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Predominant factors in milling and wheat variety influencing particle size and quality of whole wheat flour

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Abstract: This study investigated the effects of mill type, milling conditions, and wheat variety on the mean particle size, particle size distribution, and quality characteristics of whole wheat flour (WWFs). Three wheat varieties (Goso [GS], Hojoong [HJ], and Joongmo [JM]), representing varying protein contents, were milled using two types of mills: an ultra-centrifugal mill (UM) and a cutting mill (CM). The milling conditions were adjusted based on the sieve openings (0.5 and 1.0 mm) and rotor speeds (UM: 6000 and 14,000 rpm; CM: 2000 and 4000 rpm). The mean particle size and particle size distribution of the WWFs were significantly influenced by the mill type, milling conditions, and their interactions. UM and CM produced distinct particle size distributions, with CM yielding a broader range and a more pronounced bimodal distribution. Furthermore, the type of mill and milling conditions, along with their interactions, affected the damaged starch content, water and sodium carbonate solvent retention capacity, pasting properties, and antioxidant activity of the WWFs. The wheat variety influenced parameters such as moisture, ash, damaged starch content, sodium dodecyl sulfate sedimentation volume, rapid viscoanalyzer (RVA) pasting properties, total phenolic content, and antioxidant activity. Notably, selecting an appropriate mill type and milling conditions is critical for producing WWFs with high gluten strength from high-protein wheat varieties.

KEYWORDS
cutting mill, mean particle size, particle size distribution, quality characteristic, ultra-centrifugal mill, whole wheat flour

Practical Application: Controlling particle size through milling optimization is essential for producing high-quality whole wheat flour, particularly from wheat varieties with high protein content.

1 | INTRODUCTION

A healthy diet for healthy living has become a global trend. Whole grain foods are experiencing increasing demand because they are rich in dietary fiber and abundant in nutrients such as vitamins, minerals, antioxidants, and phytochemicals. The intake of these nutrients is crucial for maintaining a balanced diet (Jacobs & Steffen, 2003; Jensen et al., 2004; Rosa-Sibakov et al., 2015; Vignola et al., 2016). Furthermore, consuming whole grains can help prevent chronic diseases such as cardiovascular diseases, diabetes, and obesity (Anderson et al., 2000; Ghanbari-Gohari et al., 2022). Fiber in whole grains may also contribute to the diversity of the gut microbiota (Jefferson & Adolphus, 2019).

Wheat is the most common and widely consumed grain and is often used as whole wheat flour (WWF) or wheat bran in various products. However, bran in WWF negatively affects the dough and final products. The addition of wheat bran reduces the gas-holding and water-binding capacities of dough, consequently lowering dough viscosity and negatively affecting loaf volume and texture (Han et al., 2019; Hemdane et al., 2016). Additionally, bread made with bran had a lower volume than control bread made without bran (Campbell et al., 2008).

WWF is generally produced by milling the entire wheat grain or grinding the bran and endosperm separately and then combining them (Doblado-Maldonado et al., 2012). Traditional methods, such as stone milling (SM) and roller milling (RM), are commonly used to produce commercial WWF. SM involves milling grains between large stones using pressure or friction (Kihlberg et al., 2004), whereas RM involves passing grains through smooth or grooved metal rollers at each stage and gradually reducing their size to obtain flour with the desired particle size (Carcea et al., 2020). The particle size (d50) of commercial WWFs varies from 22 to 176 μm, depending on the milling method, country, and wheat type (Moon, Xia, et al., 2021). Additionally, numerous laboratory mills are used to prepare small-scale batches of WWF to study its quality characteristics and applications. Among these, ultra-centrifugal mill (UM) has proven to be a useful tool for producing high-quality whole wheat flour. This mill works by combining a high-speed centrifugal force and rapid rotor movement, resulting in shearing, extrusion, and rubbing actions to grind grains between the high-speed rotating rotor and ring sieves, thereby reducing the particle size (Gu et al., 2021; Khalid et al., 2017). The cutting mill (CM) can also be used to grind grains, primarily through a shearing action between the rotor and the stationary cutter bar. Both mills can operate with the same sieve opening; however, their speed limitations and rated powers differ. The UM can run at much higher speeds (18,000 vs. 4000 rpm) but with less power (760 vs. 1500 W) than the CM. Additionally, it is expected to generate particle sizes similar to WWF, based on the manufacturer's information. However, questions arise regarding the impact of the mean particle size and particle size distribution of WWF produced by different mills on quality characteristics and processing capabilities. Therefore, it is worth investigating the impact of the milling actions of both mills on the quality characteristics of WWF, which affect the product attributes.

In addition to the mill type, milling conditions are crucial for the quality of WWF. In particular, the particle size of WWF is a vital parameter that must be controlled. The particle size distribution of WWF varies based on the type of wheat and milling method, which significantly affects its suitability for cookies, crackers, bread, and noodles (Barak et al., 2014; Vouris et al., 2018). Excessive milling under harsh conditions can increase the amount of damaged starch, which can negatively affect the properties of dough and cookies (Barak et al., 2014). A study on the quality characteristics and bread-making performance of Ariheuk WWF produced using an UM reported that the sieve opening size and rotational speed of the mill significantly affected the gluten strength and damaged starch generation (Avarzed & Kweon, 2023; Avarzed et al., 2022). Therefore, controlling the particle size of WWF is crucial for producing better-quality flour and understanding the resulting changes in flour characteristics. Additionally, optimizing milling through efficient operational parameters enhances economic benefits by increasing yield, controlling particle size, and reducing operational costs for commercial WWF production (Saroja et al., 2024).

Therefore, in this study, we hypothesize that both the type of mill and milling conditions, in interaction with wheat variety, significantly affect the physicochemical properties and quality characteristics and WWF. We investigated how different mill types and conditions influenced the quality characteristics of flour when wheat varieties with different gluten strengths were ground as they were in the mill.

2 | MATERIALS AND METHODS

2.1 | Materials

Three wheat varieties—Goso (GS), Hojoong (HJ), and Joongmo (JM)—with protein contents of 9.9%, 10.9%, and 15.0%, respectively, were provided by the National Institute of Crop Science, Korea. These varieties were developed for specific applications: GS for cookies and cakes, HJ for noodles, and JM for bread. First-grade reagents were used in all the experiments.

2.2 | Milling and particle size analysis of whole wheat flour

An experimental design was used to prepare whole wheat flour under different milling conditions based on three factors: wheat type, mill type, and milling conditions. Each factor had three, two, and two levels, respectively. For the mill type, an UM and a CM were selected because both are convenient laboratory mills capable of using the same sieve size. They can produce similar maximum particle sizes, but may yield different size distributions due to variations in milling actions and rotor speeds. Each of the GS, HJ, and JM wheats was milled using an UM (POWTEQ FM200) equipped with a 12-tooth rotor and sieve openings of 0.5 (S) and 1.0 mm (L). The rotor speeds were set to 6000 (L) and 14,000 rpm (H) to produce four WWFs: UM-SL, UM-SH, UM-LL, and UM-LH. Additionally, a CM (POWTEQ CM100 M Multi-functional CM) was used with sieve sizes of 0.5 (S) and 1.0 mm (L), and rotor speeds set at 2000 (L) and 4000 rpm (H). The four WWFs were named CM-SL, CM-SH, CM-LL, and CM-LH. All WWFs obtained through milling processes were immediately sealed and stored at −20°C. As a key quality indicator of WWFs, particle size distribution was determined using a particle size analyzer (LS 13 320; Beckman Coulter) with a dry method, conducted “as is” without dispersion in solvents.

2.3 | Analysis of physicochemical properties of whole wheat flour

The moisture and ash contents of the WWFs were measured according to AACC methods 44-15.02 (AACCI, 2010) and 08-01.01 (AACCI, 2010), respectively. The damaged starch content of the WWFs was determined using a Starch Damage Assay Kit (K-SDAM; Megazyme International).

2.4 | Analysis of solvent retention capacity in water and sodium carbonate solution

The solvent retention capacity (SRC) of the WWFs was measured according to the AACC method 56-11.02 (AACCI, 2010) using water and sodium carbonate solutions as solvents. Due to the tendency of wheat bran contained in WWF to float in the supernatant without precipitation after centrifugation in lactic acid and sucrose solutions, causing errors in the results of the SRC (Kweon et al., 2011), lactic acid and sucrose SRC were excluded from the experiments.

2.5 | Measurement of gluten strength

To measure the sedimentation volumes of the WWFs in sodium dodecyl sulfate (SDS)–lactic acid solution, the AACC Method 56–70.01 (AACCI, 2010) was employed. Five grams of WWF was placed in a 100-mL graduated cylinder, to which 50 mL of distilled water was added, and then sealed with a stopper. The WWF in the graduated cylinder was shaken vertically and horizontally to hydrate. Next, 50 mL of SDS–lactic acid solution (3%) was added, followed by vertical and horizontal shaking for mixing. After standing vertically for 20, 40, or 60 min, the sediment volume (mL) of the sample was recorded.

2.6 | Analysis of pasting property

The pasting properties of the WWFs were measured using a rapid viscoanalyzer (RVA 4; Newport Scientific). WWF (3.5 g) and distilled water (25 mL) were placed in an RVA canister and mixed well using an RVA plastic paddle to prevent lump formation. The mixture was run in the RVA for 13 min using the Standard 1 method (heating from 50 to 95°C at a rate of 12.2°C/min; holding at 95°C for 2.5 min; cooling from 95 to 50°C at a rate of 12.2°C/min; holding at 50°C for 2 min). The measured pasting parameters were calculated using Thermocline for Windows (ver. 2.5; Newport Scientific).

2.7 | Analysis of total phenolic content and antioxidant activity

The total phenolic content (TPC) and 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity in WWF were analyzed using a modified method from Yu and Beta (2015). Two grams of milled WWF was extracted twice with 10 mL of 80% methanol. The extract was sonicated at 0°C with a frequency of 40 kHz for 15 min. Following sonication, the mixture was centrifuged at 12,000 × g and 4°C for 15 min to collect the supernatant, which was then filtered through 90-mm qualitative filter paper (No. 2; ADVANTEC). The final volume was adjusted to 50 mL with 80% methanol, and the extract was stored at −20°C until further analysis.

For TPC analysis, 0.2 mL of the WWF extract was mixed with 1.5 mL of 10-fold diluted Folin–Ciocalteu reagent and allowed to oxidize for 5 min. Next, 1.5 mL of a sodium carbonate solution (60 g/L) was added, and the mixture was

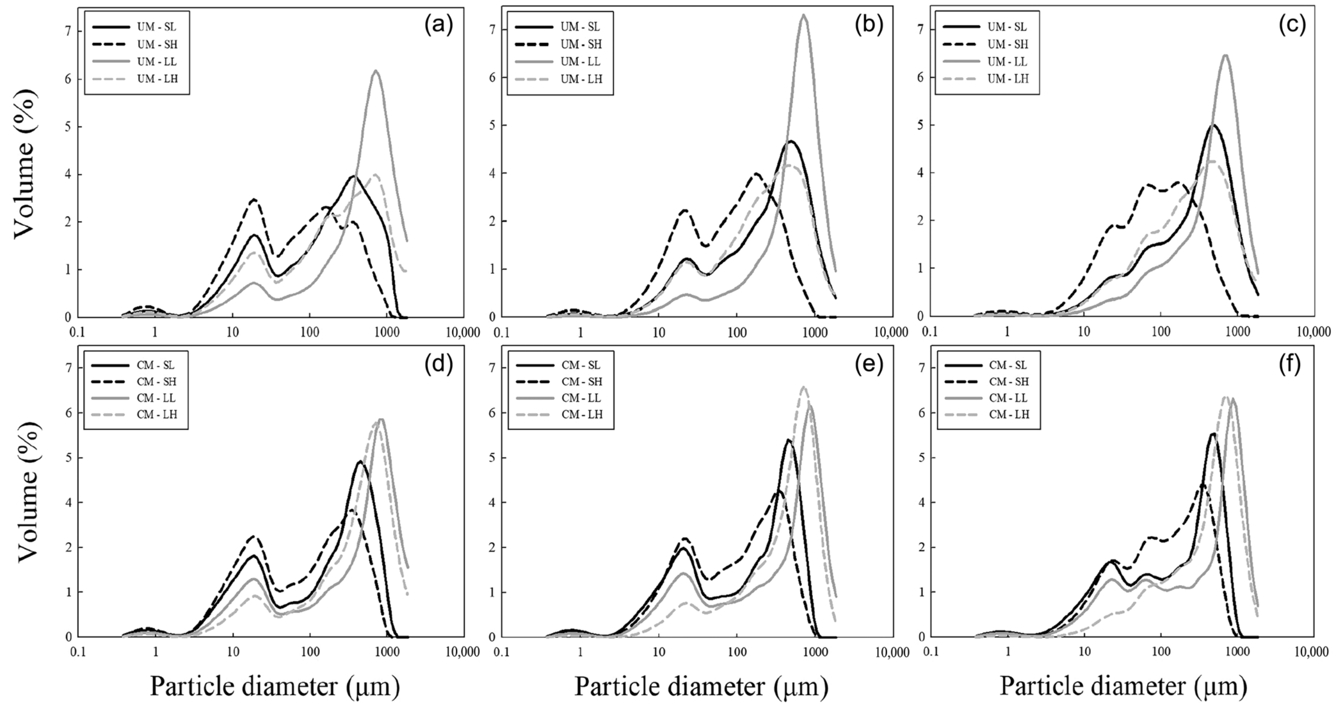

FIGURE 1 Particle size distribution of whole wheat flour samples: (a) and (d) Goso (GS); (b) and (e) Hojoong (HJ); (c) and (f) Joongmo (JM). CM, cutting mill; UM, ultra-centrifugal mill.

neutralized for 90 min. The absorbance was measured at 725 nm using a spectrophotometer (X-ma 6100 PC; Human Corporation). Gallic acid (Sigma) was used as the standard, and TPC was expressed as mg of gallic acid equivalents per 100 g of WWF.

For DPPH radical scavenging activity, a DPPH solution was prepared in methanol at a concentration of 200 μmol/L. A mixture of 2.0 mL of the DPPH solution and 0.5 mL of WWF extract was incubated at room temperature for 30 min. The absorbance was measured at 515 nm. The blank was 80% methanol, and Trolox (Sigma) served as the standard. DPPH radical scavenging activity was expressed as milligrams of Trolox equivalents per 100 g of WWF, based on a standard curve.

2.8 | Statistical analysis

All the data were obtained through a minimum of three repeated measurements. All statistical analyses were performed using the SPSS Statistics (ver. 27.0; IBM), and an analysis of variance (ANOVA) was conducted. Post hoc testing was performed using Tukey's honestly significant difference (HSD) test to determine the significance of differences among samples within each group at the $p < 0.05$ level. The significant factors and their interactions affecting the quality characteristics were analyzed and identified using ANOVA and model significance in the Design Expert program (version 13; Stat-Ease Inc.).

3 | RESULTS AND DISCUSSION

3.1 | Particle size distribution of whole wheat flours

The particle size distribution of the WWFs is presented in Figure 1, with variations in the wheat variety and milling method. The particle size distributions of the WWFs from all varieties were UM-SH < UM-SL < UM-LH < UM-LL, indicating that larger sieve opening sizes and slower rotor speeds resulted in larger particle sizes, which is consistent with the results reported in previous studies (Avarzed & Kweon, 2023; Ha et al., 2023; Park et al., 2022). The particle size distribution of the WWFs exhibited unimodal or bimodal shapes depending on the sieve opening size and rotor speed within a wheat variety. The WWFs prepared using a CM showed a more distinct bimodal shape than those prepared using an UM, indicating the production of higher proportions of small and large particles and a lower proportion of medium particles. Additionally, the range of the particle size distribution for the former (CM) was broader than that for the latter (UM).

The particle sizes of the WWFs according to the milling method are listed in Table 1. For the WWFs prepared using an UM, the d10, d50, and d95 values were in the order UM-SH < UM-SL < UM-LL < UM-LH for GS and UM-SH < UM-LL < UM-SL < UM-LH for HJ and JM. Additionally, similar trends were observed for the cultivars when considering the mean values. For the WWFs

TABLE 1 Average particle sizes of whole wheat flour samples.

Flour	d10 (µm)[a]			d50 (µm)			d90 (µm)		
	GS	HJ	JM	GS	HJ	JM	GS	HJ	JM
UM-SL[b]	12.5 ± 0.2cA	21.8 ± 0.3eB	32.6 ± 1.0eC	183.3 ± 3.6cA	289.6 ± 10.1eB	330.4 ± 7.2eC	757.6 ± 15.3dA	911.5 ± 10.4eB	932.7 ± 5.0eC
UM-SH	8.8 ± 0.1aA	12.8 ± 0.1bB	15.0 ± 0.3bC	70.6 ± 1.0aA	94.4 ± 1.2aC	86.7 ± 2.6aB	440.4 ± 4.1aC	392.9 ± 0.1aB	375.2 ± 1.2aA
UM-LL	31.7 ± 2.8fA	87.6 ± 4.7hC	74.8 ± 2.1hB	570.3 ± 3.2hB	624.7 ± 10.9hC	548.9 ± 6.5hA	1303.6 ± 3.1gC	1243.6 ± 18.8gB	1193.2 ± 3.5gA
UM-LH	15.1 ± 0.0dA	22.7 ± 0.3fB	34.5 ± 0.1fC	245.5 ± 2.2eA	253.5 ± 0.8$^{\text{dB}}$	265.6 ± 0.1dC	1023.2 ± 4.1eC	885.9 ± 5.5dA	926.0 ± 15.4dB
CM-SL	10.4 ± 0.0bA	11.4 ± 0.3aB	13.2 ± 0.1aC	229.7 ± 0.5dC	205.8 ± 12.8cB	185.2 ± 0.5cA	745.8 ± 8.9cC	649.8 ± 6.6cA	661.0 ± 0.5cB
CM-SH	9.3 ± 0.0aA	13.0 ± 0.3cB	15.5 ± 0.2cC	109.6 ± 1.4bA	122.2 ± 4.6bC	113.9 ± 2.3bB	516.4 ± 0.4bC	476.0 ± 1.1bB	464.0 ± 4.0bA
CM-LL	15.3 ± 0.1dA	17.0 ± 0.4$^{\text{dB}}$	19.8 ± 0.1dC	558.9 ± 4.4gC	542.9 ± 44.3gB	481.0 ± 17.4fA	1379.7 ± 5.8hC	1249.0 ± 39.0hA	1265.8 ± 3.9hB
CM-LH	23.3 ± 2.3eA	42.3 ± 0.1gB	54.8 ± 1.2gC	491.6 ± 17.2fA	519.8 ± 6.8fC	506.0 ± 13.8gB	1221.2 ± 24.6fC	1115.0 ± 25.79fA	1123.0 ± 20.7fB

Note: Values (expressed as means ± SD) with different lowercase letters within the same column and those with different uppercase letters within the same row for the same parameter are significantly different ($p < 0.05$) according to Tukey's HSD test.

Abbreviations: GS, Goso; HJ, Hojoong; JM, Joongmo.

[a]d10, d50, and d90 indicate the median particle size diameters of 10%, 50%, and 90% in cumulative distribution.

[b]UM-SL and UM-SH: WWF milled with an ultra-centrifugal mill equipped with a 0.5-mm sieve at rotor speeds of 6000 and 14,000 rpm, respectively; UM-LL and UM-LH: WWF milled with an ultra-centrifugal mill equipped with a 1.0-mm sieve at rotor speeds of 6000 and 14,000 rpm, respectively; CM-SL and CM-SH: WWF milled with a cutting mill equipped with a 0.5-mm sieve at rotor speeds of 2000 and 4000 rpm, respectively; CM-LL and CM-LH: WWF milled with a cutting mill equipped with a 1.0-mm sieve at rotor speeds of 2000 and 4000 rpm, respectively.

prepared using a CM, the d10 values were in the order of CM-SH < CM-SL < CM-LL < CM-LH for GS, but CM-SL < CM-SH < CM-LL < CM-LH for HJ and JM. The d50 and d90 values of the WWFs were in the order CM-SH < CM-SL < CM-LH < CM-LL for GS, HJ, and JM, respectively. The results demonstrated the differences between the two mill types and the complex particle size distribution according to the milling conditions and wheat cultivar. Differences in the milling time and force between the two mill types could be a major factor in the variations in the particle size of the WWFs. Overall, the mill types and conditions, such as the sieve opening size and rotor speed, significantly affected the particle size. Among the wheat varieties, GS WWFs showed smaller average particle sizes for d10 and a mixed trend for d50 but larger average particle sizes for d90, indicating a broader particle size distribution than HJ and JM WWFs. In contrast, the JM WWFs exhibited the opposite trend, with larger average particle sizes for d10, a mixed trend for d50, and smaller average particle sizes for d90, indicating a narrower particle size distribution than the GS and HJ WWFs. Additionally, GS WWFs generated a much larger proportion of smaller particle sizes than JM WWFs, reflecting the impact of the wheat variety on the particle sizes of WWFs. The quality of wheat-based products made with WWFs is influenced by particle size. WWFs with fine or medium-sized particles produce bread with greater volume and a softer crumb (Bressiani et al., 2017; Lin et al., 2020). In noodle production, WWFs with a fine bran fraction result in higher firmness and improved sensory scores (Chen et al., 2011). In contrast, WWFs with coarse particles enhance product quality by yielding cookies with a larger diameter, higher spread ratio, and lower hardness (Xia et al., 2021).

3.2 | Physicochemical property of whole wheat flours

The moisture, ash, and damaged starch contents of the WWFs are listed in Table 2. The moisture contents of UM-SL and UM-SH were lower than those of UM-LL and UM-LH, indicating the impact of the sieve opening size. Additionally, the WWFs prepared using a CM exhibited a similar trend (CM-SL and CM-SH < CM-LL and CM-LH). As the particle size of the flour decreases, the surface area increases, leading to increased interaction with external air and ultimately resulting in high moisture loss (Protonotariou et al., 2015). When comparing the mill types, the CM resulted in WWFs with a lower moisture content for each variety. This difference could be attributed to the varying extent of moisture evaporation in the WWFs owing to heat generation during milling. The initial moisture content of

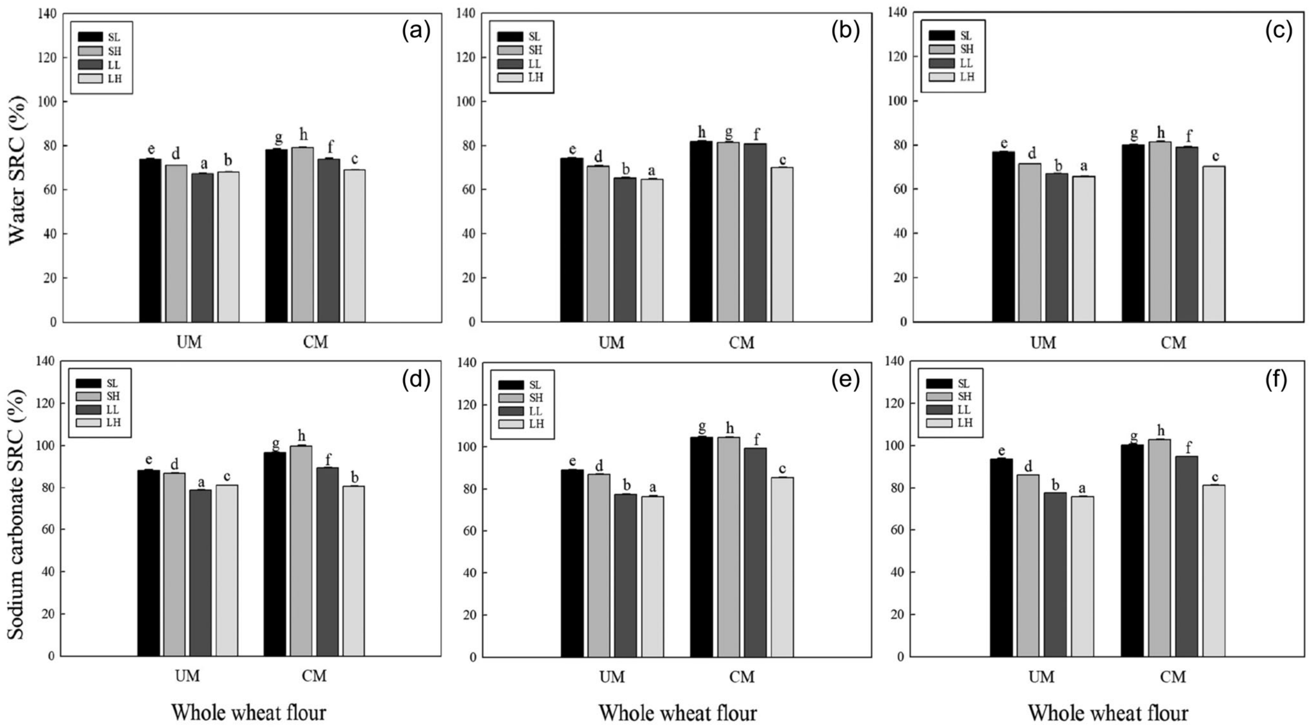

FIGURE 2 Solvent retention capacity in water and sodium carbonate solution of whole wheat flour samples: (a) and (d) Goso (GS); (b) and (e) Hojoong (HJ); (c) and (f) Joongmo (JM). Ultra-centrifugal mill (UM) and cutting mill (CM) refer to ultra-centrifugal milling and cutting milling, respectively. SL, SH, LL, and LH represent different milling conditions based on sieve size and rotor speed: sieve size: 0.5 mm (S) and 1.0 mm (L) for UM and CM; rotor speed: 6000 rpm (L) and 14,000 rpm (H) for UM, and 2000 rpm (L) and 4000 rpm (H) for CM. Data represent the means ± standard deviations ($n = 3$). Different letters above the bars within the same flour are significantly different ($p < 0.05$) according to Tukey's HSD test. SRC, solvent retention capacity.

the wheat kernels before milling and the milling time also affected the moisture content of the WWFs.

The ash content of the WWFs showed significant variations among varieties (HJ < GS < JM) (1.39%–1.63% vs. 1.45%–1.69% vs. 1.69%–1.86%), but no noticeable trend was observed based on the milling conditions, although WWFs milled with an UM exhibited lower ash content than those milled with a CM. The three wheat varieties were grown in the same environment, indicating varietal differences, likely due to the relatively higher bran content of wheat kernels (Shi et al., 2017).

Damaged starch content also exhibited significant variations among varieties (GS < JM ≤ HJ) (1.5%–3.4% vs. 2.1%–6.0% vs. 2.3%–6.4%), mill types (UM < CM) (1.5%–4.4% vs. 1.8%–6.4%), and milling conditions (LL and LH < SL and SH for each mill) (1.5%–5.7% vs. 2.6%–6.4%). Damaged starch can influence water absorption capacity and dough-mixing properties, resulting in sticky dough owing to the higher damaged starch content in the flour (Bettge et al., 1995). This can be explained by the competition for water absorption between damaged starches and other components of flour, such as proteins and arabinoxylans. The increased milling time for preparing WWFs with smaller particle sizes from harder kernels or with slower rotational speeds could be associated with an increased damaged starch content (Barrera et al., 2007). In addition, the mill blade shape and friction force can affect the amount of damaged starch. In our study, damaged starch content showed a significant negative correlation with the particle size d25 of WWFs ($r = -0.494$, $p < 0.05$). As the particle size of WWFs produced by SM decreased (from 180 to 96 μm), the damaged starch content increased (from 29.9% to 32.3%) (Cai et al., 2023). Similarly, Lin et al. (2020) reported an increase in damaged starch content (from 4.68% to 7.22%) as the particle size of WWFs processed using a pulverizing machine decreased (from 1315 to 199 μm).

3.3 | Solvent retention capacity of whole wheat flours

The water and sodium carbonate SRC values of the WWFs are shown in Figure 2. WWFs with smaller particle sizes had higher water and sodium carbonate SRC values, which is consistent with previous findings (Bressiani et al., 2019).

TABLE 2 Moisture, ash, and damaged starch contents of whole wheat flour samples.

Flour	Moisture content (%)			Ash content (%)			Damaged starch content (%)		
	GS	HJ	JM	GS	HJ	JM	GS	HJ	JM
UM-SL[a]	12.3 ± 0.1eB	11.3 ± 0.0cA	12.2 ± 0.1dB	1.55 ± 0.00dB	1.48 ± 0.00cA	1.73 ± 0.00cC	2.9 ± 0.0dA	4.4 ± 0.3eB	4.4 ± 0.0dB
UM-SH	11.8 ± 0.0cA	11.6 ± 0.5dA	11.8 ± 0.1cA	1.45 ± 0.00aA	1.49 ± 0.00cB	1.74 ± 0.00cC	2.6 ± 0.2cA	3.9 ± 0.1dC	3.5 ± 0.0cB
UM-LL	13.0 ± 0.2gA	12.9 ± 0.1fA	12.9 ± 0.1fA	1.50 ± 0.00bB	1.39 ± 0.00aA	1.71 ± 0.00bC	1.5 ± 0.0aA	2.5 ± 0.0bC	2.1 ± 0.0aB
UM-LH	12.8 ± 0.1fB	12.4 ± 0.0eA	12.7 ± 0.1eAB	1.58 ± 0.00eB	1.43 ± 0.00bA	1.71 ± 0.00bC	1.5 ± 0.0aA	2.3 ± 0.0aB	2.0 ± 0.0aB
CM-SL	10.9 ± 0.1aC	10.2 ± 0.2aB	9.8 ± 0.1aA	1.63 ± 0.00fB	1.52 ± 0.00dA	1.83 ± 0.00eC	3.4 ± 0.0fA	6.1 ± 0.1gC	5.7 ± 0.0eB
CM-SH	11.3 ± 0.1bB	11.1 ± 0.1bAB	10.9 ± 0.1bA	1.69 ± 0.00gB	1.53 ± 0.00dA	1.80 ± 0.00dC	3.2 ± 0.0eA	6.4 ± 0.0hC	6.0 ± 0.0fB
CM-LL	12.0 ± 0.0dB	11.2 ± 0.2bcA	10.9 ± 0.2bA	1.59 ± 0.00eA	1.63 ± 0.00eB	1.86 ± 0.00fC	2.9 ± 0.0dA	5.4 ± 0.0fB	5.7 ± 0.0eB
CM-LH	12.7 ± 0.1fB	12.4 ± 0.1eAB	12.3 ± 0.1dA	1.53 ± 0.00cB	1.43 ± 0.00bA	1.69 ± 0.00aC	1.8 ± 0.0bA	3.4 ± 0.0cC	2.8 ± 0.0bB

Note: Values (expressed as means ± SD) with different lowercase letters within the same column and those with different uppercase letters within the same row for the same parameter are significantly different ($p < 0.05$) according to Tukey's HSD test.

Abbreviations: GS, Goso; HJ, Hojoong; JM, Joongmo.

[a]UM-SL and UM-SH: WWF milled with an ultra-centrifugal mill equipped with a 0.5-mm sieve at rotor speeds of 6000 and 14,000 rpm, respectively; UM-LL and UM-LH: WWF milled with an ultra-centrifugal mill equipped with a 1.0-mm sieve at rotor speeds of 6000 and 14,000 rpm, respectively; CM-SL and CM-SH: WWF milled with a cutting mill equipped with a 0.5-mm sieve at rotor speeds of 2000 and 4000 rpm, respectively; CM-LL and CM-LH: WWF milled with a cutting mill equipped with a 1.0-mm sieve at rotor speeds of 2000 and 4000 rpm, respectively.

The SL and SH groups prepared with smaller sieve openings in both UM and CM exhibited relatively higher SRC values than the LL and LH groups prepared with larger sieve openings. Water SRC is an indicator of the water absorption capacity of flour. When comparing UM and CM, WWFs milled with UM showed lower SRC values in water and sodium carbonate solution than the corresponding WWFs milled with CM. Additionally, the WWFs milled with UM showed a clearer distinction in SRC values between groups with small and large particle sizes in both solvents than those milled with CM. The SRC trend of the WWFs mirrored the trend observed for damaged starch content, as shown in Table 2. Damaged starch content and sodium carbonate SRC serve as practical indicators of flour quality, helping to predict the processing performance of wheat-based products and the quality of the final product (Kweon et al., 2011).

In general, WWFs with a high damaged starch content are not preferred for soft wheat-based bakery products, which typically have a low final moisture content. The damaged starch content in soft white winter wheat flour from the Pacific Northwest ranges from 2.76% to 4.77% (Lin & Czuchajowska, 1996). For bread production, a certain amount of damaged starch that contributes sugars to sufficient fermentation of bread dough is desirable. However, excessive damaged starch can hinder gluten formation by competing for water absorption, thereby adversely affecting bread quality. Belderok (2000) reported that a damaged starch content exceeding 9% in refined flour is undesirable, as it leads to sticky dough. Therefore, to meet specific product requirements, the damaged starch content of WWFs needs to be controlled by selecting the appropriate mill type and milling conditions. With respect to the damaged starch content of WWFs, UM, and CM, a large sieve opening size and high rotor speed could be suitable for preparing GS WWFs for cookies and crackers, with UM being potentially more effective. Conversely, UM and CM with small sieve openings can be used to prepare JM WWFs for bread regardless of the rotor speed.

3.4 | SDS sedimentation volume of whole wheat flours

The SDS sedimentation volume of the WWFs, an indicator of flour gluten strength, is shown in Figure 3. Wheat variety, mill type, and milling conditions significantly influenced the SDS sedimentation volume. However, the impact of wheat variety was particularly pronounced. Among the wheat varieties, JM, characterized by high protein content, was significantly influenced by mill type and milling conditions. In contrast, GS and HJ showed no significant effects. WWFs milled with UM showed more

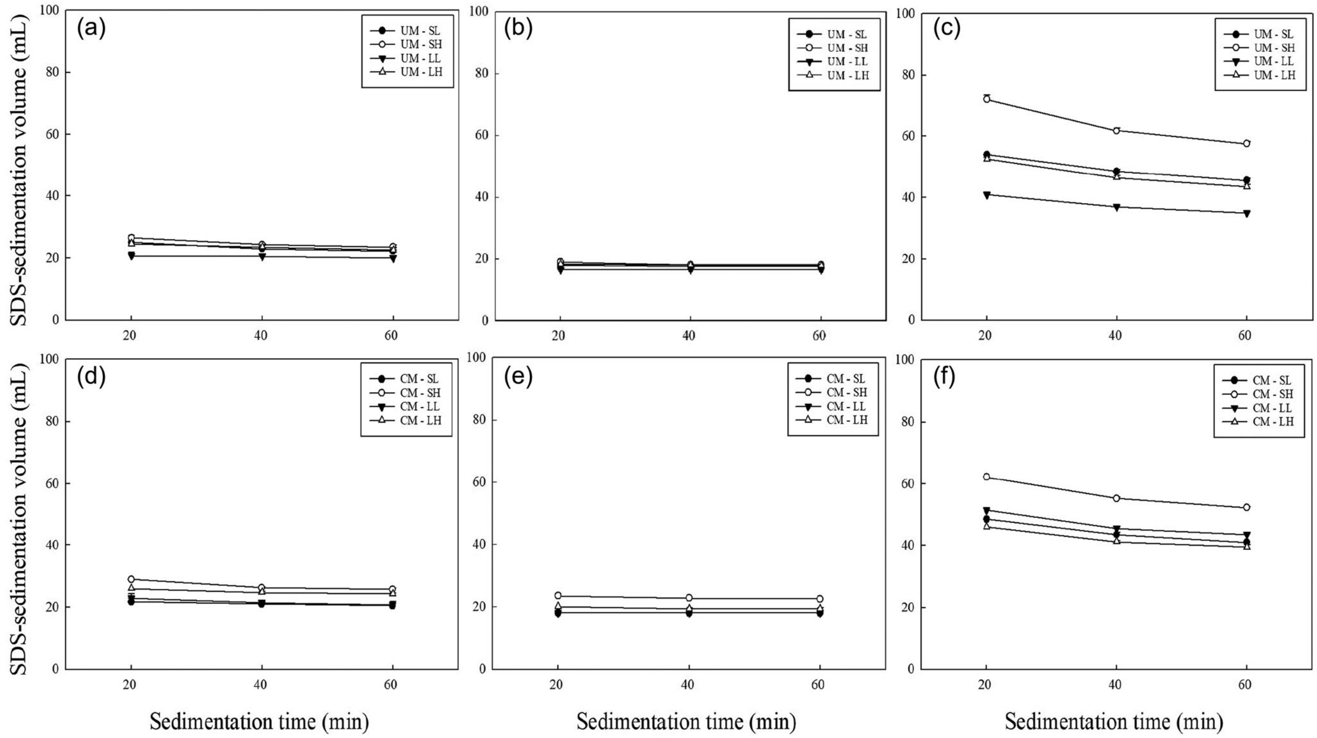

FIGURE 3 Sodium dodecyl sulfate (SDS) sedimentation volume of whole wheat flour samples: (a) and (d) Goso (GS); (b) and (e) Hojoong (HJ); (c) and (f) Joongmo (JM). Data represent the means ± standard deviations (n = 3). CM, cutting mill; UM, ultra-centrifugal mill.

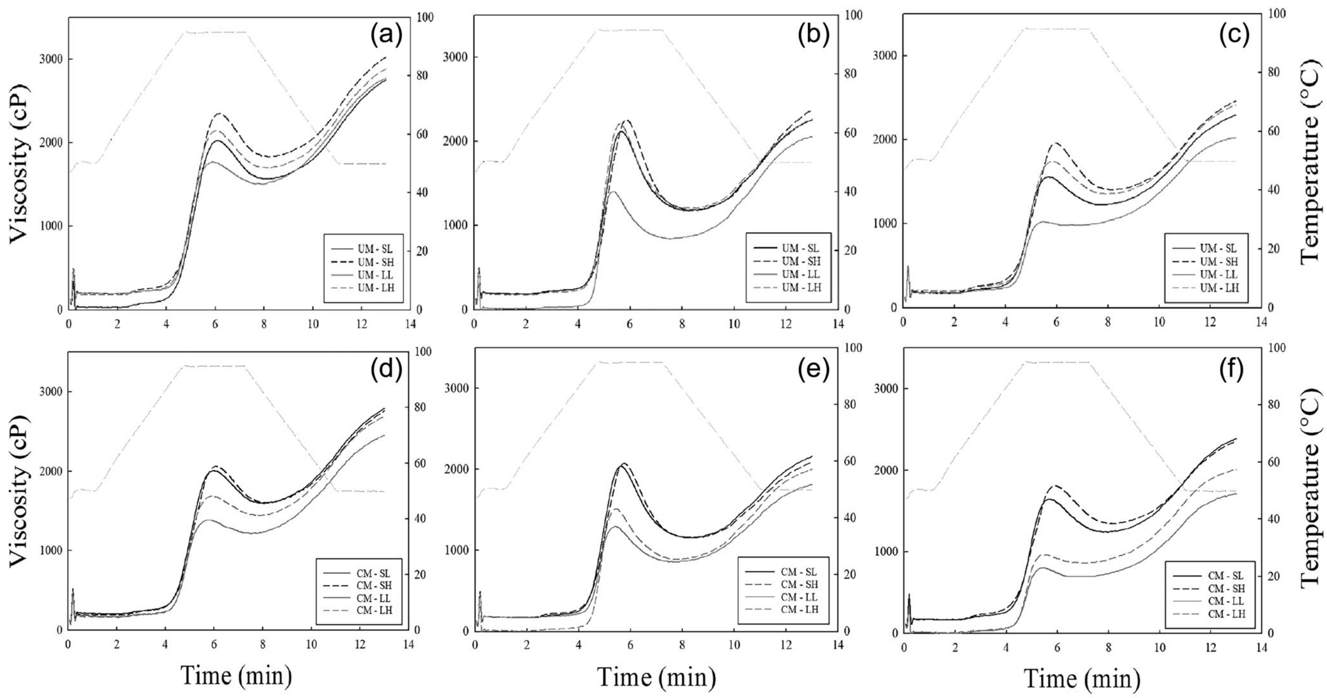

FIGURE 4 Rapid viscoanalyzer (RVA) pasting curves of whole wheat flour samples: (a) and (d) Goso (GS); (b) and (e) Hojoong (HJ); (c) and (f) Joongmo (JM). CM, cutting mill; UM, ultra-centrifugal mill.

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TABLE 3 Pasting characteristics of the whole wheat flour samples.

Flour	Peak viscosity (cP)			Breakdown viscosity (cP)			Final viscosity (cP)			Setback viscosity (cP)			Pasting temp (°C)		
	GS	HJ	JM	GS	HJ	JM	GS	HJ	JM	GS	HJ	JM	GS	HJ	JM
UM-SL[a]	2030 ± 8eB	2102 ± 15fC	1678 ± 24eA	481 ± 2gB	935 ± 4fC	416 ± 44fA	2811 ± 7fC	2152 ± 4eA	2355 ± 18dB	1262 ± 13fC	986 ± 15cA	1093 ± 2fB	88 ± 1bcA	87 ± 1aA	88 ± 1bcA
UM-SH	2349 ± 14hC	2258 ± 11hB	1959 ± 3hA	518 ± 13hA	1073 ± 16hC	558 ± 6hB	3023 ± 21hC	2374 ± 30hA	2462 ± 3hB	1192 ± 20cB	1189 ± 35gB	1061 ± 0dA	85 ± 2aA	89 ± 1bcB	87 ± 1abA
UM-LL	1769 ± 11cC	1403 ± 28bB	1023 ± 4cA	269 ± 25cB	564 ± 19bC	46 ± 4aA	2774 ± 28dC	2052 ± 24cB	2025 ± 6cA	1274 ± 42gC	1213 ± 15hB	1048 ± 6cA	88 ± 1bcA	90 ± 0cB	90 ± 0dAB
UM-LH	2144 ± 1gB	2208 ± 9gC	1744 ± 8fA	444 ± 3eB	1011 ± 2gC	394 ± 17dA	2886 ± 17gC	2266 ± 9gA	2417 ± 29gB	1186 ± 18bB	1069 ± 2eA	1067 ± 37eA	87 ± 0bA	89 ± 0bcA	88 ± 1bcA
CM-SL	2006 ± 8dB	2038 ± 11dC	1646 ± 3dA	411 ± 9dB	882 ± 6dC	406 ± 9eA	2788 ± 16eC	2163 ± 1fA	2387 ± 6fB	1193 ± 16cC	1007 ± 4dA	1147 ± 6hB	88 ± 0bcA	87 ± 0aA	88 ± 1bcA
CM-SH	2062 ± 1fB	2077 ± 15eC	1811 ± 12gA	460 ± 12fA	925 ± 1eC	466 ± 1gB	2759 ± 24cC	2094 ± 7dA	2359 ± 1eB	1157 ± 35aC	942 ± 7aA	1015 ± 9bB	88 ± 1bcA	88 ± 1aA	86 ± 0aA
CM-LL	1388 ± 16aC	1296 ± 6aB	802 ± 4aA	173 ± 6aB	442 ± 14aC	106 ± 4cA	2451 ± 4aC	1807 ± 6aB	1706 ± 25aA	1236 ± 6dC	953 ± 14bA	1011 ± 18aB	88 ± 1bcA	89 ± 1bcA	90 ± 0dA
CM-LH	1696 ± 1bC	1511 ± 4cB	962 ± 4bA	256 ± 5bB	622 ± 10cC	99 ± 6bA	2698 ± 22bB	2002 ± 4bA	2005 ± 1bA	1258 ± 28eC	1113 ± 3fA	1141 ± 3gB	89 ± 0cA	89 ± 1bcA	89 ± 1cdA

Note: Values (expressed as means ± SD) with different lowercase letters within the same column and those with different uppercase letters within the same row for the same parameter are significantly different ($p < 0.05$) according to Tukey's HSD test.

Abbreviations: GS, Goso; HJ, Hojoong; JM, Joongmo.

[a]UM-SL and UM-SH: WWF milled with an ultra-centrifugal mill equipped with a 0.5-mm sieve at rotor speeds of 6000 and 14,000 rpm, respectively; UM-LL and UM-LH: WWF milled with an ultra-centrifugal mill equipped with a 1.0-mm sieve at rotor speeds of 6000 and 14,000 rpm, respectively; CM-SL and CM-SH: WWF milled with a cutting mill equipped with a 0.5-mm sieve at rotor speeds of 2000 and 4000 rpm, respectively; CM-LL and CM-LH: WWF milled with a cutting mill equipped with a 1.0-mm sieve at rotor speeds of 2000 and 4000 rpm, respectively.

significant variations in the SDS sedimentation volume than those milled with CM. Within JM WWFs, UM-SH and CM-SH displayed the highest SDS sedimentation volumes (57.5–72.0 mL vs. 52.3–62.3 mL), suggesting better gluten formation in WWFs with smaller particle sizes. The average SDS sedimentation volume of the WWFs in the SH groups in UM and CM (18.0–72.0 mL and 22.5–62.3 mL) was higher than that of those corresponding varieties in the LL groups in UM and CM (16.5—41.0 mL and 18.0-51.5 mL), indicating stronger gluten strength.

Based on these results, selecting the appropriate mill and milling conditions is critical for producing WWFs with a higher gluten strength. However, the number of wheat varieties used in this study was limited, and the impact should be confirmed in future studies using a larger number of wheat varieties. Previous studies by Hatcher et al. (2002) and Vignola et al. (2018) reported that while milling conditions in various mills, such as cyclonic mill and blade mill, resulted in different particle sizes of WWFs, they did not quantitatively alter the protein content. However, they do induce qualitative changes, as indicated by an increase in SDS sedimentation volume with decreasing WWF particle size (Ha et al., 2023), which is consistent with our findings.

Slopes were derived from the SDS sedimentation volume over time. A larger slope indicates a rapid decrease in volume and weaker gluten stability, whereas a smaller slope reflects a slower decrease and greater stability related to dough mixing (Moon, et al., 2021a). WWFs with smaller particle sizes (UM-SH and CM-SH) showed larger slope values, likely due to their faster swelling and slower sedimentation.

3.5 | Pasting properties of whole wheat flours

The RVA pasting curves of the WWFs are shown in Figure 4, and the 415 calculated pasting parameters are listed in Table 3. Flour pasting is mainly associated with the starch characteristics in WWFs. The three varieties exhibited noticeable differences in their RVA patterns, with JM having the lowest peak viscosity, HJ having the highest breakdown viscosity, and GS having the highest final and setback viscosity, indicating differences in starch characteristics. JM WWFs suppressed the swelling and pasting of starch granules. The higher HJ breakdown viscosities of HJ WWFs indicate greater disruption of the swollen starch granules during heating with continuous agitation (Bressiani et al., 2017). The higher final viscosities of the GS WWFs reflect a greater degree of rearrangement of the disordered starch molecules that gelatinize during heating because of interactions such as hydrogen bonding upon

TABLE 4 Total phenolic content and 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity of the whole wheat flour samples.

Flour	TPC (mg GAE/100 g)			DPPH radical scavenging activity (mg TE/100 g)		
	GS	HJ	JM	GS	HJ	JM
UM-SL[a]	279.5 ± 8.7cA	400.6 ± 7.2bC	325.8 ± 10.8bB	135.1 ± 7.7bcA	143.4 ± 1.3abA	141.4 ± 14.7abcA
UM-SH	273.0 ± 4.5abcA	431.2 ± 5.5cC	335.8 ± 8.8Bb	140.4 ± 4.0cA	152.4 ± 23.9bA	165.8 ± 24.2cA
UM-LL	264.9 ± 6.4abA	374.5 ± 7.0aC	296.0 ± 8.0aB	116.5 ± 21.1abcA	129.9 ± 3.2abA	131.2 ± 2.8abA
UM-LH	281.9 ± 3.0cA	393.0 ± 7.6bC	299.5 ± 6.7aB	130.8 ± 6.9abcA	140.4 ± 4.6abA	141.3 ± 2.7abcA
CM-SL	276.1 ± 3.0abcA	397.0 ± 6.0bC	363.9 ± 6.4cB	133.9 ± 19.8bcA	134.2 ± 6.6abA	133.6 ± 2.5abA
CM-SH	285.7 ± 4.9cA	394.6 ± 5.4bC	358.9 ± 4.7cB	134.8 ± 3.5bcA	143.7 ± 7.5abA	149.8 ± 7.7bcA
CM-LL	276.8 ± 6.6bcA	396.1 ± 7.4bC	359.5 ± 4.8cB	99.9 ± 2.7aA	116.3 ± 9.6aA	115.7 ± 5.3aA
CM-LH	262.4 ± 8.2aA	398.2 ± 10.5bC	370.6 ± 10.0cB	105.7 ± 7.7abA	121.7 ± 6.2aAB	131.6 ± 8.2bAB

Note: Values (expressed as means ± SD) with different lowercase letters within the same column and those with different uppercase letters within the same row for the same parameter are significantly different ($p < 0.05$) according to Tukey's HSD test.

Abbreviations: GS, Goso; HJ, Hojoong; JM, Joongmo; TPC, total polyphenol content.

[a]UM-SL and UM-SH: WWF milled with an ultra-centrifugal mill equipped with a 0.5-mm sieve at rotor speeds of 6000 and 14,000 rpm, respectively; UM-LL and UM-LH: WWF milled with an ultra-centrifugal mill equipped with a 1.0-mm sieve at rotor speeds of 6000 and 14,000 rpm, respectively; CM-SL and CM-SH: WWF milled with a cutting mill equipped with a 0.5-mm sieve at rotor speeds of 2000 and 4000 rpm, respectively; CM-LL and CM-LH: WWF milled with a cutting mill equipped with a 1.0-mm sieve at rotor speeds of 2000 and 4000 rpm, respectively.

cooling (Nishita & Bean, 1979). The higher setback viscosities of GS WWFs are associated with a greater extent of rapid starch retrogradation (Chung et al., 2012). In addition, UM-LL for all varieties showed distinctively lower peak viscosities than the corresponding UM-LH, UM-SL, and UM-SH WWFs. In contrast, CM-LL and CM-LH, for all varieties, have lower peak viscosities than CM-SL and CM-SH, suggesting variations in starch-adhering brans and particle sizes caused by different mill types. Smaller particles can swell due to greater water absorption and paste more easily during heating than larger particles (Bressiani et al., 2017), which affects product quality during processing (Jo et al., 2021). No significant impact of wheat variety, mill type, or milling conditions on the pasting temperature values of WWFs was observed.

3.6 | Total phenolic content and antioxidant of whole wheat flours

The total phenolic content (TPC) and DPPH radical-scavenging activities of the WWFs are presented in Table 4. The TPC values of the WWFs milled using both mill types (UM and CM) varied significantly by wheat variety, increasing in the following order: GS < JM < HJ. However, the wheat varieties had no significant difference in DPPH radical-scavenging activity. Antioxidant activity is influenced not only by polyphenols but also by various compounds such as flavonoids, carotenoids, and ferulic acid (Hatcher & Kruger, 1997), which may explain why the TPC and DPPH results do not always align. Among the wheat varieties, HJ exhibited the highest nutritional benefits based on TPC compared to GS and JM. The mill type significantly influenced the TPC of HJ and JM but did not affect GS. Additionally, DPPH radical-scavenging activity was consistently higher in WWFs milled with UM than those milled with CM. The milling conditions also affected the DPPH radical-scavenging activity, with higher rotational speeds and smaller sieve openings leading to increased activity. WWFs with smaller particle sizes exhibited relatively higher TPC and DPPH radical-scavenging activities, with the effect being more pronounced in HJ and JM WWFs milled with UM. This observation aligns with previous findings that TPC values increase with smaller particle sizes (Zhou et al., 2021), likely because of the greater surface area, enabling enhanced phenolic compound extraction. In contrast, for the WWFs milled with CM, the TPC values showed no significant difference, although the DPPH radical-scavenging activity varied significantly.

3.7 | Significant factors and interactions affecting quality characteristics of whole wheat flours

The significant factors and interactions influencing the quality characteristics of the WWFs are summarized in Table 5. Wheat variety affects moisture and ash content, damaged starch content, SDS sedimentation volume, sodium carbonate SRC, RVA pasting viscosity, TPC, and DPPH radical-scavenging activity. The mill type influenced particle size, moisture and ash content, damaged starch content, water and sodium carbonate SRC, RVA pasting viscosities, TPC, and DPPH radical-scavenging activity. Milling conditions affect particle size, moisture content,

TABLE 5 Analysis of variance mean squares by linear model procedure for quality responses of whole wheat flour samples with various milling conditions.

Source	DF	D10	D50	D90	Moisture	Ash	DS	WSRC	SCSRC	SDS-20
WV	2	629.0*	1230.6	8658.1	0.5**	0.2***	7.7***	3.8	15.4*	2749.1***
MT	1	693.4	10,546.2*	9636.0	6.0***	0.0*	15.4***	325.1***	833.8***	0.0
MC	3	1061.9*	228,028.5***	766,394.7***	2.6***	0.0	6.0***	105.4***	315.2***	118.1*
WV x MT	2	92.6	2348.5	3000.0	0.3*	0.0	1.2**	11.7*	31.9**	12.1
WV x MC	6	92.6	1048.7	3297.0	0.1	0.0	0.2	1.4	4.8	37.7
MT x MC	3	1091.9*	31,753.5***	39,673.8**	0.8**	0.0	1.0**	20.0**	46.9**	16.4
Source	**DF**	**SDS-40**	**SDS-60**	**Peak viscosity**	**Breakdown viscosity**	**Final viscosity**	**Setback viscosity**	**Pasting temperature**	**TPC**	**DPPH**
WV	2	1930.9***	1602.8***	532,670.5***	579,670.3***	1,011,348.2***	63,473.8**	1.6	30,325.8***	435.2**
MT	1	0.2	1.5	473,766.0***	88,938.4***	235,620.2***	9087.0	0.4	1412.2*	907.7***
MC	3	75.3*	64.9*	725,882.3***	181,765.3***	160,567.4***	2223.3	4.7*	383.4	943.1***
WV x MT	2	8.5	5.6	585.1	4921.9	20.7	8099.5	1.6	1701.4*	0.1
WV x MC	6	26.9	21.6	16,724.5	6393.0	11,782.6	3952.0	1.5	37.5	35.3
MT x MC	3	9.4	8.0	98,181.7**	19,900.6*	29,919.6*	11,190.2	0.5	285.0	41.5

Abbreviations: MC, milling conditions; MT, mill type; SDS, sodium dodecyl sulfate; WV, wheat variety; WSRC, water solvent retention capacity; SCSRC, sodium carbonate solvent retention capacity.

***, **, * indicate significance at $p < 0.001$, $p < 0.01$, $p < 0.05$, respectively.

damaged starch content, water and sodium carbonate SRC, RVA pasting viscosity, and DPPH radical-scavenging activity. Among these interactions, the wheat variety and mill type affected the moisture content, damaged starch content, water and sodium carbonate SRC, and TPC. Additionally, the type of mill and milling conditions influence the particle size, moisture content, damaged starch content, water and sodium carbonate SRC, and RVA pasting viscosities.

4 | CONCLUSION

This study highlights the significant impact of the mill type, conditions, and wheat variety on the mean particle size and distribution, physicochemical properties, SDS sedimentation volume, pasting characteristics, TPC, and antioxidant activity of WWFs. UM and CM produced distinct particle size distributions, with CM producing a broader range and more pronounced bimodal distribution. The type of mill also influenced the moisture, ash, and damaged starch contents, which in turn affected water absorption and dough properties. The SRC and SDS sedimentation volume further emphasize the role of particle size in determining flour quality, with smaller particles leading to higher water absorption and stronger gluten formation. The pasting properties revealed varietal differences, with GS demonstrating higher viscosities and JM showing lower peak viscosities.

Based on the quality results of WWFs, UM and CM with large sieve openings and high rotor speeds (e.g., LH) are suitable for preparing cookies and crackers due to their lower damaged starch. In contrast, those with small sieve openings and high rotor speed (e.g., SH) are better suited for bread as well as noodles due to their higher gluten strength. Additionally, further tests should be conducted to evaluate the processability of WWFs in bread, cookies, and noodles, which were not addressed in this study, considering variations in particle size and damaged starch content due to wheat variety, mill type, and milling conditions.

In summary, the particle size and water/sodium carbonate SRC were significantly influenced by the mill type and conditions. Moisture and damaged starch content, RVA pasting viscosities, and DPPH radical-scavenging activity were primarily influenced by the wheat variety, mill type, and milling conditions. However, the SDS sedimentation volume and TPC were more strongly influenced by the wheat variety than by the mill type or milling conditions. Selecting suitable mill types, conditions, and wheat varieties is essential for optimizing the properties of WWFs with higher gluten strength from high-protein wheat varieties for specific applications such as breads or noodles. Future studies should explore a broader range of wheat varieties to validate these findings, which are more relevant to milling and baking industries.

AUTHOR CONTRIBUTIONS

Hyeonsu Han: Methodology; formal analysis; data curation; validation; writing–original draft. **Eunji Lee**: Methodology; data curation; formal analysis; writing–original draft. **Meera Kweon**: Conceptualization; supervision; funding acquisition; visualization; writing–review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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