wheat flour milling and product quality, including sensory, texture, and storage^[3]. Moreover, the complex plant tissue and insoluble cell wall matrix of bran limit the bioaccessibility of phenolics and proteins^[4–5]. An advantageous strategy to overcome the drawbacks of bran dietary fiber is to separately process flour and bran before

mixing them^[6–7]. Superfine milling has been widely practiced as an ecofriendly and economical means of modifying wheat bran^[4]. The micronization process improved the techno-functional properties of dietary fiber (e.g., color, solubility, dispersibility, and palatability) and facilitated the release and adsorption of phenolics and protein in the intestine^[8–9].

A challenge in the production of micronized bran-enriched products is their impact on quality. Reportedly, the particle size of dietary fiber has a significant impact on dough characteristics and product texture, which is increasingly recognized as a key parameter requiring optimization^[10]. Smaller particles normally provide better taste but have a greater negative impact on the quality of products requiring gluten development, such as bread and steamed bread, because dietary fiber and phytochemical components in micronized bran likely interact with gluten, inhibiting its development^[11]. Reducing the average particle size of bran from 433 to 39 μm increased the hardness of steamed bread and promoted starch retrogradation^[12]. Huang et al.^[13] also reported that whole wheat steamed bread made with coarse bran ($D_{50} = 105 \mu\text{m}$) had a larger

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specific volume, brighter color, and softer texture. Additionally, noodles were found to be prone to breakage and had poor dry color when added with bran contents of $> 15\%$ ^[14]. By contrast, products that do not require gluten development have different particle size requirements^[15]. Smaller particles of wheat bran dietary fiber produced larger cookies compared with larger particles dietary fiber^[16]. Additionally, using micronized wheat bran dietary fiber ($D_{50} = 50 \mu\text{m}$) to replace wheat flour produced a softer cake with higher sensory acceptability^[17]. However, the dietary fiber content in such products is not sufficient, as cereal flour only accounts for approximately a quarter of the cake ingredients. Therefore, there is a need to explore new cereal products that can contain high levels of micronized dietary fiber to fully utilize its health benefits.

Steamed sponge cake (SPC) is a traditional food with a long history in countries such as China, Thailand, and Vietnam. It is made by steaming rice batter or wheat batter to form continuous starch network and is well known for its open gas cell structure and soft texture^[18–19]. However, the lack of gluten network reduces the retention rate of carbon dioxide, resulting in SPC with rough texture and low specific volume. Some studies have attempted to improve the quality of gluten-free steamed rice cake by enhancing the viscosity and gas-holding properties of rice batter using soybean residue^[19–20] and mulberry leaves^[21]. Additionally, the high starch digestibility of SPC is not conducive to postprandial blood glucose control, and adding dietary fiber is expected to make up for this deficiency. It was hypothesized that the influence of wheat bran dietary fiber with various particle size on the rheology and gas-holding properties of wheat batter was different, and could further affect the quality, staling, and starch digestibility of SPC.

Based on these facts, this study evaluated: 1) the effect of wheat bran with different particle size (19–110 μm) at 10%, 20%, and 30% addition on the rheological properties of the batter; 2) the texture, gas cell structure, gel structure, and sensory quality of fiber-enriched SPC; and 3) the nutritional quality and starch digestibility of fiber-enriched SPC. The objective was to explore the potential of SPC as an ideal carrier for high-content micronized dietary fiber. This study can provide valuable information for the preparation of nutritionally fortified cereal products with satisfactory quality.

2. Materials and methods

2.1 Materials

Wheat bran of different particle sizes were the same as in our previous study^[22]. Briefly, an industrial airflow impact mill was used to prepare different particle size wheat bran, including coarse wheat bran (CWB, $D_{50} = 110 \mu\text{m}$), medium wheat bran (MWB, $D_{50} = 235 \mu\text{m}$), fine wheat bran (FWB, $D_{50} = 84 \mu\text{m}$), and superfine wheat bran (SWB, $D_{50} = 19 \mu\text{m}$). The chemical composition of these bran samples was similar (approximately 41.29%–42.71% total dietary fiber, 19.54%–20.21% protein, 19.72%–20.43% starch, and 4.77%–5.16% fat) as the samples were prepared without sieving. Low-gluten wheat flour was purchased from New Land Group (Henan, China) and contained approximately 73.50% total starch, 8.00% protein, and 1.10% fat. Sugar and yeast were purchased from a local supermarket. α -Amylase (A3176), pepsin (P6687), and pancreatin (P1750) were purchased from Sigma-Aldrich (Louis, USA). Amyloglucosidase,

total dietary fiber assay kit (K-TDFR), and total starch assay kit (K-TSTA) were purchased from Megazyme (Bray, Ireland).

2.2 Preparation of SPC

SPC was prepared according to the method used by Cao et al.^[6] with modifications. Wheat flour (100 g) was mixed with 1.5 g of yeast, 15 g of sucrose, and 130 g of water to prepare the batter, which was fermented in a cabinet at 30 °C for 40 min. The fermented batter (approximately 60 g) was transferred to a cake mold (6 cm $\times$ 6 cm $\times$ 5 cm) and left at room temperature (approximately 25 °C) for 10 min. Subsequently, the batter was steamed in a steamer for 25 min to obtain SPC (control). The SPC was cooled and stored in polypropylene bags at room temperature for subsequent analysis. In our pre-experiment, the specific volume, cohesiveness and sensory quality of SPC with $> 30\%$ wheat bran were much lower than those of SPC with 10%, 20% and 30% wheat bran. Therefore, SPC with 10%, 20% and 30% different particle size wheat bran was prepared to investigate the effect of bran particle size on quality and starch digestibility of SPC. The preparation procedure for bran-enriched SPC was similar to that of the control, and bran-enriched SPC was named using bran abbreviation and the addition amount: for example, SPC with 10% wheat bran was designated as CWB10, MWB10, FWB10, and SWB10, respectively.

2.3 Specific volume, color, and texture of SPC

The volume of the SPC samples were determined using the rape seed replacement method (AACC method 10-05). The specific volume of SPC was calculated as the ratio of volume to mass of the sample. A colorimeter (CR-400, Konica Minolta Holdings, Tokyo, Japan) was used to evaluate the color characteristics of SPC, including lightness (L^*), green-red chromaticity (a^*), blue-yellow chromaticity (b^*), and total color difference (ΔE).

The SPC samples were cut into 2.5 cm $\times$ 2.5 cm $\times$ 2.5 cm squares and subjected to a texture profile analysis (TPA) dual compression test using a TA.XT texture analyzer (Stable Micro Systems Ltd., Godalming, UK). The sample was compressed using a P/36R cylindrical probe at a rate of 1.0 mm/s until 50% compression was achieved. Textural parameters, including hardness, adhesiveness, springiness, cohesiveness, and chewiness, were derived from the TPA graphs. The TPA test was repeated 6 times for each group.

2.4 Gas cell structure of SPC

According to a previously described method^[23], the SPC samples were cut into approximately 0.5 cm-thick pieces, and the cell structure was evaluated using a C-Cell color imaging system (Calibre Control International Ltd., Warrington, UK). Measurements included cell number per slice area, cell contrast, average cell wall thickness, and average cell size to access the gas cell structure of SPC.

2.5 Sensory evaluation

According to the method reported by Feng et al.^[18], the sensory evaluation panel comprised 10 trained members (4 men and 6 women) knowledgeable about texture and aroma parameters. All the SPC samples were coded with 3 random numbers and subsequently

presented to the panelists in a random order. The panelists were provided with drinking water for palate cleansing between tasting different SPC. The appearance, aroma, elasticity, fluffiness, and overall acceptability of SPC were assessed using a 7-point hedonic scale (7 = like very much, 4 = neither like nor dislike, 1 = dislike very much).

2.6 Gas yield of batter

The gas yield (mL) of batter was determined by measuring the change in batter volume during fermentation. The batter was prepared as described in Section 2.2. A mixed batter (100 mL) was poured into a volumetric cylinder (500 mL) and fermented at 30 °C for 40 min, and the volume of batter after fermentation was recorded^[20].

2.7 Batter rheology

The rheological properties of the fermented batter were determined using an AR1500ex rheometer (TA Instruments, New Castle, DE, USA) with parallel plates (diameter = 40 mm, clearance = 1 mm). The parameters for determining apparent viscosity were as follows: test temperature of 25 °C and shear rate range of 0.1–100.0 s⁻¹. Furthermore, the dynamic rheological properties of the batter were evaluated at a strain of 0.5% in the linear viscoelastic range and frequency sweep range of 0.1 to 100 rad/s. The edge of the plate was coated with a thin layer of silicone oil to prevent moisture evaporation during testing. The power-law model ($\tau = K\gamma^n$, $G' = K'\omega^{n'}$, $G'' = K''\omega^{n''}$) was used to calculate the consistency coefficient (K), elasticity coefficient (K'), and viscosity coefficient (K'') of the batter, where τ represents shear stress (Pa), γ represents the shear rate (s⁻¹), n represents flow behavior index, ω stands for the angular frequency, and n' and n'' denote the dimensionless frequency index.

2.8 Microstructure of SPC

A scanning electron microscope (SEM, SU8010, Hitachi, Tokyo, Japan) was used to observe the microstructure of lyophilized SPC samples at 5.0 kV acceleration voltage and 50× magnification.

2.9 Chemical composition and starch digestibility of SPC

The moisture (method 44-15-A), total starch (method 76-12), total dietary fiber (method 32-07.01), and protein (method 46-10) contents of SPC were measured using the AACC Approved Methods. The SPC sample (containing 50 mg of total starch) was dispersed in 2 mL of distilled water, and starch digestibility was determined using an *in vitro* digestion model^[24]. Briefly, oral, gastric, and small intestinal digestion processes were simulated *in vitro* using α -amylase, pepsin, and pancreatic enzymes, respectively, as detailed in our previous study^[22]. The percentages of rapidly digested starch (RDS), slowly digested starch (SDS), and resistant starch (RS) were calculated using the following formulas:

$$\text{RDS (\%)} = \frac{\text{G20} \times 0.9}{\text{TS}} \quad (1)$$

$$\text{SDS (\%)} = \frac{(\text{G120} - \text{G20}) \times 0.9}{\text{TS}} \quad (2)$$

$$\text{RS (\%)} = \frac{\text{TS} - (\text{RDS} + \text{SDS})}{\text{TS}} \quad (3)$$

Where TS denotes the total starch content in the sample and G20 and G120 represent the glucose content at 20 and 120 min, respectively.

2.10 Microscopic water migration of SPC

According to our previous method^[23], 1.0 g of SPC stored for 1 day at room temperature was accurately weighed and placed in the NMR tube. The relaxation distribution of water in SPC was determined by setting the measurement parameters as $T_w = 1\,000$ ms, $SF = 21$ MHz, and $NS = 4$ in CPMG mode.

2.11 Statistical analysis

All the tests were repeated at least thrice. SPSS software (IBM, Chicago, USA) was used to perform one-way ANOVA followed by Duncan's test at the 0.05 level to assess significant differences between the means. Pearson correlation analysis was performed using R v.4.1.1 ($P < 0.05$).

3. Results and discussion

3.1 Batter rheology

3.1.1 Batter viscosity

Fig. 1 shows the effect of bran particle size and addition amount on the apparent viscosity of the batter. The apparent viscosity of all the samples was dependent on the shear rate and exhibited shear-thinning behavior, which can be classified as that of non-Newtonian fluid. Bran addition of 30% increased the apparent viscosity of the batter; however, the influence of 10% and 20% bran addition was difficult to discern from the curves. Therefore, the consistency value (K) of the batter was further characterized using the power-law model (Table S1). The results revealed that there was no significant effect of 10% bran addition on the K value, whereas 20% and 30% bran addition significantly increased the K value from 10.34–11.86 (10%) to 12.53–17.38 (20%) and 20.09–30.29 (30%), respectively ($P < 0.05$). Similar trends were found in wheat dough^[9] and cake batter systems^[17]. This could be explained by the stronger water-holding capacity of bran than wheat flour^[25]. The competition between bran and the gluten-starch systems for water decreased water lubrication and increased batter consistency. Furthermore, the addition of bran diluted the batter system, which may explain the insignificant effect on the K value at the 10% addition amount. More interesting results were found regarding the particle size effect. With the same addition level (30%), reducing the bran particle size from 1110 μm (CWB) to 234 μm (MWB) and 84 μm (FWB) markedly reduced the apparent viscosity of the batter (Fig. 1A and Table S1), but the K value of SWB30 ($D_{50} = 19\,\mu\text{m}$) was considerably higher than that of the other batters. However, our previous study revealed that dry milling, especially superfine milling, drastically reduced the water-retention capacity of wheat bran by destroying its tissue pores^[26]. This suggests that competing water binding may not be the only factor influencing the effect of bran particle size on batter viscosity. The disruptive effect of insoluble materials such as wheat bran on the gluten-starch network should also be considered. SWB has a small particle size and is more likely to act as a filler in the batter continuity network, enhancing batter viscosity^[9, 27], whereas large flaked dietary fiber

may disrupt the continuous network structure of batter^[28–29]. Therefore, it was suggested that hydration and filler effects together changed the viscosity of the batter enriched with different particle sizes of wheat bran.

3.1.2 Batter viscoelasticity

The frequency scan curves of the batter reflected the elastic (G') and viscous (G'') characteristics of the batter (Figs. 1B and C). The G' value was positively correlated with disintegration resistance and hardness, whereas the G'' values reflected batter viscosity. A frequency dependence of G' and G'' was observed for all the batters, and there was a crossover point between G' and G'' . In the range of 0.1–0.3 rad/s, $G'' > G'$ (loss tangent ($\tan\delta$) > 1) indicated the dominance of viscous characteristics in the low-frequency range, whereas in the range of 1–100 rad/s, the batter exhibited a weak gel structure, namely a predominance of elastic characteristic ($G' > G''$). The increase in bran addition significantly increased the G' and G'' values, implying that the bran-enriched batter exhibited a more viscoelastic network structure. This was also supported by the K' and K'' results. At 30% addition, the K' values of CWB30 (208.2), MWB30 (79.4), FWB30 (100.8),

and SWB30 (150.4) increased by 723%, 214%, 298%, and 494%, respectively, compared with those of the control (25.3). The K'' values significantly increased from 16.6 (control) to 150.5 (CWB), 53.7 (MWB), 69.7 (FWB), and 92.8 (SWB), increasing by 804%, 223%, 318%, and 458%, respectively. The drastic increase in the viscoelasticity of the batter with 30% bran was related to the stronger water-retention capacity of the bran. It can also be attributed to the fact that bran could act as a filler in the batter network. Overall, the rheological results revealed that the addition of bran enhanced the apparent viscosity and dynamic viscoelasticity of the batter, which may affect its gas production capacity and the texture of the final product^[17,25].

3.2 Gas yield of batter

Gas yield is used to assess the gas-retention capacity of batter during fermentation and predict the volume of steamed rice cake^[19]. The addition of wheat bran reduced the gas yield of batter from 122 mL (control) to 101–118 mL (Table S1), and no significant correlation was found between apparent viscosity, viscoelasticity, and gas yield (Fig. 7, $P > 0.05$). Conversely, previous studies have

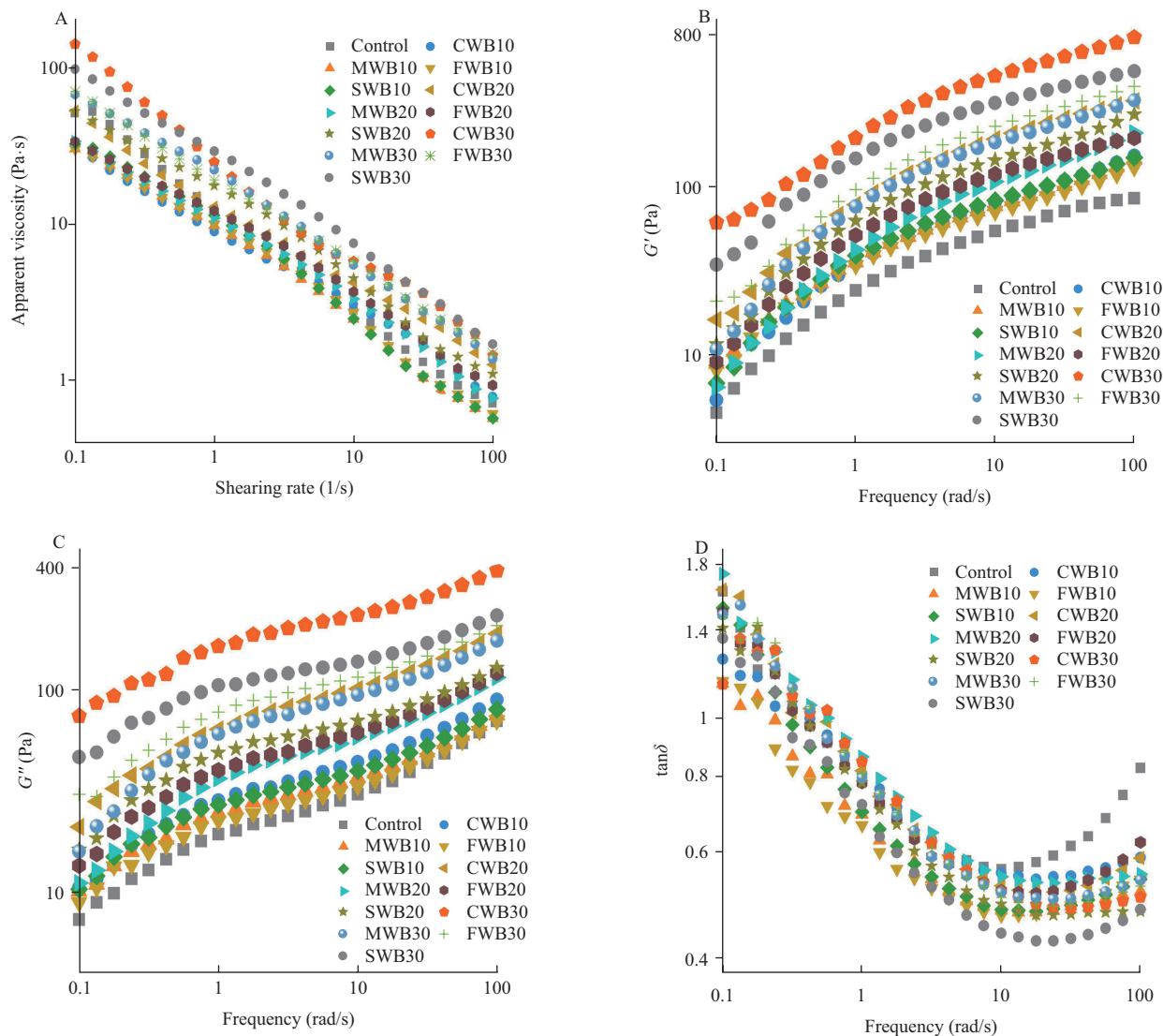


Fig. 1 Rheological properties of batter with different particle size wheat bran at 10%, 20% and 30% concentration. (A) Apparent viscosity; (B) G' (C) G'' (D) $\tan\delta$.

reported that soybean residue significantly improved the gas yield of rice cake by increasing the batter viscosity and forming a viscoelastic gel network^[19,20]. The opposite result of this study could be owing to the superior gluten-starch continuous network of the wheat flour batter (control group), which could retain CO₂ gas well during fermentation. While the addition of wheat bran increased the viscosity of the batter, it could also disrupt the continuity of the batter network, which was more detrimental to gas retention. Nevertheless, the volume of batter more than doubled in all the groups after 40 min of the fermentation procedure and showed significantly higher gas yield compared with the fiber-enriched rice batter^[20]. Therefore, it was confident that satisfactory dietary fiber-enrich SPC products could be produced.

3.3 Appearance characteristics of SPC

Appearance characteristics play an important role in the general acceptability of food and herein, they were evaluated in terms of morphology, color, and specific volume. Fig. 2 shows the longitudinal cross-sectional morphology of all the SPCs. All the samples showed visually fluffy and porous morphology, indicating that bran spiked up to 30% addition could be incorporated into the SPC without drastically altering its basic morphology, consistent with the gas yield results. Nevertheless, the more open gas cell was notably observed in CWB20, CWB30, and MWB30 (Fig. 2). This indicated that a sufficient amount of large dietary fiber particles rendered the cell wall of the gas chamber more brittle and prone to rupture, facilitating the formation of larger chambers. The gas cell structure of SPC was further quantified using the C-CELL system (Fig. 3). The results showed that the average cell number was 0.84 and the average cell size was 1.86 mm for the control. C-CELL analysis of wheat bread and steamed wheat bread revealed that their mean cell sizes were 1.20–1.80 and 0.82–1.14 mm^[24,32], respectively, demonstrating that SPC had a more open gas cell structure than bread. The effect of wheat bran on the gas cell structure of SPC was related to its particle size. The addition of 10% CWB, MWB, and FWB significantly reduced the mean cell number and cell contrast and increased the

mean cell wall thickness and mean cell size of SPC. The increase in CWB, MWB, and FWB additions further deteriorated the gas cell structure of SPC, typically characterized by a decrease in cell contrast and an increase in mean cell size. This suggested that adding bran with an average particle size of 84–110 µm led to a coarser and more inhomogeneous gas cell structure in SPC. However, adding SWB ($D_{50} = 19 \mu\text{m}$) in the range of 10%–30% had no significant impact on the average cell number or cell wall thickness of SPC. SWB20 and SWB30 even had smaller average cell sizes and finer gas cell structures compared with the control. The improvement of gas cell structure by particle size reduction was not significantly correlated with the rheological characteristics of the batter ($P > 0.05$) and was more likely a result of the less reduced disruption of gas cells by smaller bran particles. Similarly, bread made with fine wheat flour exhibited a finer gas cell structure and contributed to an enhanced elastic texture^[30].

The bran-enriched SPC became visually darker and more yellow with increasing addition of bran compared with the control (Fig. 2). The color characteristics of the SPC were evaluated using a colorimeter (Fig. S1). The ΔE value difference of > 3 between the samples indicated a visually different overall color. The results showed that the overall color difference and brightness of bran-enriched SPC were influenced by the addition amount of bran but independent of the bran particle size. The addition of bran (10%–20%) significantly reduced the brightness of the SPC (Fig. S1A), whereas increasing the bran addition to 30% did not further impair brightness. Additionally, SWB30 exhibited significantly higher a^* and b^* values compared with other bran-enriched SPC (Figs. S1B and C), indicating that increasing the addition amount and decreasing the particle size of wheat bran resulted in a redder and more yellow product. Interestingly, our previous results revealed that SWB powder was brighter and less yellow than coarse bran^[26]. The contrasting color results between the bran and the final product suggest that the preparation process plays a decisive role in the color of the steamed product. Similar results were reported for bran-enriched bread^[28] and cake^[31]. Bran contains more yellow pigments compared with the

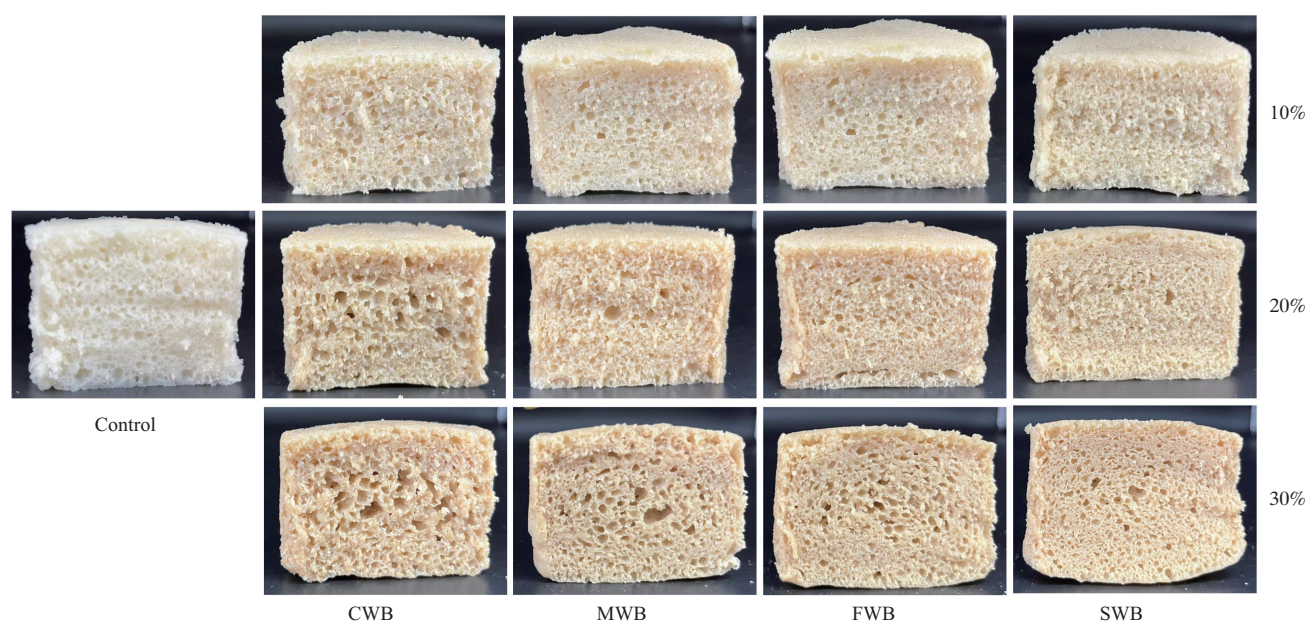


Fig. 2 Longitudinal cross-sectional morphology of steamed sponge cake with different particle size wheat bran at 10%, 20% and 30% concentration.

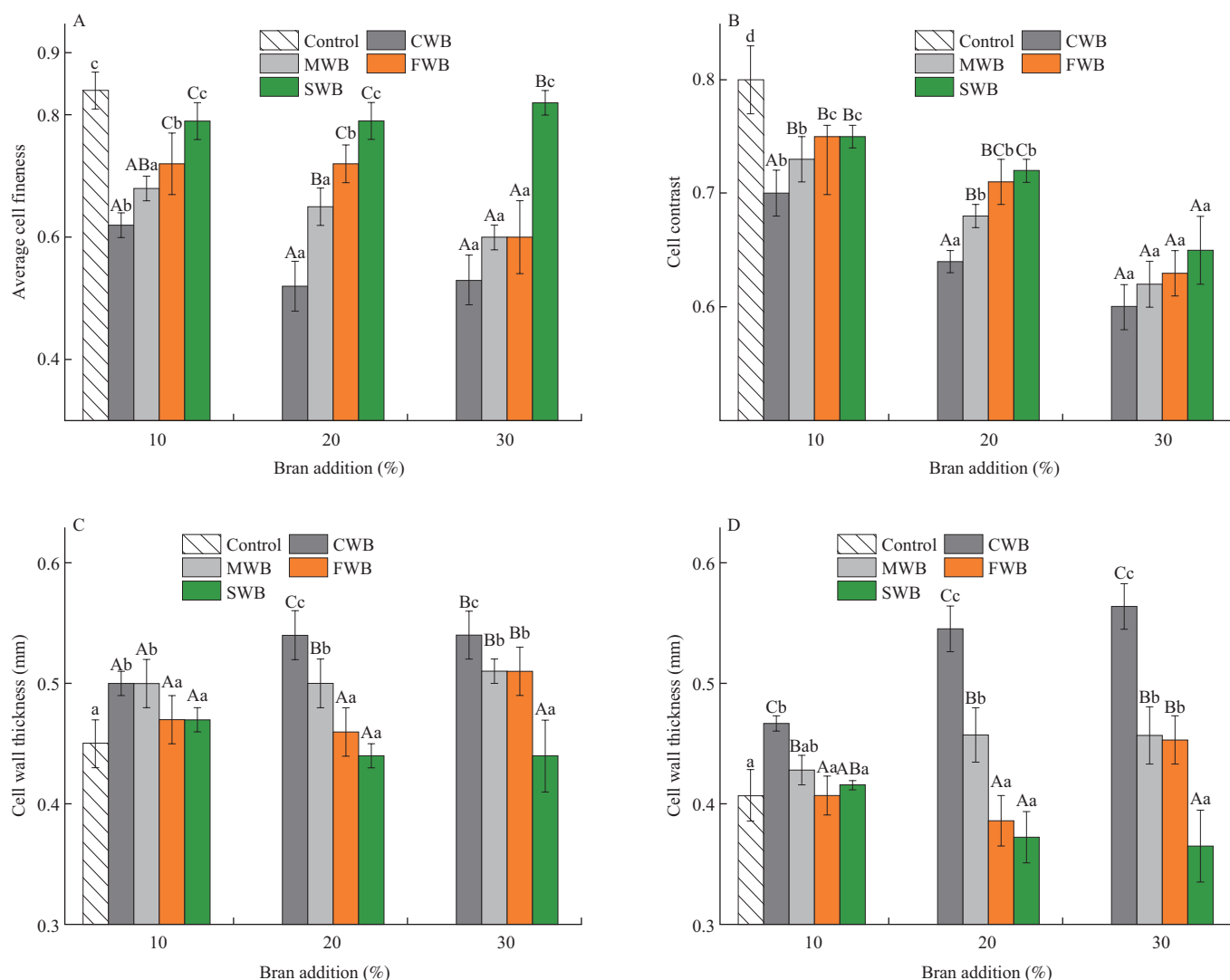


Fig. 3 Gas cell structure characteristics of steamed sponge cake with different particle size wheat bran at 10%, 20% and 30% concentration. Different uppercase letters mean significantly difference with different particle size but same addition ($P < 0.05$); different lowercase letters mean significantly difference with same particle size but different addition ($P < 0.05$).

endosperm, and the fine particles dispersed more uniformly in SPC. Moreover, milling increased the specific surface area of bran and promoted the release of phenolics and free amino acids^[5], facilitating the oxidation of pigment and phenolics and the Maillard reaction during steaming^[21].

Specific volume is another important appearance characteristic of SPC. At 10% addition, coarse bran (CWB and MWB) had no significant effect on the specific volume of the product (Table 1), whereas the specific volume of FWB10 and SWB10 decreased significantly by 11.1% and 14.9%, respectively ($P < 0.05$). The detrimental effect of particle size reduction on specific volume was also reported in bread products^[12,23,32]. It is mainly related to the stronger interaction of reactive components (dietary fiber and phenolic acids) in fine bran with gluten, which weakened the gluten network and reduced the gas-retention capacity^[32]. Increasing the addition of milled bran (MWB, FWB, and SWB) from 10% to 30% and reducing the particle size from 234 to 19 μm did not affect the specific volume of SPC, consistent with morphology observation and gas yield results. However, increasing bran addition over 20% in bread, steamed bread, and noodles adversely affected the appearance and specific volume^[28,33-34]. Therefore, SPC may

be more suitable for carrying high levels of wheat bran and delivering dietary fiber and antioxidants while maintaining desirable quality.

3.4 Texture property of SPC

TPA simulated chewing to assess the textural characteristics of SPC, including hardness, adhesiveness, cohesiveness, elasticity, and chewiness (Table 1). At 10% addition, CWB10 and MWB10 (6.25–6.55) exhibited a hardness similar to that of the control (6.15), whereas the superfine milling of bran significantly increased the hardness of SWB10 (7.54). The hardness of all bran-enriched SPC at 20% and 30% addition levels (7.79–8.27) was higher than that of the control, but neither the addition level nor the particle size significantly affected hardness. The hardness of SPC was highly correlated with specific volume ($r = -0.87$, $P < 0.01$) and K' ($r = 0.63$, $P < 0.01$), similar to the findings of bread^[23] and cake^[17]. This correlation can be attributed to the denser, more rigid internal structure of bran-fortified products^[35]. The adhesiveness of all bran-enriched SPC (0.19–1.64) was substantially higher than that of the control (0.07) and positively correlated with K'' ($r = 0.76$, $P < 0.01$).

Table 1

Specific volume and texture characteristics of steamed sponge cake with different particle size wheat bran at 10%, 20% and 30% concentration.

Sample	Bran addition (%)	Specific volume (mL/g)	Hardness (N)	Adhesiveness (N·mm)	Cohesiveness	Springiness (mm)	Gumminess (N)	Chewiness (mJ)
Control	0	1.98 ± 0.11 ^b	6.15 ± 0.38 ^a	0.07 ± 0.01 ^a	0.71 ± 0.01 ^d	7.40 ± 0.50 ^b	4.39 ± 0.23 ^b	32.47 ± 0.70 ^{bc}
CWB	10	1.95 ± 0.09 ^{Bb}	6.25 ± 0.01 ^{Aa}	0.19 ± 0.02 ^{Ab}	0.60 ± 0.02 ^{Ac}	6.22 ± 0.34 ^{Aa}	3.75 ± 0.01 ^{Aa}	23.31 ± 1.51 ^{Aa}
	20	1.66 ± 0.03 ^{Aa}	8.00 ± 0.56 ^{Ab}	1.04 ± 0.07 ^{Cc}	0.50 ± 0.01 ^{Ab}	7.37 ± 0.03 ^{Ab}	3.96 ± 0.30 ^{Aa}	29.19 ± 2.04 ^{Ab}
	30	1.69 ± 0.07 ^{Aa}	8.27 ± 0.74 ^{Ab}	1.64 ± 0.02 ^{Cd}	0.46 ± 0.00 ^{Aa}	7.43 ± 0.34 ^{Ab}	3.81 ± 0.34 ^{Aa}	28.27 ± 3.39 ^{Ab}
MWB	10	1.81 ± 0.08 ^{ABab}	6.55 ± 0.43 ^{Aa}	0.20 ± 0.03 ^{Ab}	0.60 ± 0.01 ^{Ab}	6.24 ± 0.09 ^{Aa}	3.94 ± 0.33 ^{Aa}	24.64 ± 2.36 ^{Aa}
	20	1.69 ± 0.03 ^{Aa}	7.93 ± 0.30 ^{Ab}	0.87 ± 0.04 ^{Bc}	0.52 ± 0.03 ^{ABa}	7.42 ± 0.10 ^{Ab}	4.11 ± 0.24 ^{Bb}	30.48 ± 1.99 ^{Ab}
	30	1.68 ± 0.01 ^{Aa}	8.13 ± 0.32 ^{Ab}	1.02 ± 0.08 ^{Bd}	0.50 ± 0.01 ^{Ba}	7.30 ± 0.35 ^{Ab}	4.05 ± 0.18 ^{ABab}	29.53 ± 2.45 ^{Ab}
FWB	10	1.76 ± 0.11 ^{ABa}	6.41 ± 0.22 ^{Aa}	0.20 ± 0.01 ^{Ab}	0.59 ± 0.01 ^{Ab}	6.42 ± 0.49 ^{Aa}	3.78 ± 0.13 ^{Aa}	24.29 ± 1.97 ^{Aa}
	20	1.66 ± 0.05 ^{Aa}	7.98 ± 0.31 ^{Ab}	0.85 ± 0.03 ^{Bc}	0.55 ± 0.04 ^{Ba}	7.38 ± 0.16 ^{Ab}	4.28 ± 0.13 ^{Bb}	31.59 ± 1.64 ^{Ab}
	30	1.67 ± 0.06 ^{Aa}	8.23 ± 0.16 ^{Ab}	1.00 ± 0.02 ^{Bd}	0.50 ± 0.02 ^{Ba}	7.30 ± 0.53 ^{Ab}	4.12 ± 0.05 ^{ABb}	30.06 ± 2.80 ^{Ab}
SWB	10	1.65 ± 0.02 ^{Aa}	7.54 ± 0.26 ^{Bb}	0.42 ± 0.04 ^{Bb}	0.60 ± 0.03 ^{Ab}	6.70 ± 0.48 ^{Aa}	4.54 ± 0.35 ^{Bb}	30.46 ± 2.58 ^{Bb}
	20	1.65 ± 0.05 ^{Aa}	7.79 ± 0.22 ^{Ab}	0.44 ± 0.03 ^{Ab}	0.58 ± 0.01 ^{Cb}	7.89 ± 0.53 ^{Abc}	4.52 ± 0.10 ^{Bb}	35.67 ± 2.11 ^{Bc}
	30	1.69 ± 0.01 ^{Aa}	7.88 ± 0.59 ^{Ab}	0.43 ± 0.05 ^{Ab}	0.55 ± 0.02 ^{Ca}	8.19 ± 0.78 ^{Bc}	4.30 ± 0.33 ^{Bb}	35.19 ± 2.24 ^{Bc}

Note: Values of A–C are significantly different with different particle size but same addition, while values of a–d are significantly different with same particle size but different addition ($P < 0.05$).

Increasing bran addition from 10% to 30% improved the springiness of SPC, related to its higher K value ($r = 0.72$, $P < 0.01$), a trend also observed in gluten-free steamed bread^[36] and rice bread^[37]. Increased batter viscoelasticity could improve the adhesiveness and springiness of the final product. The correlation coefficient between springiness and chewiness was 0.90. Increasing the addition amount of wheat bran from 10% to 30% and reducing its particle size to a micron-scale improved the chewiness of bran-enriched SPC. Cohesiveness indicates the integrity of the internal structure of SPC, which was highly correlated with the mean cell number ($r = 0.75$), cell contrast ($r = 0.93$), and cell wall thickness ($r = -0.61$). The fine gas cell structure of SWB20 and SWB30 improved cohesiveness. Generally, the TPA results revealed that adding wheat bran up to 30% increased the hardness and adhesiveness of SPC and weakened its cohesiveness and gumminess. SWB30 exhibited better cohesiveness, elasticity, and chewiness compared with CWB30, MWB30, and FWB30. Therefore, superfine wheat bran could be more suitable for making high bran content SPC with satisfactory textural quality, despite its more significant negative effects at lower additions.

3.5 Sensory evaluation of SPC

Sensory evaluation was conducted to assess the edible quality of the SPC, with trained sensory personnel evaluating the appearance, aroma, elasticity, fluffiness, and overall acceptability of the SPC. The addition amount of bran and its particle size affected the sensory scores of SPC to varying degrees (Fig. 4, Table S3). For SPC with 10% bran addition, the appearance score (5.9–6.2) and overall acceptability (5.5–5.8) were not significantly different from those of the control (6.4 and 5.9), although the elasticity was significantly lower. Decreasing the bran particle size did not affect the appearance, elasticity, aroma characteristics, and overall acceptability of SPC. Notably, increasing the addition of CWB, MWB, and FWB to 20% significantly reduced the appearance score (4.6–5.3), fluffiness (4.6–4.8), and overall acceptability (4.5–4.6) of SPC.

Some panelists described the SPC with 20% CWB, MWB, and FWB as coarse and gritty in texture, which can be attributed to the nonuniform distribution of coarse bran particles in SPC^[28], whereas superfine bran particles were sufficiently small to be well dispersed in SPC, improving its overall acceptability. Significantly, the overall acceptability of SPC with 30% addition of coarse bran (CWB30) increased compared with that of CWB20 and was even significantly better than those of MWB30 and FWB30. The panelists noted that the coarse bran in CWB30 tasted similar to oatmeal and provided excellent chewiness, giving a perception of healthiness rather than grittiness. This suggests that un-milled flaked bran can enhance the chewiness of products at specific additions, such as mooncakes and porridge. Additionally, increasing the addition amount of superfine bran from 10% to 30% did not significantly alter the elasticity and overall acceptability of SPC, highlighting the suitability of superfine bran for the ideal development of SPC featuring high dietary fiber content.

3.6 Microstructure of SPC

Fig. 5 illustrates the microstructure of SPC enriched with different particle sizes of wheat bran at 10%, 20%, and 30%. SEM images revealed that the continuous network structure of SPC is a starch gel with a typically porous honeycomb structure. The addition of 10% wheat bran (CWB, MWB, and FWB) did not significantly disrupt the continuous network of SPC, but more small pores ($< 100 \mu\text{m}$) were observed in SWB10. This difference may be owing to the interaction of the free phenolic acid released *via* superfine milling with proteins that disturbed the formation of the continuous network^[22,28]. Increasing the bran addition to 20% for all the particle sizes caused cell wall fragmentation of the SPC gel network, but the continuous network remained intact. This was because of the interaction of dietary fiber and gluten and physical disruption friction^[29]. Furthermore, adding 30% CWB hindered the formation of a continuous network structure, indicating a lack of solid gel structure within CWB30. This was consistent with the reduced cohesiveness and increased open gas

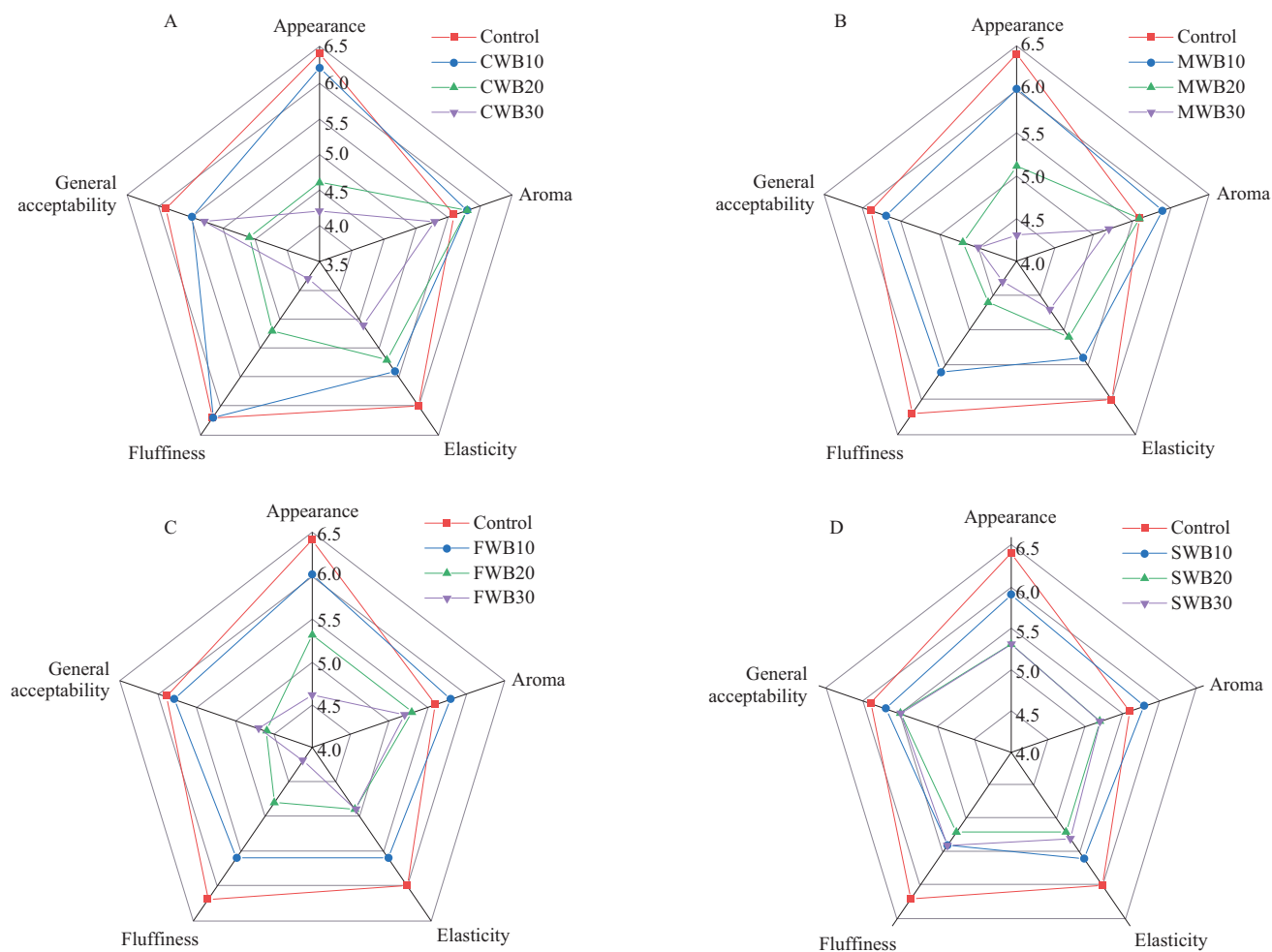


Fig. 4 Sensory evaluation of steamed sponge cake with different particle size wheat bran at 10%, 20% and 30% concentration. (A) CWB; (B) MWB; (C) FWB; (D) SWB.

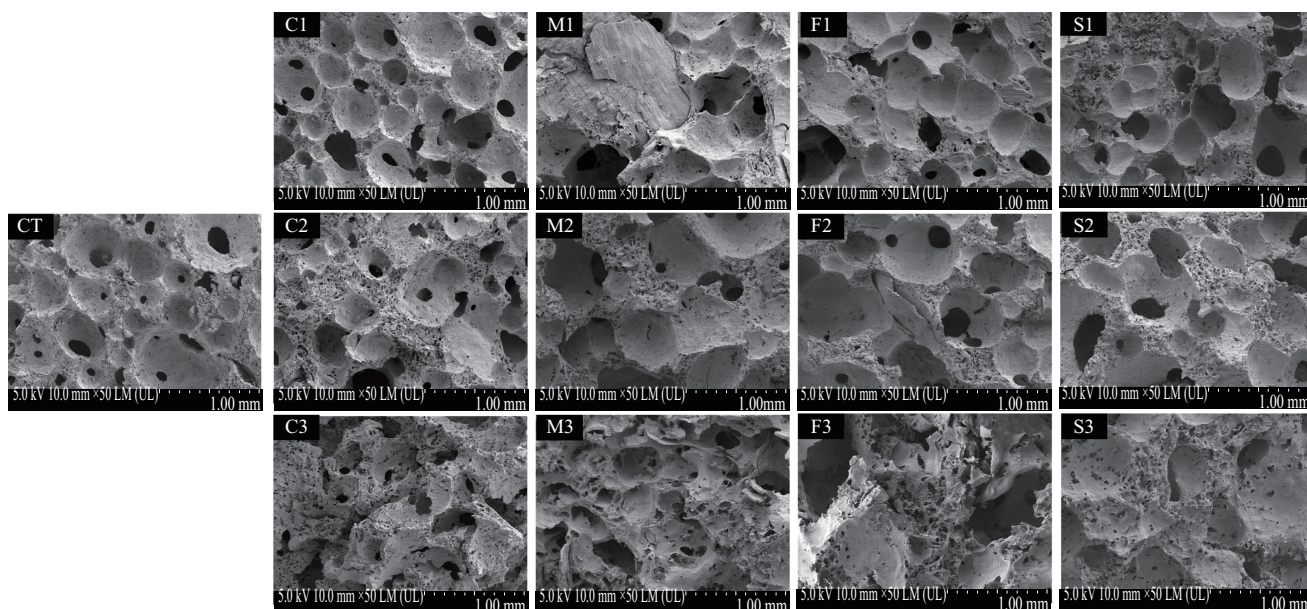


Fig. 5 Microstructure of steamed sponge cake with different particle size wheat bran at 10%, 20% and 30% concentration. CT, control; C1, 2, 3, coarse wheat bran at 10%, 20%, 30%; M1, 2, 3, medium wheat bran at 10%, 20%, 30%; F1, 2, 3, fine wheat bran at 10%, 20%, 30%; S1, 2, 3, superfine wheat bran at 10%, 20%, 30%.

cells. Similar results were reported in fiber-enriched bread, pasta, and rice flour, as the presence of numerous coarse particles disrupted the continuity of the protein–starch matrix^[28,34,38]. Conversely, better continuity of the network was observed in SWB30 owing to significantly less physical disruption of the gel network by superfine particles. This further confirmed that SWB is a better choice for making SPC with high-content dietary fiber SPC from a microscopic perspective.

3.7 Proximate composition and starch digestibility of SPC

The proximate composition of SPC is presented in Table 2. SPC contained 56.14% moisture, 30.06% total starch, 3.26% protein, and 0.65% dietary fiber (wet basis), indicating it is a high-moisture starchy food. Particle size did not affect the proximate composition of bran-enriched SPC because these wheat bran samples had similar chemical composition. The total dietary fiber and protein contents of bran-enriched SPC (10%–30% bran addition) increased significantly by 244%–775% and 12.3%–33.7%, respectively, whereas the total starch content decreased by 7.4%–23.7%. Bran-enriched SPC contained 2.24%–5.57% dietary fiber and 3.66%–4.73% protein (wet basis), respectively. The increase in dietary fiber and protein content may help reduce starch digestibility and postprandial glycemic response of SPC.

The starch digestion characteristics were assessed using an *in vitro* model. The control showed RDS, SDS, and RS contents of 46.62%, 43.50%, and 9.88%, respectively (Table 2). Adding 10% wheat bran of different particle sizes significantly reduced the RDS content of SPC by 8.5%–11.1% and increased RS content by 17.3%–47.6%. This result revealed the ability of wheat bran to retard the digestive rate of starch, attributed to its dietary fiber and antioxidants. However, while increasing bran addition significantly boosted the total dietary fiber content, there was no significant change in RDS and SDS contents in SPC supplemented with 20%–30% CWB, MWB, and FWB compared with CWB10 and FWB10. This

suggests that increasing coarse bran addition ($D_{50} = 84\text{--}110\text{ }\mu\text{m}$) did not further decrease the starch digestive rate in SPC. This could be explained by the disruption of the starch gel network caused by high additions of coarse bran (as confirmed by the SEM results) and the rougher gas cell structure that promotes the hydrolysis of starch digestive enzymes. Similarly, CWB and insoluble dietary fiber disrupted the protein–starch matrix continuum in bread and pasta, thereby increasing starch digestibility^[28,34]. Therefore, the development of low starch digestibility products required consideration of textural factors. While increasing coarse bran content did not further reduce starch digestibility in the small intestine, adequate dietary fiber intake has been widely shown to modulate chronic diseases such as cardiovascular disease and type 2 diabetes by regulating gut microbiota and promoting the production of short-chain fatty acids^[4,39]. Notably, increasing the SWB addition from 10% to 30% further reduced starch digestibility and increased RS content. The RS content in SWB30 increased by 85.9% compared with that in the control group, and the maximum starch digestibility decreased from 90.12% to 81.63%. SWB released more starch digestive enzyme inhibitors (including phenolic acids and peptides) in the intestine^[5,28]. Additionally, SWB30 had a relatively intact internal structure compared with CWB30, MWB30, and FWB30. Therefore, 30% addition of SWB further reduced starch digestibility of SPC.

3.8 Microscopic water migration of SPC

The microscopic water distribution characteristics of SPC after 1 day of storage were evaluated using LF-NMR to preliminarily investigate the anti-staling effect of wheat bran of different particle sizes on SPC. The T_2 value reflects water freedom and is categorized into 3 time zones: T_{21} (0–10 ms), T_{22} (10–100 ms), and T_{23} (100–1000 ms), which represent strongly bound water by hydrogen binding to macromolecules such as starch, structured water with high mobility in SPC, and free water, respectively. The peak area corresponding to

Table 2

Proximate composition (wet basis) and starch digestive properties of steamed sponge cake with different particle size wheat bran at 10%, 20% and 30%.

Sample	Bran addition (%)	Chemical composition				Digestive properties			
		Moisture (%)	Total starch (%)	Total dietary fiber (%)	Protein (%)	RDS (%)	SDS (%)	RS (%)	Cmax
Control	0	56.14 ± 0.29 ^a	30.06 ± 0.26 ^d	0.65 ± 0.09 ^a	3.26 ± 0.10 ^a	46.62 ± 1.28 ^c	43.50 ± 1.10 ^{ab}	9.88 ± 0.36 ^a	90.12 ± 0.37 ^c
CWB	10	57.32 ± 0.64 ^{Aa}	27.48 ± 0.24 ^{Ac}	2.27 ± 0.12 ^{Ab}	3.66 ± 0.06 ^{Ab}	42.54 ± 0.75 ^{Aa}	45.87 ± 1.14 ^{Aa}	11.59 ± 0.31 ^{Ab}	88.41 ± 0.53 ^{Bbc}
	20	56.34 ± 0.83 ^{Aa}	25.52 ± 0.16 ^{Ab}	3.94 ± 0.20 ^{Ac}	4.24 ± 0.11 ^{Ac}	42.76 ± 0.83 ^{Ba}	43.74 ± 1.63 ^{Aa}	13.50 ± 0.25 ^{ABc}	86.50 ± 0.46 ^{Ab}
	30	56.86 ± 0.76 ^{Aa}	23.14 ± 0.20 ^{Aa}	5.69 ± 0.28 ^{Ad}	4.63 ± 0.09 ^{Ad}	41.61 ± 0.80 ^{Ba}	45.53 ± 0.93 ^{Ba}	13.16 ± 0.36 ^{Ac}	86.84 ± 0.67 ^{Bb}
MWB	10	56.08 ± 0.47 ^{Aa}	27.80 ± 0.32 ^{Ac}	2.33 ± 0.16 ^{Ab}	3.74 ± 0.13 ^{Ab}	42.05 ± 1.03 ^{Aa}	45.72 ± 0.96 ^{Aa}	12.24 ± 0.41 ^{Ab}	87.76 ± 0.72 ^{Ba}
	20	57.09 ± 0.50 ^{Aa}	25.42 ± 0.21 ^{Ab}	3.91 ± 0.18 ^{Ac}	4.11 ± 0.12 ^{Ac}	41.18 ± 0.77 ^{Ba}	45.81 ± 1.04 ^{Aa}	13.01 ± 0.38 ^{Ab}	86.90 ± 0.79 ^{Aa}
	30	57.34 ± 0.43 ^{Aa}	22.93 ± 0.18 ^{Aa}	5.57 ± 0.18 ^{Ad}	4.53 ± 0.15 ^{Ad}	42.14 ± 0.82 ^{Ba}	45.36 ± 0.84 ^{Ba}	12.50 ± 0.40 ^{Bb}	87.50 ± 0.64 ^{Ba}
FWB	10	56.68 ± 0.51 ^{Aa}	27.52 ± 0.19 ^{Ac}	2.24 ± 0.15 ^{Ab}	3.70 ± 0.08 ^{Ab}	42.09 ± 0.68 ^{Aa}	44.34 ± 1.23 ^{Aa}	13.57 ± 0.24 ^{Bb}	86.43 ± 0.49 ^{ABa}
	20	56.41 ± 0.43 ^{Aa}	25.46 ± 0.16 ^{Ab}	3.85 ± 0.16 ^{Ac}	4.20 ± 0.15 ^{Ac}	42.86 ± 1.33 ^{Ba}	43.07 ± 1.15 ^{Aa}	14.01 ± 0.41 ^{ABb}	86.38 ± 0.52 ^{Aa}
	30	56.09 ± 0.66 ^{Aa}	23.34 ± 0.22 ^{Aa}	5.52 ± 0.23 ^{Ad}	4.73 ± 0.18 ^{Ad}	42.16 ± 0.86 ^{Ba}	43.61 ± 0.97 ^{ABa}	14.23 ± 0.47 ^{ABb}	85.77 ± 0.66 ^{Ba}
SWB	10	56.17 ± 0.43 ^{Aa}	27.84 ± 0.21 ^{Ac}	2.28 ± 0.17 ^{Ab}	3.73 ± 0.13 ^{Ab}	41.46 ± 0.45 ^{Ab}	43.95 ± 1.35 ^{ABb}	14.58 ± 0.29 ^{Bb}	85.42 ± 0.48 ^{Ab}
	20	56.48 ± 0.49 ^{Aa}	25.45 ± 0.17 ^{Ab}	3.88 ± 0.25 ^{Ac}	4.16 ± 0.07 ^{Ac}	39.64 ± 0.62 ^{Aa}	45.60 ± 0.88 ^{Ab}	14.76 ± 0.35 ^{Bb}	85.24 ± 0.37 ^{Ab}
	30	56.80 ± 0.37 ^{Aa}	23.17 ± 0.13 ^{Aa}	5.53 ± 0.22 ^{Ad}	4.62 ± 0.14 ^{Ad}	39.38 ± 0.65 ^{Aa}	42.25 ± 0.67 ^{Aa}	18.37 ± 0.36 ^{Cc}	81.63 ± 0.51 ^{Aa}

Note: Values of A–C are significantly different with different particle size but same addition, while values of a–d are significantly different with same particle size but different addition ($P < 0.05$). Cmax, maximum digestibility of starch.

T_{22} was the largest across all the samples (91.17%–93.62%, Table S2), indicating that water in SPC was predominantly structured and mobile, contributing to the pseudoplasticity and soft texture of the SPC matrix^[40]. Furthermore, as shown in Fig. 6 and Table S2, the T_{22} and T_{23} values of SPC decreased significantly with bran addition compared with the control group. This suggests that wheat bran, with its high water-retention capacity, could hinder the movement of water in SPC at the microscopic level, thereby delaying aging.

Notably, the T_2 value of SPC decreased with the reduction of bran particle size contrary to the results of the water-retention capacity of bran. As noted earlier, micronized dietary fiber exhibited an excellent filler effect, allowing for better dispersion within the SPC matrix, enhancing starch-water molecule interactions, and reducing water mobility. This result was consistent with observations in anti-staling studies of teok^[41] and bread^[23].

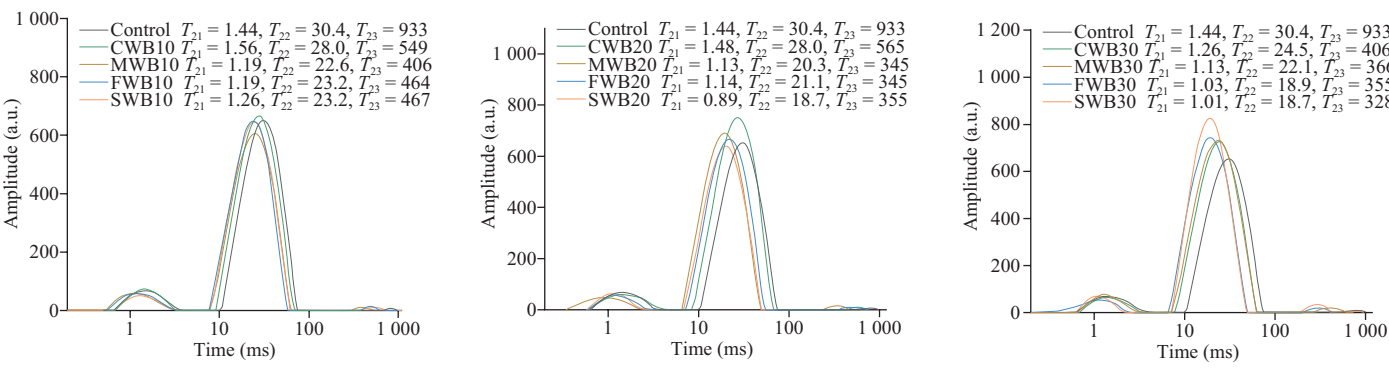


Fig. 6 Microscopic water migration of steamed sponge cake with different particle size wheat bran at 10%, 20% and 30% concentration.

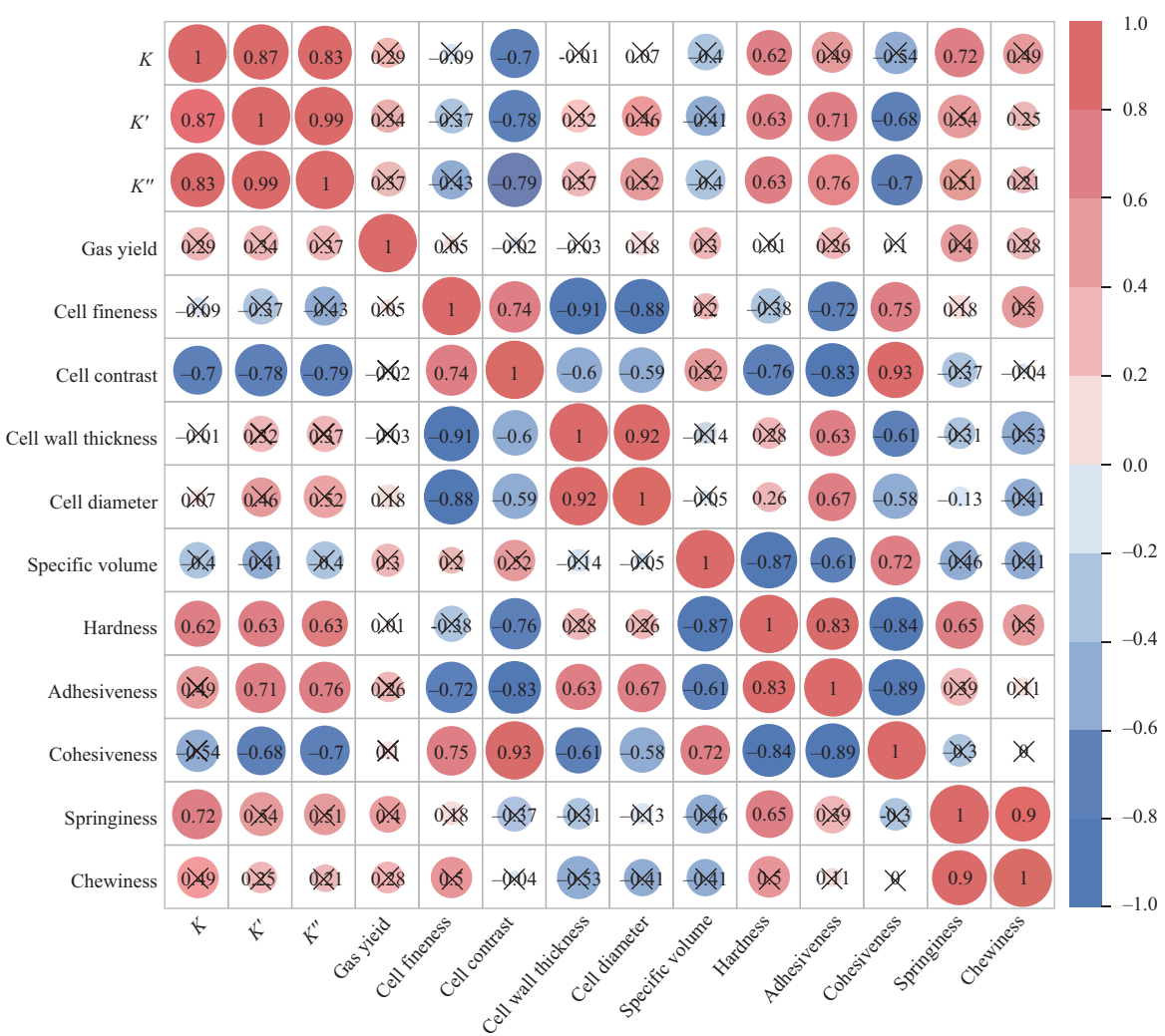


Fig. 7 Correlations between batter rheological properties, gas yield, gas cell structure and texture characteristics of bran-enriched steamed sponge cake. The correlation coefficient with × indicates that the correlation between the 2 indicators is not significant ($P > 0.05$).

4. Conclusion

This study revealed the possibility of replacing wheat flour with micronized wheat bran in developing SPC with satisfactory texture, enriched dietary fiber, and lower starch digestibility. The addition of wheat bran increased the apparent viscosity and dynamic viscoelasticity of batter, enhancing the adhesiveness, elasticity, and chewiness of SPC. Increased addition of coarse bran (84–110 µm) from 10% to 30% reduced the overall acceptability of SPC and compromised the integrity of the gas cell and starch gel structure, hindering starch digestibility reduction. Contrarily, the 30% addition of superfine bran resulted in finer gas cell structure compared with the control group, causing less damage to the starch gel structure and improving the cohesiveness of SPC, thereby further reducing starch digestibility. Thus, this study revealed that SWB is suitable for developing cereal products not requiring gluten development. SPC is an ideal carrier for high levels of superfine bran dietary fiber, ensuring satisfactory quality product and improved nutritional characteristics. Additionally, the high moisture content of SPC needs further research into the anti-staling mechanism of SWB and the evaluation of the health benefits of superfine bran-fortified steamed SPC *in vitro* and *in vivo*.

Declaration of interests

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

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://doi.org/10.26599/FSHW.2024.9250451>.

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