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Research Article

Effects of Milling Methods and Cultivars on Physicochemical Properties of Whole-Wheat Flour

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The aim of the present study was to investigate the influence of milling methods (jet mill (JM) and hammer mill (HM)) and wheat cultivars (Keumkang (K), Jokyung (J), and Anzunbaengi (A)) on physicochemical and dough properties of whole-wheat flour (WWF). The color, particle size, starch damage (SD), falling number (FN), water absorption index (WAI), water solubility index (WSI), pasting and Mixolab® properties, and dough extensibility of WWF were measured. Significant differences were observed in proximate compositions as well as in color, particle size, FN, and WAI between the distinct milling methods and cultivars ($p < 0.001$). The particle sizes of each cultivar milled with a HM (K: 188.5 μm; J: 115.7 μm; A: 40.34 μm) were larger than those milled with a JM (K: 41.8 μm; J: 50.7 μm; A: 20.8 μm). The final viscosity of WWF milled with a HM (K: 1304 cP; J: 1249 cP; A: 1548 cP) was higher than that of cultivars milled with a JM (K: 1092 cP; J: 1062 cP; A: 994 cP). Dough extensibility and resistance to extension also differed among the cultivars, and the C2 Mixolab® parameter (an indicator of protein weakening) was influenced by the milling method. Overall, results from principal component analysis showed that, among the three cultivars, Keumkang WWF was the most affected by the milling method.

1. Introduction

Wheat (*Triticum aestivum* L.) is one of the most important major crops in the world and is generally utilized in the form of flour to make products such as noodles, chapati, dumplings, pasta, bread, and cookies. Over the past two centuries, refined wheat flour has been more preferred by consumers than whole-wheat flour (WWF) because of its texture, taste, and the appearance of its end products. However, recently, the food industry and consumer market have gained greater interest in whole-wheat products because of their health-promoting components, including fiber, antioxidants, vitamins, and phytochemicals [1]. In addition, numerous studies have shown that WWFs or whole-wheat products contribute to the prevention of chronic diseases such as cardiovascular disease, diabetes, and obesity [2, 3]. A WWF is defined as the flour prepared from wheat (other than durum) that contains the same proportions of bran, germ, and endosperm as found in nature [4]. As the proportions of the intact grains should not be altered, milling methods may be important for the quality of WWF.

Despite the growing demand for WWF, appropriate milling techniques for producing WWF have not yet been well established [5]. Certain difficulties are present in determining quality standards for WWF because the ideal quality of WWF may differ depending on the purpose of use and desired physicochemical properties, which may be modified by the milling method. Kent [6] reported that the traditional milling techniques used for WWF production were stone milling, roller milling, ultrafine milling, and hammer milling. Among traditional milling techniques, hammer milling (HM) is an uncomplicated general-purpose method that consumes little energy and effectively produces WWF [7]. Additionally, this technique does not generate enough heat to denature proteins or reduce the unsaturated

fatty acid content during grinding [8]. During the grinding process, the size of grains decreases, and the bran, germ, and endosperm are damaged. As a result, the starch is also damaged, and the spaces between the particles are modified. These changes can influence the quality of WWF, including its water absorption capacity and the rheological properties of dough [9–13]. In case of WWF, a smaller particle (<125 μm) size has been associated with better dough mixing properties compared to WWF with a larger particle size (>125 μm) [14] because finer bran particles might have less destructive effect on the gluten network in dough [15]. Jet milling is a suitable method for superfine grinding down to few microns [16]. Furthermore, JM was reported by Chamayou and Dodds [17] as an alternative process for reducing the particle size of WWF. In case of jet milling, the particles in high velocity air pressure accelerate the small particle size, that is, the result of colliding the inner particles or impacting between the solid surfaces [18]. The small particle size has the high surface-to-volume ratio, in food application, which indicates easy to access the enzymes and water. Protonotariou et al. [19] reported that JM had a significant effect on the water-holding capacity, starch damage, and color of wheat flour compared to standard milling. Furthermore, JM combined with air classification is available to separate starch from protein matrix (Graveland and Henderson, 1991) [20].

Several quality aspects of WWFs are modified by the milling method. Additionally, the wheat cultivar is known to affect the characteristics of the resulting flour [8, 21]. Jones [22] reported that, during milling processes, starch damage occurs as a result of surface abrasion but it also depends on the hardness of wheat grains, which determines the forces between particles. The protein content of flour also differs depending on the type of wheat (hard, medium, or soft), which is related to the differences in gluten network formation and dough properties. These different aspects of wheat cultivars would also be influenced by the milling method. However, no information is available on the effects of JM, which is a relatively new milling method [20], in comparison to HM, which is regarded as the standard milling method, on the properties of WWF prepared from different types of wheat (hard, medium, and soft). Thus, the purpose of the present study was to investigate the effects of two milling methods (JM and HM) and different wheat cultivars on the properties of WWF.

2. Materials and Methods

2.1. Materials. The three wheat samples analyzed in this study were harvested in 2016. The cultivars and harvesting locations were as follows: Keumkang (Yeonggwang, Korea; geographic coordinates: 35°16′N, 126°30′E), Jokyung (Hapcheon, Korea; geographic coordinates: 35°33′N, 128°9′E), and Anzunbaengi (Jinju, Korea; geographic coordinates: 35°10′N, 128°6′E). Keumkang is a typical medium wheat, while Jokyung and Anzunbaengi are classified as hard and soft wheats, respectively, in Korea. Three wheat cultivars were grinded into WWF using HM (Korea Pulverizing Machinery Co., Ltd., Korea) and JM (Korea Pulverizing Machinery Co., Ltd., Korea). The WWFs were then packaged in a vacuum-sealed bag and stored at 0°C until a day prior to use.

2.2. Proximate Composition and Wet Gluten Content of WWFs. The moisture, protein, ash, and total dietary fiber (TDF) contents of WWF samples were measured by the following AACC methods: 44-15.02, 46-13.01, 08-01.01, and 32-05.01 [4], respectively. The free, bound, and total lipid content of WWF samples were analyzed according to the report by Ruibal-Mendieta et al. [23]. The wet gluten content of WWFs was determined using the Glutomatic® system (Glutomatic 2200, Perten Instruments, Hagersten, Sweden) according to AACC method 38-12.02 [4]. The carbohydrate content was calculated by difference as described in Schmiele et al. [24].

2.3. Particle Size, Starch Damage, Falling Number, and α-Amylase Activity of WWFs. Median particle size (d50) of the WWF samples was measured using a laser diffraction particle size analyzer (LS 13 320, Beckman Coulter, Inc., Fullerton, CA, United States). The damaged starch content of WWFs was determined using a starch-damage assay kit (Megazyme Int., Wicklow, Ireland) according to AACC method 76-31. The falling number of WWFs was analyzed according to AACC method 56-81.03 [4] using falling number 1500 (Perten Instruments, Stockholm, Sweden). The α-amylase activity of WWF was determined using an α-amylase assay kit (Ceralpha method—Megazyme Int., Wicklow, Ireland) according to AACC method 22-02.01.

2.4. Color Characteristics, Water Solubility Index (WSI), and Water Absorption Index (WAI) of WWFs. The color characteristics of WWFs were determined using a colorimeter (CM-700d; Konica Minolta Inc., Tokyo, Japan). Black and white calibration references were used to standardize the instrument before analysis. Specifically, L (lightness), a (greenness to redness), and b (yellowness to blueness) values were measured. The water absorption index (WAI) and water solubility index (WSI) of WWF samples were calculated according to Anderson et al. [25].

2.5. Dough Properties of WWFs Based on Mixolab® Analysis. Dough mixing and pasting property of WWFs was investigated using a Mixolab® (Chopin, Paris, France) according to the ICC Standard Method 173 [26]. First, 50 g of WWF was placed into the Mixolab® bowl, and water was added until reaching a torque value of 1.1 ± 0.05 Nm. Then, the dough was formed and heated for 15 min under increasing temperature at a rate of 4°C/min until 90°C was reached and held for 7 min. After heating, the dough was cooled to 50°C at a rate of 4°C/min before being mixed at 50°C for 5 min. The Mixolab® parameters measured in this study are as follows: water absorption (Wabs, %), dough development time (DDT, min), and mixing stability (min). In addition, the C1, C2, C3, C4, and C5 parameters were also determined. C1 (Nm) is the force required to reach 1.1 Nm;

it is the initial maximum consistency during mixing and is reflective of the water absorption capacity. C2 (Nm) is the minimum torque value produced by dough passage through mechanical and thermal constraints, indicating protein weakening. C3 (Nm) is the maximum torque produced during the heating stage, representing pasting properties. C4 (Nm) is the minimum torque after the heating period, and C5 is the torque obtained after cooling (50°C). The difference between C3 and C4 represents the percent breakdown or cooking stability, and the difference between C4 and C5 indicates the retrogradation tendency [27].

2.6. Pasting Properties of WWFs. The pasting properties of WWFs were measured using a Rapid Visco Analyzer (RVA) (Super 4, Newport Scientific Inc., Sydney, Australia) according to AACC method 76-21 [4]. The WWF samples (3 g based on 14% moisture content) and distilled water (25 ml) were mixed to form a slurry, which was then homogenized using a plastic paddle to remove any lump formations. The flour slurries were held at 50°C for 1 min, heated to 95°C at a rate of 12.16°C/min, held at 95°C for 2.5 min, cooled to 50°C at a rate of 12.16°C/min, and finally held at 50°C for 2 min. The measured RVA parameters were peak viscosity (maximum hot-paste viscosity), trough viscosity (holding strength at the minimum hot-paste viscosity), and final viscosity (viscosity at the end of the test after cooling to 50°C and holding at this temperature). Breakdown was calculated by the difference between peak viscosity and holding strength, and setback was defined as the difference between final viscosity and holding strength.

2.7. Resistance to Extension and Extensibility of WWFs. Dough resistance and extensibility were measured using a texture analyzer (TA-HD plus, Stable Micro System Ltd., Haslemere, England) according to Barros et al. [28], which uses Kieffer dough and gluten extensibility. The WWF samples (200 g) and 2% NaCl solution were mixed to form a dough using a Kitchenaid K5SS stand mixer (Kitchenaid, Benton Harbor, MI, USA). 2% NaCl solution was added according to the water absorption (%) of Mixolab® parameters within 45 s and were then mixed for 3 min for paddle and 2 min for hook. After making the dough, the rapped dough was incubated for 30 min at 30°C under 70% relative humidity. Strips (8 × 50 × 5 mm) were prepared from the dough and were placed on a flat metal plate. Every 8 strips from each WWF dough were analyzed, and the average data were used. The resistance (N) and extensibility (mm) were measured using a probe (Kieffer dough & gluten extensibility rig, Haslemere, England) in the tension mode at a pre-test speed of 2.0 mm/s, test speed of 3.3 mm/s, post-test speed of 10.0 mm/s, and distance of 100 mm.

2.8. Statistical Analysis. Three replications of the experiments were performed, and all resulting data are presented as the mean ± standard deviation. First, analyses of variance (ANOVA) were carried out in XLSTAT (2016, Addinsoft, Paris, France) to determine differences in each tested variable among six samples (three cultivars × two milling methods). When significant differences were found, the Student–Newman–Keuls (SNK) multiple comparison test was performed to separate the means at $p < 0.05$ Two-way analysis of variance (ANOVA) was done to investigate the effect of cultivars, milling methods, and interactions between cultivars and the milling method. Additionally, a principal component analysis (PCA) was conducted to summarize the data on proximate composition, physicochemical characteristics, and dough properties of the WWF samples.

3. Results and Discussion

3.1. Proximate Composition and Wet Gluten Content of WWFs. The proximate compositions and wet gluten content of WWFs milled by JM and HM are presented in Table 1. Overall, as shown in Supplementary Table 1, the milling method and cultivar significantly affected the proximate compositions and wet gluten content of the WWFs. The moisture content ($p < 0.001$) significantly differed among samples, ranging from 8.94 to 11.46%. The wheat cultivars milled by HM had a higher moisture content than those milled by JM. This implied that the large surface of particles produced by colliding the inner particles of JM process caused the evaporation of moisture. Furthermore, Liu et al. [21] reported that the grinding strength of the mill used during flour production affected the moisture content of flour.

The Keumkang and Jokyung cultivars used in this study were cultivars developed in Korea for noodles and bread, respectively [29], and Anzunbaengi was reported to be the suitable cultivar for cookies [30]. The wet gluten contents of Jokyung milled by both JM and HM were the highest among the samples, confirming the properties of this cultivar developed for bread. The protein content might be a critical factor for the end functionality of wheat flour [31], and especially, it has a correlation with wet gluten, which is the principle factor of dough's rheological properties. In the present study, the protein content (%) of WWFs was in the range of 9.73–10.71%. Each cultivar milled with HM had more protein content than that of milled with JM. This is consistent with the report by Liu et al. [21] who reported that WWF milled with HM had more protein content than that of milled with ultrafine mill. Furthermore, wet gluten (%) and protein content of WWF samples had significant positive correlation ($r = 0.623$, $p < 0.01$). The carbohydrate content (%) of samples was in the range of 69.48–76.48%. Consistent with the tendency of protein content, carbohydrate content was higher in the HM group than that in the JM group. Considering limited information on carbohydrate and protein content by milling methods, further research is needed to investigate the reason for this result. On the other hand, total lipid of each cultivar was higher in the JM group than that in HM group. The subaleurone, adjacent to the aleurone cells and part of endosperm [31] is the portion where oil body is concentrated [32]. Since the aleurone layer is considered as part of the bran when wheat is milled [31], total lipid content might be caused by the bran fractions in WWF. Not only total lipid but also total dietary fiber is

Table 1: Proximate compositions and wet gluten of WWFs milled with jet mill and hammer mill.

	Proximate compositions								
	Moisture (%)***	Protein[1] (%)***	Free lipid[1] (%)***	Bound lipid[1] (%)***	Total lipid[1] (%)***	Ash[1] (%)***	Total dietary fiber[1] (%)***	Carbohydrate[1,2] (%)***	Wet gluten[1] (%)***
Jet mill									
Keumkang	9.45 ± 0.07^{d}	9.73 ± 0.11^{d}	2.60 ± 0.06^{b}	0.52 ± 0.06^{cd}	3.12 ± 0.01^{b}	1.61 ± 0.02^{a}	12.97 ± 0.17^{b}	72.57 ± 0.11^{d}	13.36 ± 0.90^{b}
Jokyung	8.94 ± 0.09^{e}	10.31 ± 0.15^{b}	2.67 ± 0.04^{b}	0.55 ± 0.02^{cd}	3.22 ± 0.02^{b}	1.66 ± 0.04^{a}	12.60 ± 0.22^{b}	72.20 ± 0.30^{e}	15.87 ± 0.30^{a}
Anzunbaengi	9.70 ± 0.03^{c}	9.80 ± 0.06^{d}	2.93 ± 0.01^{a}	1.10 ± 0.03^{a}	4.03 ± 0.02^{a}	1.67 ± 0.03^{a}	15.03 ± 0.09^{a}	69.48 ± 0.08f	11.30 ± 1.51^{c}
Hammer mill									
Keumkang	11.46 ± 0.02^{a}	10.71 ± 0.05^{a}	1.82 ± 0.11^{d}	0.58 ± 0.00^{c}	2.40 ± 0.11^{d}	1.63 ± 0.03^{a}	11.10 ± 0.06^{c}	74.17 ± 0.08^{b}	14.15 ± 0.24^{b}
Jokyung	9.69 ± 0.10^{c}	10.57 ± 0.13^{a}	2.10 ± 0.00^{c}	0.45 ± 0.10^{d}	2.55 ± 0.09^{c}	1.60 ± 0.02^{a}	8.81 ± 0.26^{d}	76.48 ± 0.04^{a}	16.47 ± 1.09^{a}
Anzunbaengi	10.87 ± 0.12^{b}	10.11 ± 0.04^{c}	1.79 ± 0.09^{d}	0.74 ± 0.05^{b}	2.52 ± 0.04^{c}	1.44 ± 0.02^{b}	12.90 ± 0.17^{b}	73.03 ± 0.19^{c}	13.89 ± 1.03^{b}

All values are means of three replications ± standard deviations. Values with the same alphabet within a column are not significantly different. ***Significantly different at $p < 0.001$. [1]Proximate compositions except moisture and wet gluten were calculated on the basis of dry contents. [2]Calculated by difference.

caused by the bran fraction in WWF, and there is a significant positive correlation between total lipid and total dietary fiber ($r = 0.757$, $p < 0.001$). Free and bound lipid contents of samples were in the range of 1.79–2.93% and 0.45–1.10%, respectively. Free lipid of each cultivar was significantly higher in the JM group than in the HM group. For bound lipid, only Anzunbaengi was significantly affected by the milling method, which was higher in WWFs by JM than in those by HM, similar to results of free lipid content. The results of this study confirmed the report by Prabhasankar and Rao [33], who reported a similar trend between free and bound lipid to that of Anzunbaengi sample in this study when the free and bound lipid in mill streams were compared. However, no difference was found in Keumkang and Jokyung samples in bound lipid by milling methods.

The milling methods and cultivars also significantly affected the ash content ($p < 0.001$) of the WWFs, which was in the range of 1.44–1.67%. Ash is concentrated in the bran layer, and its concentration increases from the center toward the husk of wheat. Thus, ash content is usually considered reflective of the extent to which wheat is milled during the milling process and may be indicative of the degree of refinement of white flour or, sometimes, the quality of flour [34]. In case of the WWFs, ash content represents the portion of aleurone remaining in the bran layer after grinding [31]. As shown in Table 1, the ash contents of Anzunbaengi was affected by the milling method, while that of Jokyung and Keumkang were not affected by the milling method. Previously, Inamdar et al. [35] reported that the ash content of WWF did not significantly differ depending on the milling method. The high level of ash content in Anzunbaengi [30] might be related to different ash contents by milling methods in this study. However, further research is needed to identify the reason for this result.

Total dietary fiber, which is the main component of bran, was in the range of 8.81–15.03%. Among the three cultivars, Anzunbaengi contained the highest total dietary fiber, while Jokyung had the lowest fiber content regardless of the milling method. With respect to the milling method, each cultivar had a higher total dietary fiber content when milled by JM rather than HM. The wet gluten content of WWFs used in this study ranged from 11.30 to 16.47%. Wet gluten is often used to predict the ability of a gluten matrix to form during baking [36]. The wet gluten content of Jokyung (JM: 15.87%; HM: 16.47%) and Keumkang (JM: 13.36%; HM: 14.15%) did not differ per milling method. Anzunbaengi contained the lowest wet gluten content among the three cultivars (Table 1), indicating its suitability for cookies, cakes, or other baking products. As Khan [31] reported, a lower wet gluten content in flour contributes to a better cookie spread and crumb texture in cakes. Thus, the use of Anzunbaengi WWF milled by JM would provide the best texture in products such as cakes or cookies compared to HM.

3.2. Particle Size, Starch Damage, Falling Number, α-Amylase, Color Characteristics, WAI, and WSI of WWFs. The median particle size, starch damage, falling number, α-amylase (CU)/g, and color characteristics of WWFs milled by JM and HM are shown in Table 2. The median particle size significantly differed among samples ($p < 0.001$), ranging from 20.79 to 188.47 μm. As shown in Table 2 and Supplementary Table 1, the median particle size of WWFs milled by JM was significantly ($p < 0.001$) smaller than that of WWFs milled by HM. Also, the particle size of samples was negatively correlated with the WAI ($r = -0.712$, $p < 0.01$), confirming the finding of Protonotariou et al. [37] that WWF with a smaller particle size had a higher water holding capacity. Since whole-wheat noodle produced by superfine grinding (<125 μm) improved the structure characteristics [38], Keumkang milled by JM (versus HM) might be better for making whole-wheat noodles. Meanwhile, Bressiani et al. [39] suggested that WWF with a fine particle size (<90 μm) did not produce the best specific volume or firmness in bread. Therefore, it can be inferred that Jokyung WWF milled by HM would be of better quality for making bread than that milled by JM.

As shown in Table 2, significant differences were also found in the starch damage ($p < 0.001$) and falling number ($p < 0.001$). The starch damage of the WWFs ranged from 2.15 to 4.71%. Notably, the starch damage of Keumkang and Anzunbaengi was not affected by the milling method. Among the cultivars, the starch damage exhibited a decreasing tendency in the following order: Jokyung, Keumkang, and Aneunbangi. This implies that harder wheat kernels produce more starch damage during milling. These results are in agreement with the report of Kundu et al. [40], who found that the damaged starch content was related to the hardness of wheat kernels. Also, the falling number (FN) of the WWFs was in the range of 412–465 s, differing significantly ($p < 0.001$) among the samples. The calculation of FNs is one method for determining the activity of α-amylase, although these cannot determine the amount of enzyme present [27]. The lower FN means the shorter time is required for the piston to fall, implying the higher α-amylase activity. However, excessive α-amylase activity could produce problems during breadmaking and result in sticky dough, discoloration, sticky crumbs, or difficulty in mechanical handling [31, 41]. The results of the present study showed lower FNs for WWFs milled by JM than those milled by HM, especially for Keumkang and Jokyung, implying that these cultivars had higher α-amylase activity. The α-amylase of WWF samples was in the range of 0.72–0.117 CU/g. Similar to the result of FN in Keumkang and Jokyung, α-amylase was significantly higher in the JM group (Keumkang: 0.110 CU/g; Jokyung: 0.117 CU/g) than in the HM group (Keumkang: 0.102 CU/g; Jokyung: 0.106 CU/g). The FN of Anzunbaengi was not affected by the milling method, while α-amylase was significantly different by milling methods. This might be because Anzunbaengi, the soft wheat, milled with HM was able to produce fine particle size (<50 μm), similar to the particle size range of the JM group, which indicates the large surface available for enzyme activity site. In other words, the FN of WWF was induced by the particle size of it rather than the milling method.

The color characteristics of the WWFs milled by JM and HM also differed significantly ($p < 0.001$), as shown in Table 2. Among the three WWFs produced by JM, significant

Table 2: Median particle size (d50), starch damage, falling number (FN), and color characteristics of WWFs milled with jet mill and hammer mill.

	Particle size (d50) (μm)***	Starch damage (%)***	FN (s)***	α-Amylase (CU)/g***	Color characteristics		
					L value***	a value***	b value***
Jet mill							
Keumkang	41.82 ± 1.22^{d}	3.43 ± 0.10^{c}	412 ± 2.52^{c}	0.110^{b}	88.55 ± 0.09^{a}	0.75 ± 0.01^{de}	9.74 ± 0.11^{c}
Jokyung	50.67 ± 0.90^{c}	4.08 ± 0.26^{b}	414 ± 8.14^{c}	0.117^{a}	88.28 ± 0.03^{a}	0.71 ± 0.02^{e}	9.90 ± 0.01^{c}
Anzunbaengi	20.79 ± 0.17^{e}	2.21 ± 0.03^{d}	439 ± 3.51^{b}	0.078^{e}	88.73 ± 0.28^{a}	0.83 ± 0.09^{cd}	8.19 ± 0.35^{d}
Hammer mill							
Keumkang	188.47 ± 4.35^{a}	3.37 ± 0.32^{c}	465 ± 11.37^{a}	0.102^{d}	85.38 ± 0.12^{c}	1.26 ± 0.06^{a}	11.45 ± 0.14^{a}
Jokyung	115.70 ± 4.49^{b}	4.71 ± 0.15^{a}	428 ± 4.93^{b}	0.106^{c}	87.28 ± 1.15^{b}	1.08 ± 0.01^{b}	11.03 ± 0.12^{b}
Anzunbaengi	40.34 ± 5.55^{d}	2.15 ± 0.03^{d}	435 ± 4.58^{b}	0.072^{f}	88.97 ± 0.29^{a}	0.87 ± 0.05^{c}	7.56 ± 0.39^{e}

All values are means of three replications ± standard deviations. Values with the same alphabet within a column are not significantly different. ***Significantly different at $p < 0.001$.

differences were not found in the L value. However, with respect to the milling method, the L value of WWFs milled by JM was higher than that milled by HM, except for Anzunbaengi flour. The lightness of color was increased with reducing particle size because of the increasing surface area which was able to reflect more light [42]. However, the samples with small particle size (<50 μm) had no significant difference on the L value. The a and b values of WWFs milled by HM were also higher than those milled by JM. The lower b value of the JM group than the HM group is supported by Kim and Shin [43] who reported that reduction of the b value with decreasing particle size would have correlation with decrease in protein content. In the present study, there was a significant correlation between b value and protein content ($r = 0.681$, $p < 0.01$).

Finally, the WAI and WSI are presented in Figure 1. Both indices presented significant differences ($p < 0.001$). All three samples milled by JM had a higher WAI and WSI compared to those milled by HM. Since the smaller particle size of flour had the larger surface area for contact with water, the smaller particle size of flour had the higher flour hydration properties [44]. The significant difference of WAI and WSI caused by the milling method would be induced by particle size.

3.3. Pasting Properties of WWFs. The pasting properties of the WWFs are indicative of certain parameters of flour quality such as starch swelling, retrogradation, and gelatinization [45, 46]. The peak, trough, breakdown, final viscosity, and setback of the WWF samples milled by JM and HM are shown in Table 3, and all samples showed significant differences ($p < 0.001$). After water is added to wheat starch during the heating process, viscosity increases following the start of gelatinization at temperatures of 50–57°C. The term "pasting" refers to the process that occurs after gelatinization and the loss of granule birefringence [45]. The WWFs milled by HM had higher viscosity than those milled by JM in terms of peak, trough, and final viscosity as well as the setback value regardless of the cultivar. The result of this study was in agreement with Liu et al. [21] who reported that the WWFs milled by HM did have higher viscosity than stone mill and ultrafine mill flours. In this study, each cultivar milled with the JM group had smaller particle size than that of the HM group, showed lower viscosity. This coincided with the report by Niu et al. [38] who reported that WWFs with smaller particle size had lower viscosity.

3.4. Dough Properties of WWFs. The Wabs, DDT, stability, C2, C3, C3-C4, and C5∗C4 of WWFs milled by JM and HM are represented in Table 4. The Wabs differed significantly ($p < 0.001$) among WWFs and range from 51.13 to 57.30%. These values are lower than those reported by Wang et al. [47] and Protonotariou et al. [48]. Wang et al. [47] reported that Wabs of WWF milled with JM was in the range of 60.3–64.0% [47], and Protonotariou et al. [48] reported that Wabs (%) of reconstituted WWF with distinct particle size was in the range of 64.1–68.0%.

These differences in the Wabs values might depend on various factors, such as the wheat cultivar, milling method, starch damage, particle size, and protein content [11, 47, 48]. Khan [31] reported that the water absorption capacity of wheat flour increased with increasing protein content. In the present study, the Wabs values of WWFs milled by HM (57.13–57.3%) tended to be higher than those milled by JM (51.13–53.47%), implying that the Wabs of WWFs was influenced by the milling method rather than the wheat cultivar. These results might be explained by the different particle sizes, similar to the findings of Liu et al. [11], who found that WWF with smaller particle size had lower Wabs values [11].

Additionally, significant differences were observed in DDT ($p < 0.001$) and stability ($p < 0.001$) of WWFs based on the calculated Mixolab parameters presented in Table 4. Xiong et al. [49] reported that DDT positively correlated with stability, and a high correlation ($r = 0.949$, $p < 0.001$) between DDT and stability was also found in the results of the present study. The DDT of Jokyung (JM: 5.34 min; HM: 5.91 min) and Anzunbaengi (JM: 3.28 min; HM: 3.64 min) did not show large differences with respect to the milling method. However, the DDT of Keumkang milled by JM (1.03 min) was significantly shorter than that of Keumkang milled by HM (DDT: 6.40 min). This result might be affected by the particle size and α-amylase activity of the samples, as an increase in the surface area with respect to volume in the

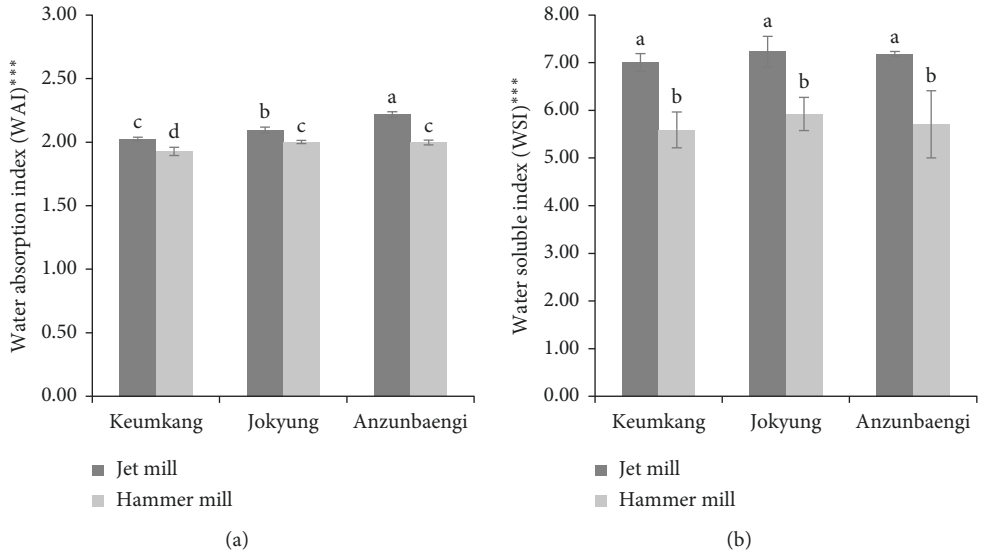

Figure 1: Water absorption index (a) and water soluble index (b) of WWFs milled with jet mill and hammer mill. ***Significantly different at $p < 0.01$.

Table 3: Pasting properties of WWFs milled with jet mill and hammer mill.

	Peak viscosity (cP)***	Trough (cP)***	Breakdown (cP)***	Final viscosity (cP)***	Setback (cP)***
Jet mill					
Keumkang	711 ± 6.03^{c}	477 ± 8.50^{d}	235 ± 4.93^{a}	1092 ± 16.07^{d}	616 ± 8.50^{d}
Jokyung	667 ± 20.88^{d}	470 ± 6.51^{d}	197 ± 26.31^{b}	1062 ± 6.08^{e}	592 ± 8.33^{e}
Anzunbaengi	565 ± 3.79^{e}	451 ± 3.79^{e}	114 ± 1.00^{c}	994 ± 7.00^{f}	543 ± 4.62^{f}
Hammer mill					
Keumkang	749 ± 4.36^{b}	576 ± 4.36^{b}	173 ± 0.00^{b}	1304 ± 11.79^{b}	728 ± 7.55^{b}
Jokyung	763 ± 18.33^{b}	565 ± 6.00^{c}	198 ± 12.49^{b}	1249 ± 17.69^{c}	684 ± 11.79^{c}
Anzunbaengi	963 ± 3.79^{a}	726 ± 4.16^{a}	238 ± 1.53^{a}	1548 ± 2.65^{a}	822 ± 3.51^{a}

All values are means of three replications ± standard deviations. Values with the same alphabet within a column are not significantly different. ***Significantly different at $p < 0.001$.

Table 4: Dough properties of WWFs milled with jet mill and hammer mill.

	Dough properties by Mixolab						
	Wabs[1] (%)***	DDT[2] (min) ***	Stability[3] (min)***	C2[4] (Nm)***	C3[5] (Nm)***	Cooking stability[6] (Nm)***	Retrogradation[7] (Nm)***
Jet mill							
Keumkang	51.13 ± 0.06^{c}	1.03 ± 0.09^{d}	8.33 ± 0.33^{e}	0.45 ± 0.01^{c}	2.06 ± 0.03^{bc}	0.09 ± 0.01^{b}	1.30 ± 0.08^{b}
Jokyung	53.00 ± 0.69^{b}	5.34 ± 0.34^{b}	10.11 ± 0.06^{b}	0.44 ± 0.02^{c}	1.96 ± 0.03^{de}	0.24 ± 0.15^{b}	1.55 ± 0.12^{ab}
Anzunbaengi	53.47 ± 0.75^{b}	3.28 ± 0.09^{c}	8.89 ± 0.13^{d}	0.50 ± 0.04^{b}	2.16 ± 0.04^{a}	0.64 ± 0.04^{a}	0.97 ± 0.17^{c}
Hammer mill							
Keumkang	57.30 ± 0.00^{a}	6.40 ± 0.64^{a}	10.86 ± 0.06^{a}	0.56 ± 0.01^{a}	2.01 ± 0.00^{cd}	0.33 ± 0.17^{b}	1.64 ± 0.19^{a}
Jokyung	57.20 ± 0.00^{a}	5.91 ± 0.24^{a}	10.92 ± 0.13^{a}	0.56 ± 0.02^{a}	1.92 ± 0.03^{e}	0.21 ± 0.11^{b}	1.48 ± 0.16^{ab}
Anzunbaengi	57.13 ± 0.46^{a}	3.64 ± 0.08^{c}	9.37 ± 0.26^{c}	0.54 ± 0.03^{a}	2.08 ± 0.04^{b}	0.62 ± 0.05^{a}	0.77 ± 0.09^{c}

All values are means of three replications ± standard deviations. Values with the same alphabet within a column are not significantly different. **,***Significantly different at $p < 0.01$ and $p < 0.001$, respectively. [1]Wabs means water absorption. [2]DDT means dough development time. [3]Stability is the remaining time after reaching 1.1 torque. [4]C2: protein weakening; [5]C3: pasting properties; [6]C3-C4: cooking stability; [7]C5-C4: retrogradation properties.

finer particles induces faster water absorption [47]. High α-amylase activity is facilitated by dough formation [31].

When heating begins during the mixing process, the dough loses its stability before reaching the minimum torque, C2. A significant difference ($p < 0.001$) in C2 was found with respect to the milling method rather than the cultivar, indicating that WWFs milled by JM (0.54–0.56 Nm) had a more stable gluten structure during heating [50] than WWFs milled by HM (0.44–0.50 Nm). In the dough heating process, protein denaturation and unfolding were induced

by the interior thermal transfer of dough [27]. From this reason, the minimum torque (C2) of samples in this study was positively correlated with the Wabs values ($r = 0.827$, $p < 0.001$) and moisture content ($r = 0.721$, $p < 0.01$).

Meanwhile, the peak torque during heating (C3) indicates the pasting properties [51]. In the present study, C3 was affected by the milling method and cultivar (Supplementary Table 1). However, the cooking stability (C3-C4) was not affected by the milling method. With respect to the starch properties of dough during heating, swelling and gel breakdown might be unchanged by the milling method. Once the cooling process begins, amylose chains that had previously leached out during swelling begin to recrystallize. For this reason, the parameter of retrogradation, C5-C4, was also recorded. In the present study, this parameter (0.77–1.64 Nm) tended to be higher than that (0.33–0.35 Nm) found in a previous study [48], implying that the WWFs used in this study might produce bread that increases in hardness over time. Furthermore, the retrogradation parameter (C5-C4) for Jokyung and Anzunbaengi did not differ by the milling method. The above results confirm the report of Protonotariou et al. [48], who found that the setback value was not affected by the milling method. The setback viscosity normally indicates the degree of retrogradation of starch, mainly amylose [52]. Therefore, the starch behavior of dough appears to retain its properties under different milling processes.

3.5. Resistance to Extension and Extensibility of WWFs. The resistance to extension and extensibility of the WWFs milled by JM and HM are shown in Figure 2. Significant differences ($p < 0.001$) were found among the samples in the resistance to extension and extensibility, which ranged from 0.30 to 0.68 N and 25.30 to 43.34 mm, respectively. These values are similar to those reported by Barros et al. [53], who reported resistance to extension and extensibility in the range of 0.3–0.6 N and 20–40 mm, respectively. Generally, resistance to extension in refined wheat flour has been found to be negatively correlated with extensibility [54]. However, resistance to extension and extensibility in the WWFs evaluated in the present study showed different trends with respect to Nash et al. [54], as a low correlation ($r = 0.069$, $p > 0.05$) was found between resistance to extension and extensibility. Boita et al. [55] reported that resistance to extension and extensibility of dough gradually decreased as the bran content of wheat flour increased from 6.25 to 25%, which also differs from the results reported by Nash et al. [54] for refined flour. These results might be explained by the differences between refined flour and WWFs in gluten network, particle size, and dietary fiber content [53]. In respect of the milling method, there was no significant difference in both resistance to extension and extensibility, as shown in the result of two-way ANOVA (Supplementary Table 1). Barros et al. [53] reported that resistance to extension depended on the flour type and found a similar tendency in resistance to extension and extensibility with respect to the present study. Meanwhile, Wang et al. [47] reported increasing extensibility of WWF with decreasing particle size. In the present study, this trend was shown only within the same cultivar.

3.6. Principle Component Analysis (PCA). The PCA loading plot of the major physicochemical characteristics and dough properties of WWFs prepared by two milling methods (JM or HM) from three cultivars is presented in Figure 3. The first two components of the PCA explained 75.61% of the variation; specifically, principle component (PC) 1 (x-axis) and PC2 (y-axis) accounted for 45.09% and 30.52% of total variation, respectively. The milling method can be explained by PC1. The WWFs milled by JM were associated with positive values on the PC1 axis, and the WWFs milled by HM were associated with negative values on the PC1 axis. WWF samples milled by JM were smaller in particle size (μm) and higher in WAI and WSI than those of HM, supporting the findings of Protonotariou et al. [19], who reported that flour produced by JM was smaller in particle size and showed increased water holding capacity.

Among the three cultivars, the Keumkang samples were located in opposite directions depending on the milling method. Keumkang milled by HM was positively located on the negative axis of PC1 and positioned near to particle size and the a value for color. On the other hand, Keumkang milled by JM was positively located on PC1 and positioned near to WAI and WSI. Niu et al. [38] reported that the JM method, which can produce small particle sizes, is the proper milling method for making whole-wheat noodles. Flour Rapid Visco Analyzer pasting properties and flour swelling power were correlated to the smoothness and softness of cooked noodles [56]. As shown in Keumkang, the milling method for the WWFs of Jokyung and Anzunbaengi was discriminated by PC1. Meanwhile, starch damage and retrogradation (C5-C4) were located between the Jokyung WWFs milled by JM and HM. In addition, Jokyung milled by JM was located near ash content (%), while that milled by HM was located near the stability (min) and DDT (min) parameters of dough. Khan [31] reported that flour of good quality for making bread requires a low ash content, and Bressiani et al. [39] suggested that WWF with a fine particle size does not produce the best specific volume and firmness of bread. For these reasons, it can be inferred that Jokyung WWF milled by HM would produce bread of better quality than that milled by JM. Finally, Anzunbaengi WWF milled by JM was positively located on PC1 and negatively on PC2, while that milled by HM was negatively located on PC1 and on PC2. Anzunbaengi milled by JM was located near total dietary fiber.

The C3 (pasting properties) and C3-C4 (cooking stability) parameters determined by the Mixolab® were positively located on PC1 and negatively on PC2. On the other hand, the wet gluten content (%), damaged starch content (%), and retrogradation parameter (C5-C4) determined by Mixolab® were negatively located on PC1 and positively on PC2. The direction of pasting properties and cooking stability of dough were opposite to that of wet gluten content (%), damaged starch content (%), and retrogradation, implying a high negative correlation. Overall, the results of the present study demonstrated that the physicochemical

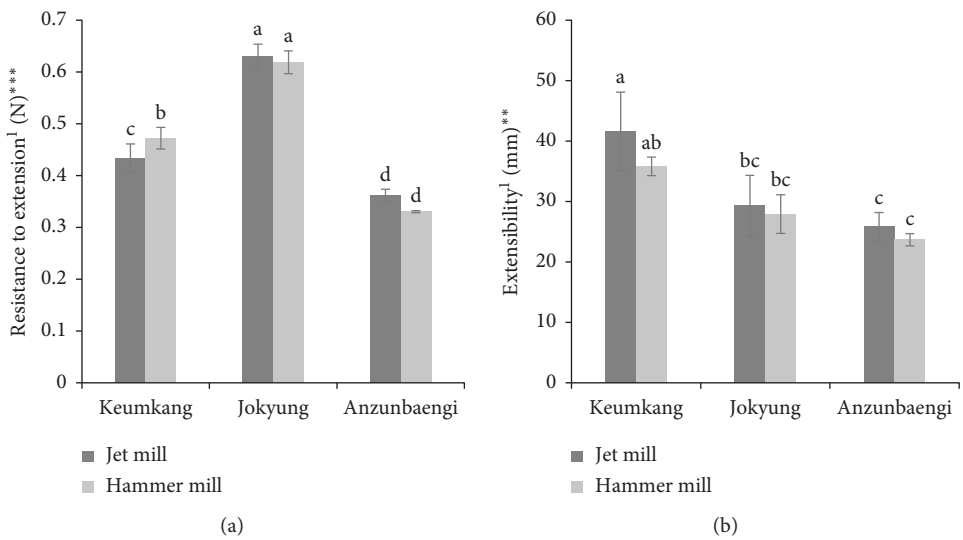

Figure 2: Resistance to extension (a) and extensibility (b) of WWF milled with jet mill and hammer mill. **,***Significantly different at $p < 0.01$ and $p < 0.001$, respectively.

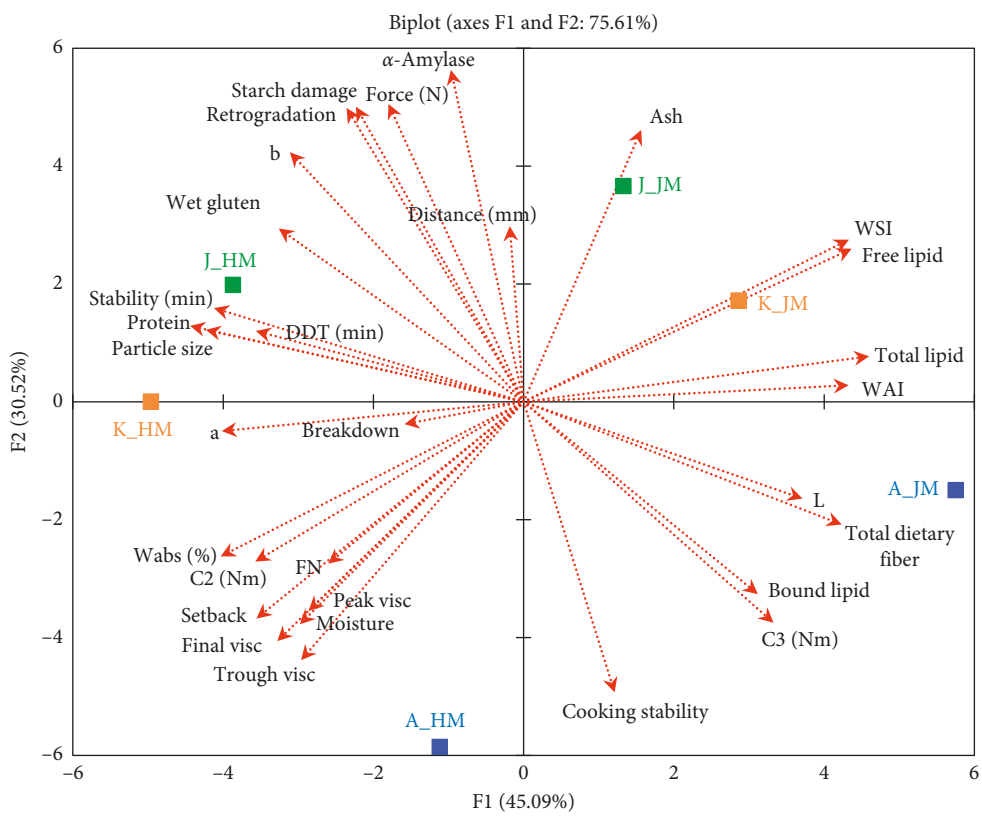

Figure 3: Principle component analysis (PCA) of WWF on proximate compositions and dough properties (K: Keumkang; J: Jokyung; A: Anzunbaengi; JM: jet mill; HM: hammer mill; WAI: water absorption index; WSI: water solubility index; Wabs: water absorption; DDT: dough development time; FN: falling number).

characteristics of the WWFs were affected by the evaluated milling methods and cultivars. The ideal characteristics of WWF differ depending on the desired end products, so the effects of distinct milling methods and cultivars should be considered based on this criterion.

4. Conclusion

The effects of two milling methods (jet milling and hammer milling) and three wheat cultivars (Jokyung, Keumkang, and Anzunbaengi) with different hardness (hard, medium, and

soft, respectively) on the characteristics of WWFs were investigated. Independent of the cultivar, the WWFs milled by JM had a significantly smaller particle size (d50) than those milled by HM, and the smaller particle size resulted in higher WAI and WSI. Starch damage, wet gluten content, and the extensional properties of dough did not significantly differ per milling method for the same cultivar. The starch damage was highest in Jokyung, followed by Keumkang and Anzunbaengi, yet the opposite trend was found for the pasting property (C3) determined by the Mixolab®. These results imply that the level of starch damage influenced the pasting properties of WWF dough. Additionally, the extensibility of Keumkang with respect to wet gluten content showed a distinct tendency compared to the other cultivars. The highest wet gluten content was found for Jokyung, yet Keumkang had the longest extensibility among the samples. Generally, the properties of Keumkang WWF were affected by the milling methods more than the other cultivars. Further research is needed to identify the reason for this result. The results of the present study suggest that Keumkang WWF milled by JM is better for making whole-wheat noodles than Keumkang WWF milled by HM and that Jokyung WWF milled by HM is better for making bread than Jokyung milled by JM based on the water absorption capacity and particle size of the flours. Overall, the results show that the milling method and type of wheat cultivar used to produce WWFs should be considered depending on final purpose of WWF products.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

An earlier version of this article was presented as a poster presentation in 2018 KoSFoST International Symposium and Annual Meeting.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Supplementary Materials

Results of two-way (milling methods and cultivars) analysis of variance. (*Supplementary Materials*)

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