Received: 29 September 2017 | Accepted: 13 December 2017
DOI: 10.1002/cche.10029

RESEARCH ARTICLE

Characterizing whole-wheat flours produced using a commercial stone mill, laboratory mills, and household single-stream flour mills

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Funding information
Oregon State University; United States Department of Agriculture National Institutes of Food and Agriculture, Grant/Award Number: 2009-31100-06041

Background and objectives: One hard wheat and one semi-hard wheat were milled on commercial, laboratory, and household-scale flour mills with rotating elements ranging from 0.1 to 1.0 m in diameter and speeds ranging from 65 to 40,000 rpm. The aim of the study was to assess and compare the quality of the flour from each of mills.

Findings: Pasting viscosities, Farinograph development time and stability, and loaf volumes (LVOL) were all markedly influenced by whole-wheat flour particle size, which differed markedly between mills. LVOLs were acceptable using the flours produced by all the mills. Best flour quality came from the three mills that produced the finest whole-wheat flour. Of these, the superior flour came from the 1.0-m-diameter Osttiroler stone mill. This mill produced whole-wheat flours with more optimal levels of starch damage and higher water absorption than did the smaller mills. There was no evidence of degradation of gluten functionality even at a flour temperature of 51°C.

Conclusions: The mill used affected almost all flour quality traits. However, the characteristics of the wheat applied to the mill were the dominant influence on flour functionality. Starch damage may better indicate milling severity than the heat generated during the milling process.

Significance and novelty: This is the only study, that we know of, on the comparative performance of household-scale flour mills. The study also presents an alternative way of visualizing particle size distributions of flours.

KEYWORDS
flour functionality, flour temperature, particle size distribution, stone mills, whole-wheat

1 | INTRODUCTION

Over the last 60 years, commercial commodity grain production has increased dramatically in pace with growing agricultural intensification (Neumann, Verburg, Stehfest, & Müller, 2010). Contemporary with the increase in large-scale agriculture, small-scale and local grain production had almost disappeared (Wallinga, 2009). However, more recently, the local agriculture movement, which was at first focused on fresh produce, has begun to make local grain production an area of economic growth. Accordingly, local grain products are increasingly in demand. The requirements of such local- to regional-scale systems include specific breeding targets for new cereal varieties, adaptations for low-input agriculture (Brouwer, Murphy, & Jones, 2015), and development and deployment of small- to medium-scale infrastructure (Ecotrust, 2015). Of these, milling infrastructure is crucial for wheat, because most wheat-based foods are made from flour rather than from intact wheat grains. However, flour milling in North America, like other food operations, is, in the modern era, the domain of large businesses (Everitt, 1993; Grey, 2000). In part, the shift of milling to large businesses resulted from the high capital costs associated with the construction of modern roller milling facilities and because roller mills very efficiently produce refined flour, which is the majority of flour consumed in the modern era.

Successful local- to regional-scale grain systems need small- to medium-sized milling operations that require relatively low capital inputs. These low-capital operations, including home-milling, provide a viable market for the grain produced on small farms, without the necessity for further processing beyond cleaning. Accordingly, there is increased interest in understanding the quality of flours milled through "single-stream" mills, ranging in size from small commercial to home scale. We define single-stream mills as mills that grind the grain in one operation and where the resultant whole-wheat flour is neither sifted, separated, or reground, regardless of whether the milling elements are stone or metallic. Single-stream mills almost universally function by grinding kernels between one stationary and one rotating element. Single-stream mills vary in size, rotational speed, and burr patterning. Along with the variations in the mills themselves, the space between the milling elements is adjustable to varying levels of precision (or imprecision) depending on the mill. Consequently, stone millers are commonly limited to subjective adjustments of process settings. Accordingly, the quality of flour is often primarily attributable to the skill and experience of the millers, both in setting the mill and the choice of wheat types to mill. There is only a small amount of peer-reviewed data available on stone-mill process settings and their impact on functional characteristics of finished flour (Gélinas, Dessureault, & Beauchemin, 2004).

The severity, or intensity, of wheat grinding during milling can, arguably, be reflected by the heat generated during the process. Milling severity or intensity might be described as tighter gaps between the milling elements (Gélinas et al., 2004; Islam & Matzen, 1994), increased roll pressures in the reduction rolls of roller milling, or increased speeds of the grinding surfaces. As a consequence, an index or indices of milling severity or intensity based on flour traits could be a way to compare different settings on the same mill, or arguably to compare different mills. The heat during the process has been shown to affect the chemical properties of the resultant flour (Prabhasankar & Rao, 2001). In addition, mill type and settings affect particle size and starch damage and thereby the functional characteristics of the flour (Baasandorj, Ohm, Manthey, & Simsek, 2015; Gélinas et al., 2004). Stone mills have also been considered to produce rather coarse particles (Gélinas, Morin, Reid, & Lachance, 2009; Gélinas et al., 2004), although this is not necessarily the case. Intuitively, for a given mill, stone tightening and/or increased mill speed result in finer flour granulation and increased starch damage and water absorption (Gélinas et al., 2004; Islam & Matzen, 1994). Particle size distribution, per se, has been shown to affect flour functionality, independent of the milling process used to produce the flour (Kihlberg, Johansson, Kohler, & Risvik, 2004). An additional impetus for this study is the recognition of the value of moving toward greater levels of whole-grain consumption for the improvement of health outcomes at both personal and population-wide levels (Huang, Xu, Lee, Cho, & Qi, 2015; Jacobs, 2015; Van Blarigan et al., 2017). Access to efficient and inexpensive household mills for some sectors of the population may increase access to whole grains and therefore increase access to the attendant health benefits of whole-grain consumption.

There are no systematic studies, that we know of, on the comparative performance of home mills, and only a few studies of mills with diameters ≤1.0 m. People interested in specialty and heritage grains, artisan baking, whole grains for health, and small-scale milling have been clamoring for information about the performance of small-scale mills. We have performed this study as a starting point to provide the needed information. The initial aim of this study was to compare the outcomes of milling two contrasting hard wheat varieties through seven single-stream mills with milling elements ranging in diameter from 0.1 to 1.0 m. For comparison, we included one laboratory-scale roller mill. This mill sifted, separated, and reground mill streams, with final reconstitution of all material to create a whole-wheat flour. The chosen mills had both metal and stone milling elements and differed in milling geometries and rotational and tangential velocities. Our hypotheses are that flour temperature is an index of milling severity, that high-speed mills will create greater levels of starch damage, and that flours with smaller median particle sizes will have better baking performance. This study is limited to the functionality of the flour. The effects of flour temperature on storage stability and of both flour temperature and median particle size on nutrition are not addressed.

2 | MATERIALS AND METHODS

2.1 | Materials

Wheat grain was purchased from Grist and Toll Milling (Pasadena, CA, USA). Two hard-red varieties were used:

"Red Fife" grown in the Willamette Valley, Oregon, USA, and harvested in 2013 and "Joaquin Oro" grown in Pomona, California, USA, and harvested in 2014. Grain was stored dry at ambient temperature (20–22°C) until milling. Grain Craft stone-milled hard-red whole-wheat (Grain Craft, Chattanooga, TN, USA) and Shepherd's Grain High-Gluten baker's flours (The Shepherd's Grain, Portland, OR, USA) were used to maintain the sourdough starters.

2.2 | Flour mills

Mill characteristics and provenance are shown in Table 1. For the Osttiroler mill, the grain feed rate was adjusted using a cogwheel below the grain hopper. For the other mills, grain feed rates were adjusted using either a magnetic vibratory feeder (Syntron model F-T01, Syntron Corp. South Saltillo, MS, USA: Meadows Mill, Brabender Quadramat Senior roller mill), the airflow into the mill (Perten Laboratory P3100 Hammer Mill), or a screw adjustment in the feed hopper (SAMAP mill). For mills where there was no explicit control of grain feed rate, the grain was allowed to feed at the "natural" rate that the mill allowed (Country Living, Hawos, and Wonder mills).

On the Osttiroler mill, the gap between the stones was adjusted by the professional miller to provide the "best" outcome possible with respect to the miller's experience. There is precedent in the literature for this approach. Kihlberg et al. (2004) used a commercial stone mill for their stone-milled flour, without any further description of the mill beyond it being "commercial." For the P3100 Hammer mill, no adjustment was available and the grain was ground until the resultant whole-wheat flour completely passed through the 0.8-mm screen. For the Brabender roller mill, the roll gaps were those described by Jeffers and Rubenthaler (1977). For the Country Living mill, Meadows mill, SAMAP mill, and Hawos mill, the stones or disks were adjusted to their finest possible setting by adjusting the milling elements until they just touched in the absence of grain, and then, the gap was backed-off until auditory evidence indicted the first point at which the milling elements were no longer touching. The Wonder mill was adjusted to its finest setting: "pastry."

For the Osttiroler mill, untempered grain was milled to whole-wheat flour using duplicate 11.4-kg samples of each variety at the Grist and Toll facility in Pasadena, CA. For the other mills, grain of the same grain lot used in the Osttiroler mill was delivered in 45.4 kg lots per variety and each lot was subdivided and recombined 9 times to mix thoroughly. Duplicate 2.5-kg untempered subsamples of each variety were milled on each single-stream mill to provide two independent replicates. The exception was the Brabender roller mill, which used two 2.5-kg subsamples that had been tempered to 15% moisture prior to milling (AACCI Approved Method 26-10.02). Between each milling, the stones or disks of each mill were disassembled,

TABLE 1 Details of the mills used in this study

Mill	Source	Type	Diameter (m)	rpm[a]	Tangential velocity at edge (m/s)	Average grain feed rate (g/min)
Brabender Quadramat Senior	Brabender GmbH & Co. Duisburg, Germany	Metal roller	0.071	1,200	4.5	110
Osttiroler A-1000	Osttiroler Getreidemühlen, Dölsach, Austria	Natural stone burr, horizontal stone disks	1.0	160	8.4	704
Meadows Mill	Meadows Mills Inc. North Wilkesboro, NC, USA	Natural stone burr, vertical stone disks	0.25	875	11.5	106
Country Living Mill	Country Living Mills, Stanwood, WA, USA	Metal burr disk, vertical	0.1	60	0.31	27
Wonder Mill	The Wonder Mill Company, http://www.thewondermill.com	Metal Pin/micronizer, horizontal	0.1	40,000	209	565
Perten Laboratory P3100 Hammer mill	Perten Instruments., Hägersten Sweden	Metal hammer, vertical	0.1	16,800	88	400
Hawos Mill #1	Hawos Kornmühlen GmbH, Bad Homburg, Germany	Composite stone burr, horizontal conical stones	0.1	1,440	7.5	463
SAMAP F100	SAMAP Ecosysteme, Colmar, France	Composite stone burr, horizontal conical stones	0.1	2,850	14.9	362

[a] rpm for the moving burrs in the single-stream mills and the fast 1st break roll in the Brabender Quadramat Senior roller mill.

cleaned, and reassembled. For the Meadows, Wonder, SAMAP, Hawos mills, the mills' construction did not allow simple disassembly and cleaning. Therefore, the mills were purged with grain of the variety to be milled next. Where possible, mills were completely "de-adjusted" and then readjusted between samples to make the replicated millings as independent as possible. Flour maximum temperature was measured on flour as close as possible to the outlet on each mill during milling once a steady-state maximum flour temperature was achieved. For the Osttiroler flour, maximum temperature was recorded using an infrared thermometer (Fluke 63 mini IR thermometer, Everett, WA, USA). For the other mills, a Type K thermocouple probe "instant-read" thermometer was used (Thermapen Mk4, ThermoWorks Inc. Lindon UT, USA). For the Brabender roller mill, bran and shorts were reground using the P3100 Hammer mill with the 0.8-mm screen to reduce bran and shorts particle size (Souza, Guttieri, & Sneller, 2011; Wang, Hou, & Dubat, 2017).

2.3 | Flour and grain analyses

Near-infrared reflectance measurements of grain and flour protein and moisture were based on AACC International Approved Methods 39-11.01 and 39-25.01. SKCS testing of grain was performed according to AACC International Approved Method 55-31.01. Solvent retention capacities (SRCs) were performed on whole-wheat flour using an SRC-Chopin Instrument (Chopin Technologies, Cedex, France) based on AACC Approved Method 56-11.02. Only water, sodium carbonate, and lactic acid SRCs were performed. Sucrose SRC was omitted as it had been previously shown to have a strong interaction with milling method (Guttieri, Souza, & Sneller, 2011). Starch damage was measured using AACC Approved Method 76-31.01. Farinograph testing of whole-wheat flour was carried out based on AACC Approved Method 54-21.02. RVA whole-wheat flour pasting analysis was carried out based on AACC Approved Method 76-21.01. Microfluidic capillary electrophoresis of gluten proteins was carried out using the method of Uthayakumaran, Listiohadi, Baratta, Batey, and Wrigley (2006) using an Agilent Bioanalyzer 2100 and Protein 230 kit (Agilent Technologies, Santa Clara, CA, USA).

Sifting analysis was carried out using a modification of the method employed by Gélinas et al. (2004) and based on AACC International Approved Method 66-20.01 using a Ro-Tap RX-29 sieve shaker (W.S. Tyler Industrial Group, Mentor, OH, USA) and sieves of 250 mm diameter with mesh openings of 250, 212, 150, 106, 75, and 63 μm. Sifting results were analyzed based on soil analysis principles outlined in Ishibashi and Hazarika (2010), and ASAE S319.4 FEB2008 (R2012). Percent-finer data were plotted on log/linear plots, and D_{10}, D_{30}, D_{50} (median particle size), and D_{60}, corresponding to the percent finer than 10%, 30%, 50%, and 60% of particles by weight, were estimated from the plots. These parameters were used to calculate the uniformity coefficient (D_{60}/D_{10}) and the coefficient of gradation ($D_{30}^2/(D_{10} \times D_{60})$). In soils, when the uniformity coefficient is between 4 and 6, it is considered to be a well-graded particle size distribution (same proportions of all the different particle size groups). When uniformity coefficient is less than 4, particles are considered to be uniformly graded (i.e., most particles in one size group).

2.4 | Test baking

Whole-wheat flour test baking was performed using a sourdough method based on a French traditional country bread: "miche" using an amalgamation of the formulations and processes of Suas (2008), Reinhart (2001), and the Poilâne bakery in Paris France. The sourdough was a type-1 back-slopped starter (De Vuyst et al., 2014; Gobetti & Gänzle, 2012). Starter and formulations are shown in Table 2. The maintenance starter was fed at 24-hr intervals and kept at 21 ± 1.5°C in a closed plastic container. The preproduction starter was compiled on day 1 and fermented for 16 hr at 21 ± 1.5°C before being used to inoculate the production starters. Production starters, each made with the test flour, were made on day 2 and allowed to ferment for 8 hr at 21 ± 1.5°C before being added to the final doughs. The use of 50% of the total flour in the formulation in the production starter was deliberate and aimed at maximizing flour-water contact time and, if possible, therefore minimizing the impact of flour particle size. Final dough formulations are shown in Table 2. Water additions were adjusted per each whole-wheat flour based on its water SRC × 0.9. All ingredients (1,100 g total) were combined and mixed in a 20-quart Hobart mixer (Hobart Corp, Troy OH, USA) using a J-type dough hook. Baking mix times were Farinograph development time × 0.5, which in practice appeared appropriate for the transition from Farinograph conditions to the full formulation and the mixing geometry of the Hobart mixer. The one exception was the Red Fife whole-wheat flour milled on the Hawos mill that mixed far quicker in the commercial mixer than predicted by the Farinograph development time × 0.5 (baking mix time was equal to Farinograph development time × 0.33). Doughs were bulk fermented for 15 min, and 2 × 500 g dough pieces were taken from the bulk, rounded by hand by an experienced baker (author Ross), and then rested 30 min at 21 ± 1.5°C. Rested doughs were hand shaped into cylinders, panned into 14 × 8 × 6 cm straight-sided baking pans (BP5640 pans, Fat Daddio's, Spokane WA, USA) with the seam down, and proofed at 4 ± 1°C for 15 hr. Doughs were removed from the cooler and held for 1 hr at 21 ± 1.5°C (total proof time 16 hr) and baked at

220°C for 30 min, with 9-sec steam at the commencement of baking, in a Baxter Mini Rotating Rack Oven (Baxter Manufacturing, Orting, WA, USA). Loaf volumes (LVOL) were measured using rape seed displacement.

2.5 | Statistical analyses

Statistical analyses were performed using SAS JMP Pro 13.0.1 (SAS Institute Inc. Cary NC, USA). All analyses were performed in duplicate. One-way ANOVAs and correlations were performed using the "Fit X × Y" platform. Two-way ANOVAs were calculated with the "Fit Model" platform using the standard least squares model. Mill and variety were used as the main effects for two-way ANOVAs. Multiple comparisons were made using Tukey's HSD. A p-value of $\leq .01$ was used to indicate significance unless otherwise noted. Curved regressions fits were calculated using the "Fit Curve" platform. Mean-centered and autoscaled principal component analyses (PCA) were performed using the "Multivariate: Principal Component" platform.

3 | RESULTS AND DISCUSSION

3.1 | Grain characteristics

Two-way ANOVA (Table 3) showed that Red Fife grain was significantly softer, more variable in hardness, slightly larger in diameter, lower in protein, and higher in moisture than Joaquin Oro grain. The difference in hardness was expected and allowed us to contrast the behaviors of a hard and a semi-hard wheat in the mills. There were no significant differences between the subsamples applied to each mill for any of the measured traits indicating that the mixing protocol had been effective and that each subsample was representative of the bulk (Table 3).

3.2 | Flour characteristics

Table 4 shows data on the whole-wheat flours produced from the eight mills. Maximum flour temperature was significantly different between mills and between the two varieties. The softer Red Fife milled to significantly lower maximum flour temperatures, as expected. For both varieties, flours from the Wonder and P3100 Hammer mills had the highest maximum flour temperatures. In general, maximum flour temperature increased with both increasing rpm and increasing tangential velocity (Figure 1). After rpm exceeded 3,000, then the rate of increase in temperature with increasing mill rotational speed appeared to decrease. Accordingly, we fit three-parameter exponential curves to the data for each variety. For Red Fife (Figure 1a), the R-square for the fit was .91, for Joaquin Oro R-square for the fit was .87. We also fit the curves using tangential velocity as the X-regressor (figures not shown) and the fit was similar: R-square values of .92 and .81 for Red Fife and Joaquin Oro, respectively. It appears that there may be a theoretical maximum temperature that the flour can reach, dependent on grain hardness, in these types of mills. We speculate that this theoretical maximum temperature occurs, in part, because of the relatively short dwell time of the grain and grain particles, particularly in the smaller (10 cm diameter) mills. When analyzing only the mills with rotational rpm < 3,000, an upward trend was evident and apparently linear. However, mill speed only accounted for 51% and 47% of the variation in maximum flour temperature for Red Fife and Joaquin Oro, respectively, and the relationships were not significant. We suspect that the other ~50% of the variability in maximum flour temperature is related to milling geometry, when using stones, to both the stone diameter and the dressing (patterning) of the stones, the relative ventilation of the mills, and whether the ventilating air was warm or cool. For example, the low maximum temperature of the flour from the relatively high-speed Brabender roller mill (Figure 1: mill "A") may be a function of the very limited time the grain and resultant mill stocks spend in the nip of the rollers, or that the rollers are only 7.1 cm in diameter and have a relatively low tangential velocity as a result. The association between mill speed and maximum flour temperature for the single-stream mills corresponds to a reasonable approximation with

TABLE 2 Sourdough starter and final dough formulations using baker's percentages (based on total flour = 100% at each stage)

Starter formulations	Maintenance starter	Preproduction starter	Production starter	Dough formulation	
Refined baker's flour	80	80	–		–
Whole-wheat flour	20	20	100	Whole-wheat flour	100
Water	100	100	100	Water	Variable
Seed from previous iteration of starter	10	20	20	Salt	2
				Production starter	200[a]

[a] The flour in the 100% hydration production starter = the amount of whole-wheat flour added in the final formulation and therefore is 50% of total flour weight in the finished dough.

TABLE 3 *F*-values and overall means from two-way ANOVA for grain characteristics

	SKCS hardness	SKCS hardness standard deviation	SKCS weight (mg)	SKCS diameter (mm)	NIRS grain protein (%: 12% m.b.)	NIRS grain moisture (%)
Two-way ANOVA						
F-values						
Variety	5,147*	587.3*	6.16 NS	225.0*	508.8*	18,818*
Subsample	1.05 NS	0.87 NS	0.52 NS	1.00 NS	1.20 NS	0.86 NS
Variety*subsample	2.20 NS	3.51 NS	0.78 NS	1.00 NS	0.80 NS	0.86 NS
Overall means: variety						
Red Fife	50.0b	20.5a	35.8a	2.8a	15.1b	11.7a
Joaquin Oro	77.7a	14.4b	35.0a	2.7b	15.7a	10.5b

SKCS, single kernel characterization system.

*Significant at $p \leq .01$; NS, not significant $p > .01$.

Values followed by the same letter within each section in a column are not significantly different based on Student's *T* test for the varietal comparison and Tukey's HSD for the subsample and variety × subsample comparisons.

the conjecture of Doblado-Maldonado, Pike, Sweley, and Rose (2012) that the severity of wheat grinding can be reflected by the heat generated during the process.

For flour moisture (Table 4: NIRS flour moisture (1)), variety had the largest effect size, followed by mill, and then by mill × variety. The problem with analyzing this data is that the higher moisture of the Brabender roller mill flour, milled from tempered grain, skewed the analysis. When flour from the Brabender roller mill was removed from the analysis (Table 4: NIRS flour moisture (2)), variety still had the largest effect and the effect sizes for mill and the variety × mill interaction were reduced by 1 and 2 orders of magnitude, respectively. The driest whole-wheat flours for both varieties came from the P3100 Hammer and the Osttiroler mills. These were, respectively, among the hottest and coolest mills in the study. The moisture loss may be expected of the P3100 Hammer mill: a high-speed mill with the grain fed by air pressure. However, the Osttiroler mill is low speed and cool. The difference may be the dwell time of the particles. Flour particles in the 1.0 m Osttiroler mill had more time for evaporation whilst still being moved through the grinding stones.

Median particle size, uniformity index, and gradation index were all correlated in both varieties (all correlations had significant *r* values, all >.89 for Red Fife and all >.78 for Joaquin Oro; Table S1a and b). This suggested that the uniformity and gradation indices may be redundant for characterizing whole-wheat flour granulation. Mill had the largest effect on median particle size, followed by variety and then the interaction term (Table 4). A notable outcome of this analysis was that mill speed was not the defining parameter for median or other measures of particle size. The finest median particle sized whole-wheat flours in both varieties came from the Brabender roller, Osttiroler, and P3100 Hammer mills, all mills with radically different grinding geometries and rotational speeds (Table 1).

Figure 2 shows the semi-log plots for particle size distribution for the varieties Red Fife (2a) and Joaquin Oro (2b). Based on our own experience of assessing Mixographs, Farinographs, and other visual representations of flour analytical data, we posit that this visual representation of particle size distribution could be employed as a defining characteristic for whole-wheat flours. In observing Figure 2, plots that are convex up to the left represent finer particle size distributions, and those that are convex down toward the right represent coarser particle size distributions. The more linear plots are indicative of a relatively even distribution of the different particles sizes (e.g., the Meadows and Wonder mill particle size distributions from Red Fife: Figure 2a). It is evident from Figure 2 that the Brabender roller, Osttiroler, and P3100 Hammer mills all had the finest particle sizes (Table 4). The next group of mills, for both varieties, was the Meadows, Wonder, and Country Living Mills. The coarsest flours were formed the SAMAP and Hawos mills. Notably, the Country Living and SAMAP mills showed large differences in particle size distribution between the whole-wheat flours milled from the semi-hard Red Fife (Figure 2a) and the hard Joaquin Oro (Figure 2b).

Table 5 shows the results of whole-wheat SRC testing. For all three SRCs, variety had the largest effect size, two orders of magnitude higher than the effect size for mill and, three orders of magnitude higher than effect size for the interaction term, except for lactic acid SRC. Red Fife had lower water and carbonate SRCs, reflecting its softer kernel texture. Red Fife also had lower lactic acid SRC, reflecting its weaker dough characteristics. Both variety and mill influenced starch damage. It was notable that the

TABLE 4 *F*-values from two-way ANOVA and least squared means from variety, mill, and variety × mill treatments for whole-wheat flour characteristics

	Maximum flour temperature (°C)	NIRS flour moisture (1) (%)	NIRS flour moisture (2) (%)	NIRS flour protein (%: 14% m.b.)	Median particle size (D50: μm)	Particle uniformity coefficient (D60/D10)	Particle gradation coefficient ($D30^2$/(D10*D60))
Two-way ANOVA							
F-values							
Variety	71.75*	1,280*	1,776*	66.27*	92.25*	6.062NS	28.03*
Mill	72.38*	796.5*	66.2*	1.48 NS	252.3*	46.32*	54.26*
Variety*mill	4.02*	118.4*	9.03*	1.67 NS	10.67*	6.77*	13.84*
Overall means: variety							
Red Fife	36.6b	12.2a	12.0a	14.9b	183.3b	3.00a	2.14b
Joaquin Oro	41.8a	11.4b	11.0b	15.4a	219.4a	3.23a	2.50a
Overall means: mill							
Brabender roller	32.3c	13.9a	–	15.3a	108.3d	1.80c	1.43e
Osttiroler A-1000	32.1c	11.2d	11.2c	15.3a	111.5d	1.90c	1.50e
Meadows 8 inch	36.6bc	11.7bc	11.7ab	15.3a	193.0c	3.50ab	2.50bc
Country Living Mill	32.8c	11.6bc	11.6ab	15.2a	253.5b	3.88ab	2.85ab
Wonder Mill	51.4a	11.6bc	11.6ab	15.1a	184.0c	3.35b	2.20cd
Perten P3100	49.0a	11.0e	11.0d	15.1a	136.8d	2.50c	1.75de
Hawos Mill #1	40.0b	11.8b	11.8a	15.2a	338.0a	3.63ab	3.08ab
SAMAP F100	39.5b	11.6c	11.6b	15.1a	285.8b	4.30a	3.25a
Variety*mill means							
Red Fife							
Brabender roller	31.4ef	13.5b	–	15.0b	107.5f	1.75h	1.35g
Osttiroler A-1000	31.7ef	11.6de	11.6bc	15.1b	104.0f	1.75h	1.40fg
Meadows 8 inch	33.8ef	12.2c	12.2a	15.1b	180.0de	3.50abcde	2.30cdef
Country Living Mill	28.4f	12.2c	12.2a	15.0b	203.5d	3.20bcdef	2.10defg
Wonder Mill	50.3abc	12.2c	12.2a	15.1b	151.0ef	2.90cdefgh	1.60fg
Perten P3100	43.9bcd	11.6d	11.6b	14.8b	130.5ef	2.25efgh	1.70fg
Hawos Mill #1	37.3de	12.3c	12.3a	14.7b	333.0a	4.10abc	3.50ab
SAMAP F100	35.7def	12.1c	12.1a	14.9b	257.0bc	4.45ab	3.15abc
Joaquin Oro							
Brabender roller	33.3ef	14.4a	–	15.7a	109.0f	1.85gh	1.50fg
Osttiroler A-1000	32.3ef	10.9g	10.9e	15.6a	119.0f	2.05fgh	1.60fg
Meadows 8 inch	39.4de	11.1fg	11.1de	15.4a	206.0cd	3.50abcde	2.70abcde
Country Living Mill	37.2de	11.1fg	11.1de	15.5a	303.5ab	4.55a	3.60a
Wonder Mill	52.4ab	11.0fg	11.0de	15.2a	217.0cd	3.80abcd	2.80abcd
Perten 3100	54.1a	10.4h	10.4f	15.4a	143.0ef	2.75defgh	1.80efg
Hawos Mill #1	42.7cd	11.3ef	11.3cd	15.6a	343.0a	3.15bcdefg	2.65bcde
SAMAP F100	43.3cd	11.1fg	11.1de	15.3a	314.5a	4.15abc	3.35ab

*Significant at $p \leq .01$.

NS, not significant $p > .01$.

D10, D30, D50, and D60 are the particle sizes where 10%, 30%, 50%, and 60%, respectively, of the mass of particles are finer by weight.

Values followed by the same letter within each section in a column are not significantly different based on Student's *T* test for the varietal comparison, and on Tukey's HSD for the mill and variety × mill comparisons.

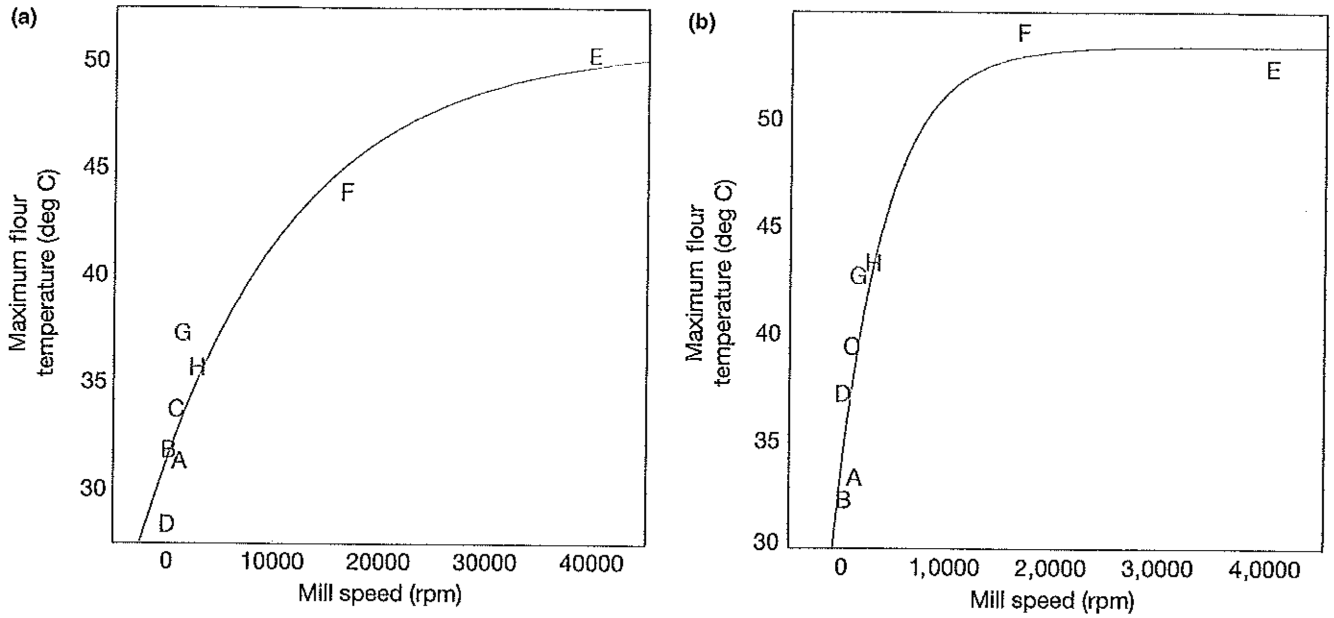

FIGURE 1 Plots of mill rpm versus maximum flour temperature. (a) Red Fife. (b) Joaquin Oro. Mills—A: Brabender roller mill; B: Osttiroler; C: Meadows; D: Country Living; E: Wonder; F: P3100; G: Hawos; H: SAMAP

slow, cool, Osttiroler mill produced whole-wheat flours with significantly higher starch damage than any of the other mills. We speculate that the dwell time of the particles in the larger mill is responsible for the increased starch damage, which was also reflected in higher water and carbonate SRC values for the whole-wheat flours from this mill (Kweon, Slade, & Levine, 2011). This also suggests that maximum flour temperature is maybe not the most effective index of grinding severity, as was concluded by Doblado-Maldonado et al. (2012). We suggest that starch damage may be a more effective index. Differences between mills for water SRC, except for the Osttiroler, were generally small in magnitude, but there was at least one surprise. The Country Living mill, which was the slowest (Table 1) and among the coolest mills (Table 4), and which gave relatively coarse whole-wheat flour (Table 4, Figure 2) ranked second overall, and within each variety, for water SRC and carbonate SRC (Table 5). This rank was reflected by its starch damage values which also ranked 2nd behind the Osttiroler mill (Table 5). It can only be speculated that the geometry of the milling elements (sharp steel burrs) was responsible for the higher than expected starch damage given the mill's low rotational speeds and low maximum flour temperatures. There were differences between mills for lactic acid SRC. The Hawos mill, with the coarsest or equal coarsest flour, had the overall highest lactic acid SRC. However, there was no overall correlation between lactic acid SRC and flour median particle size. We were also curious about the effect of maximum flour temperature on the gluten proteins. However, microfluidic capillary electrophoresis provided evidence that there was no protein degradation (reduction in molecular weight) in the flours of either variety from any of the mills (data not shown).

Results of RVA, Farinograph, and bake tests are shown in Table 5. RVA peak and final viscosities were almost equally affected by variety and mill. Starch damage was associated overall with both higher peak and final viscosities ($r = .63$ $p = .0001$, and $r = .58$ $p = .0005$, respectively) although the much higher starch damage from the Osttiroler mill was not associated with further increase in either peak or final viscosity (Table 5). Farinograph absorption, development time, and stability were primarily affected by variety with a smaller effect from the mill used. For Farinograph stability, the interaction effect was larger than the mill effect. This large statistical interaction term appears to be the relative insensitivity of the whole-wheat flour from the Hawos mill to the differences in mixing stability of the two varieties. The Hawos mill had the longest stability time for Red Fife and the shortest for Joaquin Oro (Table 5) therefore changing the rankings of the mills for each variety. Sourdough LVOL was also primarily dominated by the difference between varieties. What is also evident about the results in Table 5 is that it appears that RVA peak and final viscosities, Farinograph development time and stability, and LVOL are all sensitive to the particle size of the whole-wheat flours. This is also evident in the PCA plots (Figures 3 and 4). Figure 3 shows the PCA for all mills and both varieties. PC1 and PC2 account for 80.2% of the variability in the data. PC1 was dominated by the high/low absorption characteristics, starch damage, and Farinograph stability. The clustering in PC1 showed the

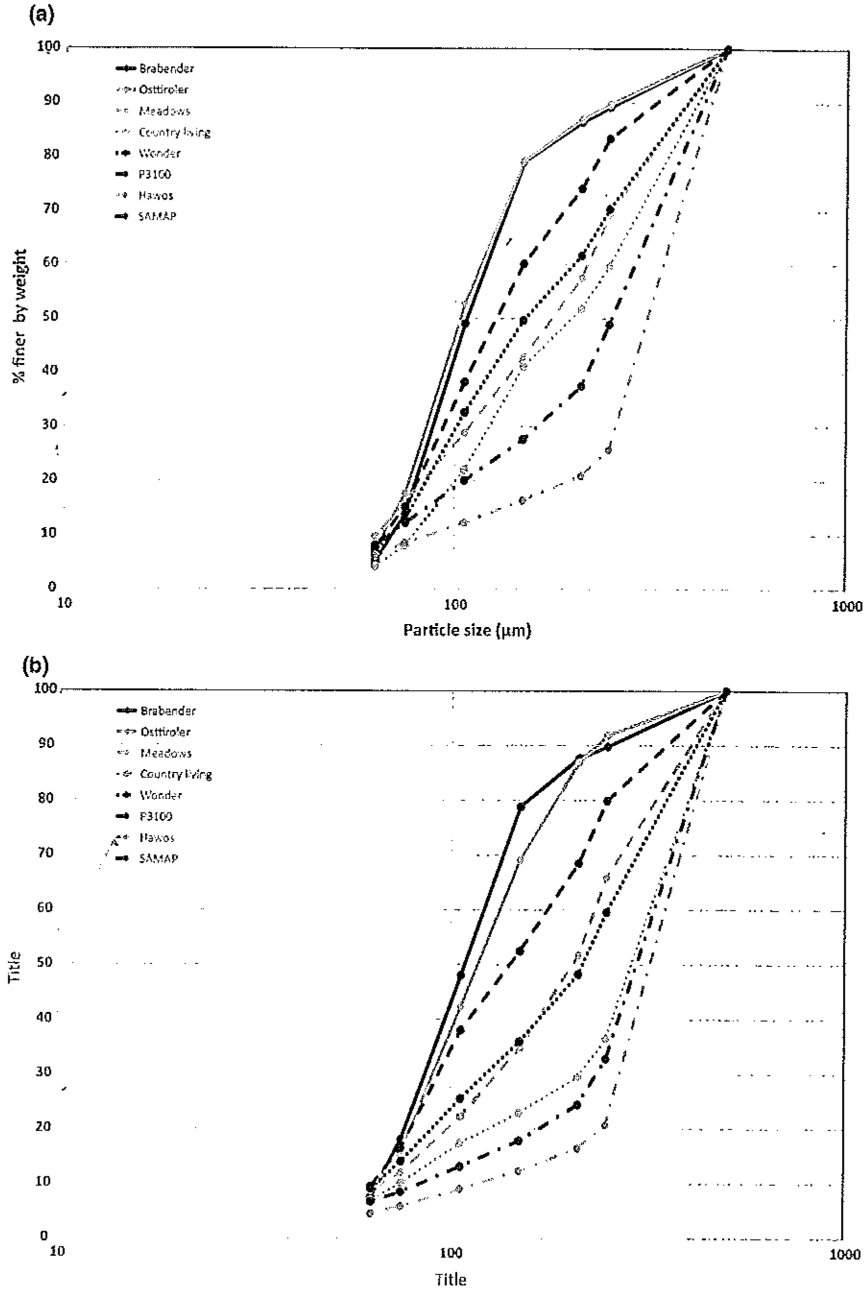

FIGURE 2 Log/linear plots of % of particles finer by weight than specified particle sizes. (a) Red Fife. (b) Joaquin Oro

softer and weaker Red Fife clustering to low SRC absorptions and Farinograph absorption, mix time, and stability and the harder and stronger Joaquin Oro the converse. PC2 was dominated by high/low particle size and there was no varietal clustering in this dimension indicating that the mills were the more likely dominant influence on particle size. LVOL, both RVA parameters, and starch damage are vectored between PC1 and PC2, suggesting the influence of both the variety and mill as defined by differences in median particle size.

Given the strong clustering by variety in the PCA of the full dataset, the PCA was repeated for each variety individually to get a better sense of the relative mill performance (Figure 4). For both varieties, PC1 and PC2 again accounted for around 80% of the total variability in the data. PC1, around 50% of the total variability in both varieties, was dominated by differences in median particle size and other parameters considered sensitive to particle size changes, RVA peak and final viscosities, Farinograph development time and stability, and LVOL (Table 5). Notably, when comparing Red Fife (Figure 4a) and Joaquin Oro (Figure 4b) is the PCA vector for Farinograph stability, which was in opposite directions for each variety (correlated positively with median particle size for Red Fife, and correlated negatively to median particle size for Joaquin Oro). We

TABLE 5 *F*-values from two-way ANOVA and least squared means for individual mill*variety treatments for water, carbonate, and lactic acid solvent retention capacities and starch damage of the flours

	Water SRC	Carbonate SRC	Lactic acid SRC	Starch damage (%)	RVA peak viscosity (cP)	RVA final viscosity (cP)	Farinograph water absorption (%)	Farinograph development time (min)	Farinograph stability (min)	Sourdough loaf volume (ml)
Two-way ANOVA										
F-values										
Variety	1,807*	1,119*	1,621*	284.4*	442.3*	42.09*	5,216*	436.2*	3,397*	20.8*
Mill	43.76*	82.37*	58.18*	103.0*	219.4*	31.37*	79.3*	27.2*	9.20*	12.1*
Variety*mill	4.49*	7.73*	14.76*	6.25*	31.06*	0.85NS	15.3*	5.25*	59.2*	2.48NS
Overall means: variety										
Red Fife	69.4b	83.5b	76.2b	2.38b	1,090b	1,721b	69.1b	4.8b	4.3b	903b
Joaquin Oro	79.9a	97.6a	91.4a	3.38b	1,521a	1,910a	77.2a	13.0a	15.4a	929a
Overall means: mill										
Brabender roller	72.3d	90.5bc	78.7d	2.78bc	1,716a	1,947a	71.3e	8.4bcd	10.7ab	940a
Osttiroler A-1000	79.4a	102.9a	89.2a	4.73a	1,579ab	1,890a	75.7a	6.4cd	9.2bc	934a
Meadows 8 inch	74.4cd	89.8bc	81.5bcd	3.03b	1,545ab	1,898a	73.8b	6.9cd	9.4bc	922a
Country Living Mill	76.7b	92.1b	84.7b	3.05b	1,069c	1,825a	74.2b	11.2b	9.0c	899ab
Wonder Mill	73.5cd	88.0cd	81.3cd	2.50c	1,435b	1,895a	72.7c	8.0bcd	10.0abc	918a
Perten 3100	72.7cd	87.5cd	80.8cd	2.48c	1,607ab	1,978a	72.5cd	6.2d	10.3abc	944a
Hawos Mill #1	74.5c	85.2d	90.1a	1.75d	425.1d	1,258b	71.7de	14.7a	11.2a	859b
SAMAP F100	74.1cd	88.4cd	84.0bc	2.75bc	1,073c	1,833a	73.4bc	9.7bc	9.2bc	911a
Variety*mill means										
Red Fife										
Brabender roller	66.9f	82.9ef	73.3i	2.25ef	1,345c	1,818a	67.9h	3.3g	3.2g	926ab
Osttiroler A-1000	73.3d	94.4bc	82.1efg	3.90b	1,259cd	1,749a	72.0f	3.8fg	2.9g	921abc
Meadows 8 inch	68.8ef	81.4f	74.6hi	2.30def	1,215cd	1,818a	69.8g	3.8fg	3.2g	912abc
Country Living Mill	71.4de	88.1de	78.1ghi	2.75cde	1,068cd	1,765a	70.0g	5.1defg	4.4g	910abc
Wonder Mill	68.4ef	81.9f	75.5hi	2.25ef	1,171cd	1,799a	68.9gh	4.2efg	3.8g	883abc
Perten 3100	66.7f	78.7f	73.5i	1.85fg	1,248cd	1,848a	68.9gh	3.1g	3.2g	930ab
Hawos Mill #1	70.3de	79.4f	79.3fgh	1.35g	436.0e	1,227b	66.3i	11.2cde	10.2f	848c
SAMAP F100	69.9def	81.5f	73.3i	2.40def	978.8d	1,745a	69.0gh	4.4efg	4.1g	895abc

(Continues)

TABLE 5 (Continued)

	Water SRC	Carbonate SRC	Lactic acid SRC	Starch damage (%)	RVA peak viscosity (cP)	RVA final viscosity (cP)	Farinograph water absorption (%)	Farinograph development time (min)	Farinograph stability (min)	Sourdough loaf volume (ml)
Joaquin Oro										
Brabender roller	77.8c	98.2b	84.2def	3.33bc	2,086a	2,077a	74.7e	13.6abc	18.2a	955a
Osttiroler A-1000	85.5a	111.5a	96.4ab	5.55a	1,900ab	2,032a	79.3a	9.0cdef	15.5bcd	946ab
Meadows 8 inch	80.0bc	98.3b	88.4cd	3.75b	1,875ab	1,979a	77.8abc	10.0bcd	15.6abcd	931ab
Country Living Mill	82.1ab	96.2bc	91.3bc	3.35bc	1,071cd	1,887a	78.3ab	17.4a	13.6de	889abc
Wonder Mill	78.6c	94.2bc	87.1cde	2.75cde	1,699b	1,992a	76.5cd	11.9bc	16.3abc	954a
Perten 3100	78.8bc	96.4bc	88.2cd	3.10bcd	1,967ab	2,109a	76.2de	9.3cde	17.4ab	959a
Hawos Mill #1	78.6c	91.1cd	100.9a	2.15efg	414.3e	1,288b	77.1bcd	18.3a	12.2ef	870bc
SAMAP F100	78.4c	95.2bc	94.8b	3.10bcd	1,166cd	1,921a	77.7bc	15.0ab	14.3cde	926ab

SRC, solvent retention capacity.

*Significant at $p \leq .01$.

NS: not significant $p > .01$.

Values followed by the same letter within each section in a column are not significantly different based on Student's *T* test for the varietal comparison and Tukey's HSD for the mill and variety × mill comparisons.

considered that this was related to the abnormally long Farinograph stability of the Red Fife whole-wheat flour milled on the Hawos mill (Table 5). When this mill was removed from the analysis (data not shown), the vector of Farinograph stability for Red Fife was also correlated negatively to the median particle size vector, as for Joaquin Oro.

For all the mills, the replicated mill runs were clustered together with the exception of the replicated milling of Red Fife on the Country Living mill (Figure 4a). We speculate that the geometry of the Country Living disk mill makes it more difficult to readjust after being de-adjusted between replicates (see Section 2). The mills showed characteristic signatures in PCA. The Osttiroler mill was primarily characterized by high starch damage, high water and carbonate SRCs, and high Farinograph absorption. However, the level of starch damage from the Osttiroler (5.6% and 3.9% for Joaquin Oro and Red Fife, respectively) was not considered excessive, and was similar to the level of starch damage measured in the Grain Craft commercial stone-milled whole-wheat flour (5.1%). The Hawos mill was unsurprisingly characterized by high median particle size and lower LVOL. The Country Living, SAMAP, Wonder, and Meadows mills were generally clustered toward the center of the PC plots showing few extremes, at least in comparison with the other mills in the study.

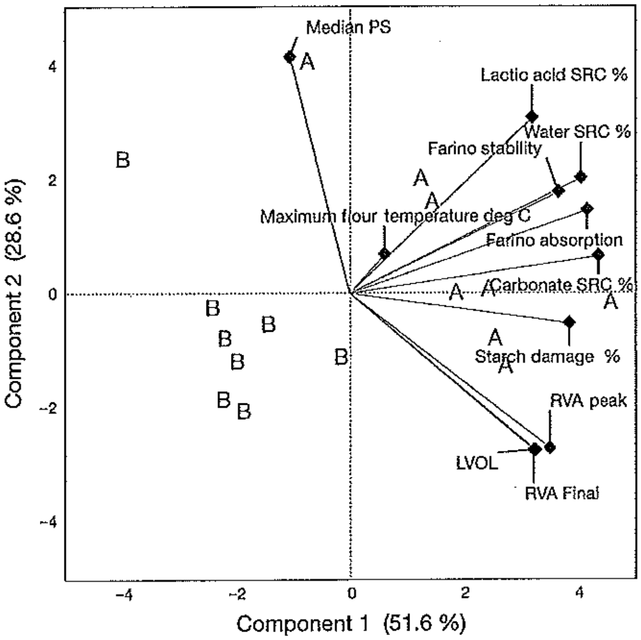

FIGURE 3 Mean-centered and scaled principal component biplots for key flour functionality traits. Varieties are plotted on the trait vectors. A: Joaquin Oro. B: Red Fife

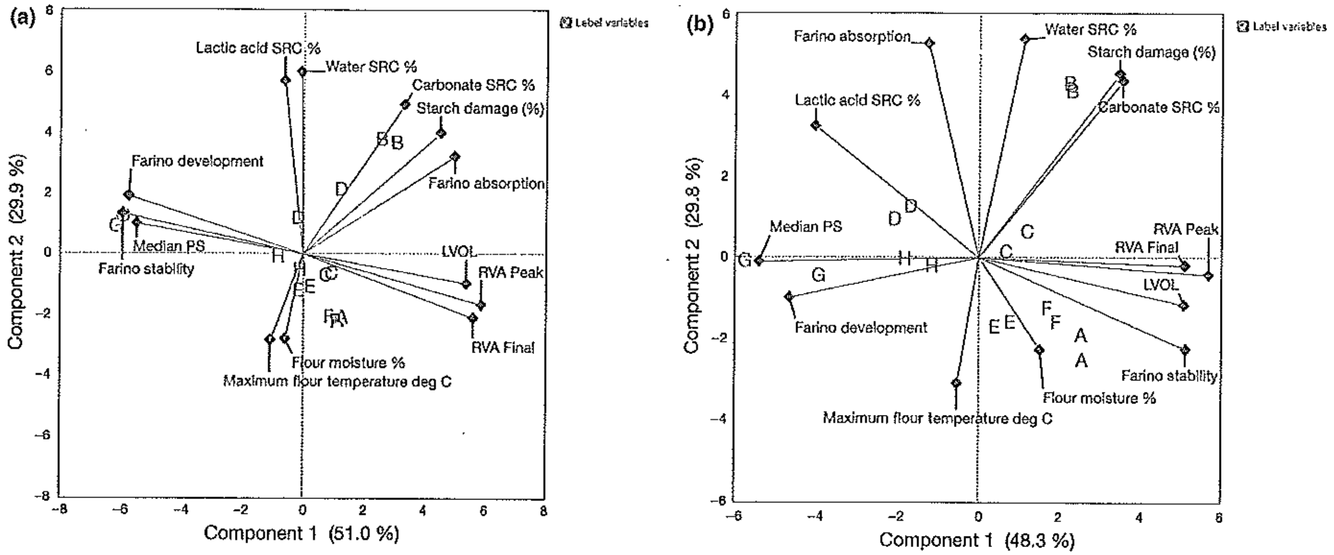

FIGURE 4 Mean-centered and scaled principal component biplots for key flour functionality traits replotted for each variety individually. (a) Red Fife. (b) Joaquin Oro. Mills are plotted on the trait vectors. A: Brabender roller mill; B: Osttiroler; C: Meadows; D: Country Living; E: Wonder; F: P3100; G: Hawos; H: SAMAP

4 | CONCLUSIONS

Two hard-red wheats of different hardness and dough characteristics were milled on eight different flour mills. In general, there were significant differences between the two tested varieties for grain, flour, and end-product quality. In general, varietal differences dominated the two-way ANOVA analyses (Tables 3–5) and the PCA on all data (Figure 3). For a majority of the measured grain, flour, and end-product parameters, the mill used to produce the flour also had significant effects on flour characteristics. There were also some significant variety × mill interactions, although in general the effect sizes of the interaction terms were 1–3 orders of magnitude smaller than the variety effects, and 0–2 orders smaller than the mill effect. The notable exception was the interaction term for Farinograph stability.

A number of traits were particularly influenced by changes in whole-wheat flour particle size. These traits were RVA peak and final viscosities, Farinograph development time and stability, and LVOL (Table 5, Figure 4). However, in our experience, all LVOLs were acceptable (Table 5) and we speculate that home millers/bakers could be happy with the flour produced by any of the small-scale mills tested here. For carbonate SRC, when milling Joaquin Oro (Figure 4b), larger median particle size was associated with lower carbonate SRC. This contradicts the findings of Liu, Hou, Lee, Marquart, and Dubat (2016) who saw an association between lower absorption and smaller particle size in whole-wheat flours. For Red Fife (Figure 4a), PCA showed that median particle size was effectively orthogonal to both water and carbonate SRCs, suggesting no impact of particle size on these parameters.

It could be argued that the best flour quality was produced by the three mills producing the finest whole-wheat flour median particle sizes (Figure 2: Brabender roller, Osttiroler, and P3100 Hammer mills). Of these three, adjudicated on multiple facets of flour quality, the superior flour came from the larger Osttiroler stone mill despite this single-stream flour being virtually indistinguishable from the reconstituted Brabender roller mill flour for particle size distribution for the variety Red Fife (Figure 4a) and slightly coarser than the reconstituted Brabender roller mill flour for the variety Joaquin Oro (Figure 4b). For both varieties, the Osttiroler mill gave whole-wheat flours with levels of starch damage similar to the Grain Craft commercial hard-red whole-wheat flour, and with desirably higher levels of water absorption (water and carbonate SRCs, Farinograph absorption: Table 5, Figure 4) than all the other, smaller, mills. It was somewhat surprising that the whole-wheat flour from this mill did not show its superiority in LVOL compared to the other mills, although in LVOL it ranked second to the flour from the P3100 Hammer mill for both varieties (Table 5). Other baking techniques may have made the difference more evident, as may have done an examination of loaf texture and staling characteristics in the baking method employed here.

We concluded that the heat generated during the process was not the only, and maybe not the best, index of the severity of grinding. We consider that the fineness of flour, the level of starch damage produced, and the maximum flour temperature to all be independent indices of severity of grinding. For example, the Osttiroler mill had the highest levels of damaged starch (Table 5) but had the equally coolest maximum flour temperature. (Table 4). Additionally, maximum flour temperature was not associated at all with baking performance, suggesting, up to the temperatures generated by the mills used in this study (Table 4), that there was no detrimental effect on the functionality of the gluten proteins. We did not assess how maximum flour temperature may impact storage stability and nutritional quality. Of our three hypotheses: (1) that flour temperature is an index of milling severity; (2) that high-speed mills will create greater levels of starch damage; and (3) that flours with smaller median particle sizes will have better baking performance, only the third hypothesis was supported by our data.

ACKNOWLEDGMENTS

We would like to acknowledge the contributions to the background research by these Oregon State University graduate students in the FST641 Cereals course: Christina D. Hahn, Clara A. Hintermeister, Christy A. McCarthy, Joseph Minarsich, Franziska Rupp, Jordan L. Smith, Susanne Trittinger, and Katrina J. Donovan and by undergraduate Honors student Victoria E. Jansen. We also acknowledge the cooperation of Nana and Chris Kohler of Grist and Toll Milling for the mill runs on the Osttiroler mill and the sourcing and cleaning of the grain. Funding was in part provided by both Royalty Funds from seed sales of Oregon State University wheat varieties and by formula grant no. 2009-31100-06041 from the United States Department of Agriculture National Institutes of Food and Agriculture.

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