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Comparative analyses of technological performance of multigrain milling with two experimental roller mills

I. Aprodu, G. Blaga and I. Banu[*]

Dunarea de Jos University of Galati, Faculty of Food Science and Engineering, Domnească Street 111, 800201 Galati, Romania; iuliana.banu@ugal.ro

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RESEARCH ARTICLE

Abstract

The multigrain blends of wheat and different levels of rye and hulled barley were milled with two experimental roller mills. The milling performance of the blends, estimated based on yield, ash and granularity of resulting flours, depended on the number of roller breaks and on the presence of the reduction rolls. Important differences were registered in terms of fibre content in the milling products. Significant negative correlation between bran extraction and fibre content was registered (Pearson r of -0.88, $P<0.05$), as well as between flour extraction and fibre content (-0.98, $P<0.05$), while in case of the short extraction and fibre content a significant positive correlation was found (Pearson r of 0.92, $P<0.05$). The solvent retention capacity profiles of the flours were influenced by the particle size. The retention of sodium carbonate was higher in case of flours resulted when the mill had higher number of technological passages. The number of milling passages influenced the water absorption and thermo-mechanical behaviour of the dough, mainly due to the differences in starch damage and small quantity of fine bran particles rich in α-amylase. The increase of the number of technological passages at milling resulted in the decrease of the torque values that define starch behaviour during heating (C3 decreased from 2.42-2.59 Nm to 2.01-2.27 Nm and C4 from 2.11-2.49 to 1.83-1.97 Nm) and cooling (C5 decreased from 3.52-3.82 Nm to 2.84-3.11 Nm). In addition to rheological properties of the dough, the type of experimental mill influenced quality of the bread.

Keywords: roller mill, multigrain, solvent retention capacity, thermo-mechanical properties

1. Introduction

Milling is a physical process consisting in cereals fragmentation, such as to obtain the separation of the endosperm into flour and the outer layers as bran. The most complex milling process is the one based on the use of a roller mill. In this case, a gradual separation of the endosperm from bran layers by the break rolls takes place, followed by a gradual reduction of the chunks of endosperm into flour by the reduction rolls. Over the successions of grinding and reduction passages result several mill streams with different composition and functional properties. The complexity of milling diagram (Doehlert and Moore, 1997; Flores *et al.*, 2005) and tempering process (Aprodu *et al.*, 2017; Dennett and Trethowan, 2012; Kiryluk *et al.*, 2000; Moza and Gujral, 2017) on the one hand, and the type of cereal with particular morphological and technological properties on the other hand, influence the quality and quantity of the mill streams. Wheat, rye, triticale, hulled oat and hulled barley are cereals that can be processed through roller milling, with varying milling yield (Aprodu and Banu, 2017; Dennett and Trethowan, 2012). Rye displays similar milling behaviour and milling performance to wheat (Verwimp *et al.*, 2006), while triticale, due to its particular grain texture but also grain size, has poor milling performance (Dennett and Trethowan, 2012). Regarding hulled oat and hulled barley milled with roller milling, the yields of the resulted refined flours appear to be significantly affected by the tempering process (Doehlert and Moore, 1997; Moza and Gujral, 2017). At the same time, experimental milling design and tempering conditions can be used for modulating the β-glucans content in bran and short (Doehlert and Moore, 1997; Flores *et al.*, 2005). Finally, the type of milling can influence the characteristics of the flours. An alternative to the separate milling of different grains, followed by blending the milling fractions to get the composite flours, is the less studied multigrain milling which involves direct processing of the blends of grains. In this study the multigrain blends of wheat, rye and hulled barley were milled with two different experimental mills with roller, and a comparative analysis of the technological performance of multigrain milling was carried out. In addition to the milling efficiency, the physical chemical, functional, thermo-mechanical and bread making properties of the flours were investigated.

2. Materials and methods

Materials

Wheat (Boema variety; 13.4% protein, 2.1% fat, 1.65% ash) and rye (Suceveana variety; 9.8% protein, 1.8% fat, 1.75% ash) grown in South East Romanian Plain, harvested in 2016, and hulled barley (11.2% protein, 3.3% fat, 1.28% ash) purchased from a specialised market (BioLogistic, Timişoara, Romania) were used in the experiment to prepare the multigrain blends.

Methods

Multigrain milling

In order to prepare the multigrain blends, each cereal was separately cleaned and tempered to raise the moisture content up to 15% in case of wheat and hulled barley, and up to 14% in case of rye. The conditioning process for wheat and hulled barley was accomplished in two stages, according the procedure described by Aprodu and Banu (2017). In short, the moisture content desired for each cereal was obtained through the following steps: about 2/3 of the total water was added in the first stage of tempering, whereas the rest of water was sprayed onto cereals after 8 hours of tempering at room temperature. The rye conditioning was realised in one stage with a tempering time of 8 h. After an additional tempering stage of 4 h the cereals were blended and finally milled. The multigrain blends were prepared by mixing the wheat, rye and hulled barley in the ratio of 80:10:10 (80W+10R+10B), 70:15:15 (70W+15R+15B) and 60:20:20 (60W+20R+20B). The wheat sample (100W) was used as control.

Two experimental mills were used for milling the multigrain blends: Buhler laboratory mill MLU (Buhler, Uzwil, Switzerland) and laboratory four-roller mill, type SK (Sadkiewicz Instruments, Bydgoszcz, Poland). Technical parameters of the two experimental mills are presented in Table 1. When using the MLU mill, which consists of three breaks rolls (BK1, BK2 and BK3) and three reduction rolls (C1, C2, C3), eight mill streams were collected as follows: six flour streams that were blended in order to form one type of flour, one bran stream and one short stream (Supplementary Figure S1Al). The SK mill consists of four rollers that realise two successive grinding steps. The milled products collected from the SK laboratory four-roller mill were further successively passed through sieves of 630 and 500 μm mesh (Supplementary Figure S1B). The mill stream retained on the 630 μm mesh formed the bran, the stream with particles size between 630 and 500 μm formed the short, and the stream sieved through 500 μm mesh formed the flour.

Table 1. Technical parameters of the experimental mills.

Type of mill	Technical parameters
Buhler laboratory mill MLU	Roller dimensions: diameter 130 mm, width 40, 90 and 70 mm in case of BK1 and C3, BK2 and C1, and BK3 and C2, respectively Roller flutes of breaks rolls: 7, 8, 9.5 per cm Roller speed: 934 rpm Sifter from break passages: two sieves with aperture size of 646 and 132 μm; Sifter from reduction passages: two sieves with aperture size of 180 and 132 μm
Laboratory four-roller mill SK	Roller dimensions: diameter 71 mm, width 30 mm Roller flutes: 5, 10, 14, 16 per cm Roller speeds: 980 rpm for rollers 1 and 3, 450 rpm for rollers 2 and 4

Chemical composition of multigrain flours, brans and shorts

The approximate composition of the multigrain flours, brans and shorts was determined as follows: moisture through SR ISO 712:2005 (ASRO, 2008), ash through SR ISO 2171:2002 (ASRO, 2008), protein with semimicro-Kjeldahl method (Raypa Trade, R Espinar, SL, Barcelona, Spain) according to SR 13013-3:1994 (ASRO, 2008), fat through Soxhlet extraction with ether (SER-148; VELP Scientifica, Usmate Velate, Italy) according to SR ISO 7302:2002 (ASRO, 2008), and crude fibre with Fibretherm Fibre Analyser (Gerhardt GmbH and Co. KG, Königswinter, Germany) (AACC International Method 32-10.01, 1999). The particles distribution of all flours was determined through sieving, using sieves with 315, 180, 125 and 90 μm mesh.

The Chroma Meter CR-410 (Konica Minolta Business Solutions Europe GmbH, Langenhagen, Germany) was used to determine the brightness value, L* (black – 0 to white – 100), redness value, a* (green (-) to red (+)) and yellowness value b* (blue (-) to yellow (+)) of the multigrain flours, brans and shorts.

Solvent retention capacity tests

Solvent retention capacity (SRC) profiles of the investigated multigrain flours were established based on AACC Method 56-11.02. The retention of the following solvents under centrifugation conditions was independently tested for each multigrain flour: water (W-SRC), 50% sucrose (S-SRC), 5% sodium carbonate (SC-SRC), and 5% lactic acid (LA-SRC). The SRC values were calculated as:

$$\%\ \text{SRC} = \frac{\text{gel weight}}{\text{flour weight} - 1} \times \frac{86}{100 - \%\ \text{flour moisture}} \times 100 \quad (1)$$

Thermo-mechanical properties of multigrain flours

The thermo-mechanical properties of the multigrain flours were evaluated using Chopin+ protocol and Mixolab device (Chopin Technologies, Villeneuve La Garenne, France) (AACC Method 54-60, 1999).

The bread-making procedure

The bread samples were prepared using the one-stage method for dough preparation (Banu *et al.*, 2010). Flour (100%), water (according to the water absorption capacity determined with the Mixolab), salt (1.5%) and commercially available Pakmaya fresh yeast (*Saccharomyces cerevisiae*; 3%, in agreement with the recommendation of the producer Rompak SRL (Pascani, Romania) were mixed in order to prepare the dough in a laboratory mixing device (HR7915; Philips, Shanghai, China P.R.). The dough was fermented at 30 °C for 150 min, then divided in two pieces, moulded and placed in baking trays. After a final leavening of 30 min, the trays were introduced into the oven (Micro 4T, Mondial Forni, Verona, Italy). The samples were baked at 230 °C for 30 min.

Bread analysis

The bread samples were characterised in terms of specific volume and crumb firmness. The specific volume of breads was determined by rapeseed displacement method SR 91/2007 (ASRO, 2008). Crumb firmness was measured with MLFTA apparatus (Guss, Strand, South Africa) using a probe with diameter of 7.9 mm. Three individual measurements were performed on two bread slices from the centre of each sample. The following parameters were selected for measuring crumb firmness: bread slices penetration wide of 25 mm, test speed of 5 mm/s, and trigger threshold force of 1.96 N.

Statistical analysis

The experiments were carried out in triplicate and the results are reported as mean values together with standard deviation. The analysis of variance was used to identify significant differences between results. The statistical relationships were determined by calculating Pearson's correlation coefficients. In addition, the Tukey test was used for post-hoc analysis. The statistical analysis of the results was performed with Microsoft Excel Software (Redmond, WA, USA).

3. Results and discussion

Multigrain milling

The extraction of flours, brans and shorts obtained by milling the control samples consisting of wheat (100%) and multigrain blends, using the experimental procedures describe above, is shown in Figure 1A, while the cumulative yield is presented in Figure 2.

Comparing the milling products delivered by the two types of mills, one can see that the Buhler MLU mill provided higher flour and short amounts than the SK mill (Figure 1A). Regardless of the investigated sample, similar amounts of shorts were produced when milling with the SK mill, while in case of milling with the Buhler MLU the bran amounts are similar for all samples (Figure 1A). The three break rolls of the Buhler MLU realised a more efficient gradual scraping of the endosperm out of the bran layers compared to the two successive grinding steps from SK mill. Therefore, higher amounts of bran and lower amounts of flour were obtained in case of milling the cereal samples with the SK mill compared to the Buhler MLU. Regardless of the mill type, the increase of rye and barley levels within the blends resulted in a decrease of flour amounts. The variation of the flour extraction rate by increasing the level of wheat substitution with rye and hulled barley was lower when milling with the SK mill compared to the Buhler MLU. In addition, the particle size of the flours produced by the SK mill is higher compared to the flours produced by the Buhler MLU (Figure 1B). The particles with size ranging from 90 to 125 μm prevailed in the flours collected from Buhler MLU, while in case of the flours from SK mill the number of particles with size over 315 μm was the highest. In case of blends with 20% hulled barley addition, the number of particles with size over 315 μm was very close for the two experimental mills considered in the experiment (Figure 1B).

The SK mill generated shorts with lower ash contents than the Buhler MLU, probably because of the break rolls scraping out large parts from the outer endosperm along with the outer layers, which are separated into bran through sieving. Moreover, there is a high adherence in the crease zone of the barley kernel between endosperm and aleurone layers, which most probably end up into the bran (Aprodu and Banu, 2017; Evers and Millart, 2002). In these conditions, there is a higher difference in terms of ash content between short and bran streams in case of SK milling compared to the Buhler MLU. The ash content appears to increase with

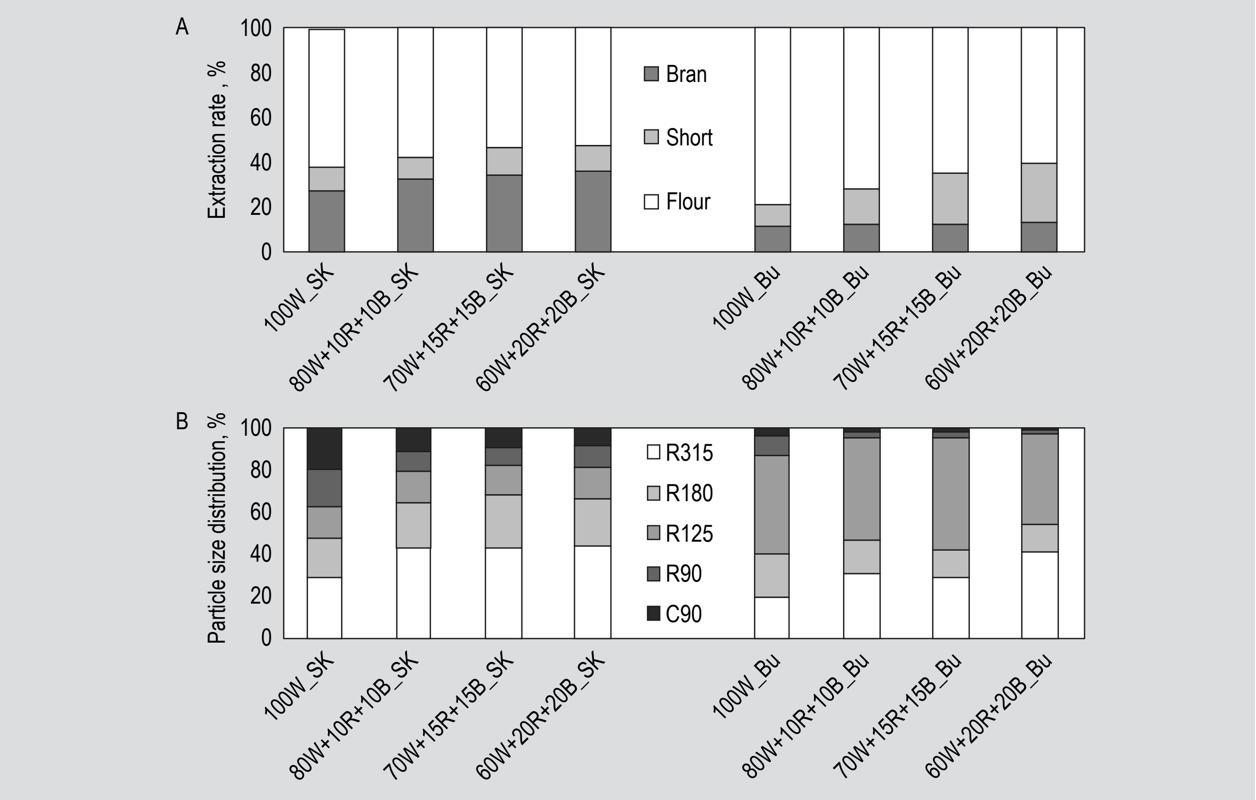

Figure 1. The extractions of flour, bran and short of wheat and multigrain milling (A) and the particle size distribution of wheat and multigrain flours (B).

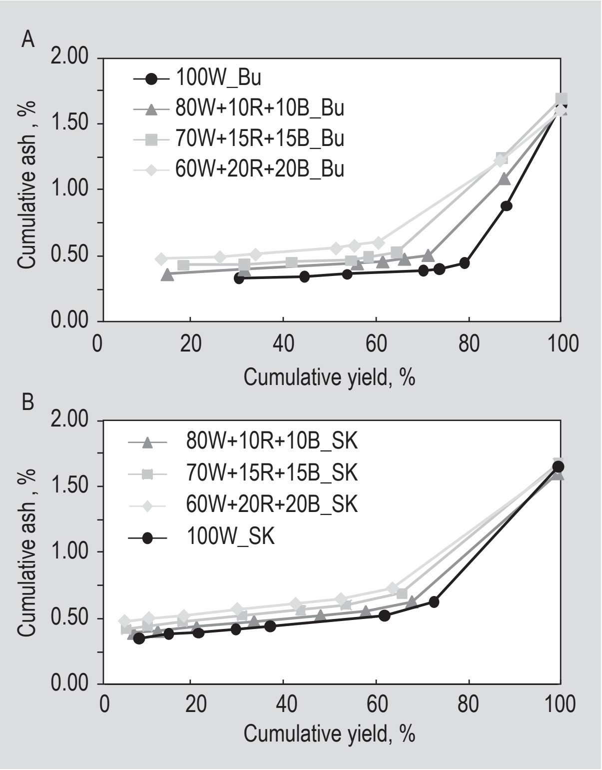

Figure 2. The cumulative yield of wheat and multigrain milling with (A) Buhler laboratory mill and (B) laboratory four-roller mill type SK.

the dimensions of the flour particles. Analysing the results presented in Figure 2, one can see that the SK mill streams used to obtain the flour (corresponding to the first six points of each representation in Figure 2) had a higher increase of the ash content (up to 0.52% for the wheat flour, and up to 0.65% for the flour resulting from multigrain blends with 20% hulled barley) with increasing the extraction (from 0 to 52% for the multigrain blends with 20% hulled barley, and to 62% for the wheat flour), compared to the Buhler MLU, when the ash content increased up to 0.44% and 0.60%, respectively, and flour extraction increased from 0 to 61% and 79%, respectively.

The brightness (L*), redness (a*) and yellowness (b*) values for flours, shorts and brans obtained through multigrain millings are presented in Table 2. The increase of the rye and hulled barley level within the multigrain blends caused the decrease of the L* value in case of flours produced with both experimental mills. A direct correlation was found between L* values and ash content of flours (-0.84, $P<0.05$). Additionally, the flours produced by the Buhler MLU had higher L* values, compared to the flours produced by the SK mill. The differences in terms of L* value between flours produced with the two different mills can be explained by the variation in the particles size of each flour. In particular, a significant correlation (0.87, $P<0.05$) was established between the amounts of particles with size lower than 125

Table 2. The brightness value (L*), redness value (a*) and yellowness value (b*) of flours, shorts and brans obtained through multigrain millings.[1]

Multigrain samples[2]	L*	a*	b*
Flours			
100W_SK	92.51±0.23^{a}	-0.26±0.01^{a}	10.73±0.12^{a}
80W+10R+10B_SK	91.63±0.21^{b}	-0.16±0.01^{b}	9.94±0.15^{b}
70W+15R+15B_SK	91.48±0.21^{c}	-0.33±0.01^{c}	9.54±0.15^{c}
60W+20R+20B_SK	90.01±0.14^{d}	-0.14±0.01^{d}	9.69±0.15^{d}
100W_Bu	94.91±0.18^{e}	-0.53±0.01^{e}	8.98±0.08^{e}
80W+10R+10B_Bu	93.76±0.21^{f}	-0.37±0.01^{f}	8.87±0.11^{f}
70W+15R+15B_Bu	93.23±0.21^{g}	-0.41±0.01^{g}	9.07±0.13^{abcdg}
60W+20R+20B_Bu	92.77±0.14^{h}	-0.41±0.01^{h}	8.84±0.11^{h}
Shorts			
100W_SK	75.33±0.20^{a}	4.70±0.01^{a}	15.17±0.11^{a}
80W+10R+10B_SK	81.58±0.14^{b}	2.14±0.00^{b}	13.23±0.07^{b}
70W+15R+15B_SK	83.07±0.11^{c}	1.66±0.02^{c}	12.81±0.07^{c}
60W+20R+20B_SK	85.33±0.14^{d}	1.41±0002^{d}	12.20±0.14^{d}
100W_Bu	72.57±0.12^{e}	5.32±0.01^{e}	15.56±0.15^{e}
80W+10R+10B_Bu	73.86±0.14^{f}	4.29±0.01^{f}	13.92±0.14^{f}
70W+15R+15B_Bu	72.93±0.21^{g}	4.41±0.01^{g}	14.18±0.14^{g}
60W+20R+20B_Bu	73.24±0.21^{h}	3.85±0.01^{h}	13.69±0.14^{h}
Brans			
100W_SK	65.53±0.12^{a}	6.89±0.01^{a}	15.43±0.18^{a}
80W+10R+10B_SK	66.54±0.11^{b}	6.68±0.02^{b}	16.66±0.21^{b}
70W+15R+15B_SK	67.20±0.14^{c}	5.33±0.01^{c}	14.96±0.14^{c}
60W+20R+20B_SK	69.25±0.21^{d}	5.08±0.01^{d}	14.15±0.14^{d}
100W_Bu	63.82±0.18^{e}	7.32±0.01^{e}	18.15±0.12^{e}
80W+10R+10B_Bu	64.62±0.21^{f}	6.48±0.02^{f}	16.27±0.21^{f}
70W+15R+15B_Bu	65.37±0.14^{g}	5.96±0.02^{g}	16.07±0.21^{h}
60W+20R+20B_Bu	66.42±0.14^{h}	5.57±0.02^{h}	15.08±0.14^{h}

[1] The values are mean ± standard deviation. Values followed by the same superscript, within flour, short and bran group of results, are significantly different ($P<0.05$).

[2] Multigrain samples given as percentages. W = wheat, R = rye, B = hulled barley; Bu = Buhler MLU mill; SK = SK mill.

µm, that varied from 35.2 to 33.4% in case of flours resulted from SK mill, and from 52.9 to 46% in case of flours resulted from Buhler MLU, and L* values.

The most important differences were registered for the shorts, the products provided by the SK mill having higher L* values (ranging between 81.58 and 85.33) compared to the products delivered by the Buhler MLU (ranging between 72.93 and 73.86). The low L* values obtained for shorts resulting from the Buhler MLU could be explained by the presence of endosperm parts refused when sieving through 315 µm mesh. The b* values of brans and shorts were higher in case of the products from the Buhler MLB. Regardless of the type of mill used in the experiment, increasing the levels of rye and hulled barley resulted in the decrease of b* values (Table 2). Finally, the brans and shorts produced with the Buhler MLU had higher a* values compared to the corresponding products delivered by the SK mill. Flores *et al.* (2005) reported that a* value is significantly influenced by milling method and barley type and variety.

Chemical composition of multigrain flours, brans and shorts

The protein content of the multigrain flours was not influenced by the type of experimental mill. The protein content varied from 9.08-9.12% in case of flour samples obtained from blends with 10% rye and hulled barley, to 8.82-8.85% for samples with 20% rye and hulled barley (Table 3). Regardless of the type of mill used in the experiment, the increase of the hulled barley level within the cereal blends resulted in an increase of ash and fat contents in the multigrain flours. Higher ash and fat contents were obtained for the multigrain flours generated by the SK mill. The type of experimental mill had a significant influence on the fibre content of the milling products – flour, short and bran. In case of both experimental mills, significantly higher fibre contents were found in brans compared to the shorts and flours (Table 3). When comparing the fibre contents of brans and shorts generated by the two types of mill used in the experiment, higher differences could be observed within the products resulted from the SK mill. Analysing the milling results presented in Figure 1, one can see that the shorts collected from the Buhler MLU were formed by streams from the 61-79% to 87-88% extraction zone, while in case of the SK mill the shorts were formed by streams corresponding to the 52-62% to 64-75% extraction zone. According to our results, a significant negative correlation was registered between bran extraction and fibre content (-0.88, $P<0.05$), as well as between flour extraction and fibre content (-0.98, $P<0.05$), while in case of short extraction and fibre content the correlation was significant positive (0.92, $P<0.05$). When milling the multigrain blends of wheat-green gram-barley using a Buhler roller mill, Tulse *et al.* (2014) reported higher fibre contents for coarse bran than for fine bran. The increase of the rye and hulled barley levels resulted in the decrease of the fibre content in brans and the increase in shorts and flours (Table 3). This trend might be due to the particular distribution of different anatomical components of rye and barley kernels in bran, short and flour fractions. When investigating the fate of dietary fibres at whole grain rye milling, Glitsot and Bach Knudsen (1999) showed that the pericarp/testa had about 73.3 g/100 g d.w. dietary fibre, while the aleurone layer and endosperm had about 28.3 and 6.5 g/100 g d.w., respectively. Fastnaught (2001) reported the concentration of the fibre content in the bran and short products obtained through roller milling the barley; the fibre content of the bran was 1.29 to 2.66 times higher with respect to the whole grain, while for short and flour the fibre content was 1.44 to 1.38 and 0.30 to 0.38 times higher, respectively.

Table 3. Chemical composition of multigrain products.[1]

Multigrain samples[2]	Ash, % d.w.	Protein, % d.w.	Fat, % d.w.	Fibre content, % d.w.		
	Flour	Flour	Flour	Bran	Short	Flour
100W_SK	0.44±0.01^{a}	9.94±0.10^{ab}	1.11±0.02^{bc}	7.46±0.34^{acd}	8.13±0.14^{abcde}	1.13±0.14^{bde}
80W+10R+10B_SK	0.55±0.01^{a}	9.08±0.10^{ab}	1.16±0.03^{bc}	8.08±0.37^{acd}	1.36±0.17^{abcde}	1.64±0.14^{bde}
70W+15R+15B_SK	0.60±0.01^{a}	9.06±0.07^{ab}	1.44±0.04^{bc}	7.13±0.28^{acd}	1.67±0.24^{abcde}	1.98±0.21^{bde}
60W+20R+20B_SK	0.65±0.01^{a}	8.82±0.06^{ab}	1.53±0.04^{bc}	6.14±0.34^{acd}	3.20±0.33^{abcde}	2.09±0.21^{bde}
100W_Bu	0.43±0.01^{a}	9.61±0.07^{ab}	1.07±0.03^{bc}	16.45±0.26^{acd}	8.07±0.24^{abcde}	1.17±0.14^{bde}
80W+10R+10B_Bu	0.50±0.01^{a}	9.12±0.07^{ab}	1.09±0.03^{bc}	14.22±0.56^{acd}	7.18±0.24^{abcde}	1.08±0.14^{bde}
70W+15R+15B_Bu	0.53±0.01^{a}	9.11±0.07^{ab}	1.24±0.05^{bc}	10.59±0.37^{acd}	6.11±0.14^{abcde}	1.53±0.21^{bde}
60W+20R+20B_Bu	0.60±0.02^{a}	8.85±0.11^{ab}	1.42±0.07^{bc}	10.11±0.28^{acd}	5.70±0.34^{abcde}	1.64±0.21^{bde}

[1] The values are mean ± standard deviation. Values followed by the same superscript, within flour, short and bran group of results, are significantly different ($P<0.05$). d.w. = dry weight basis.

[2] Multigrain samples given as percentages. W = wheat, R = rye, B = hulled barley; Bu = Buhler MLU mill; SK = SK mill.

Solvent retention capacity tests

The individual contribution of different components of the multigrain flours to their functional properties was estimated by determining the solvent retention capacity profiles (Table 4). According to Kweon *et al.* (2011), SC-SRC is related to the level of damaged starch, LA-SRC is a measure of gluten quality and functionality, S-SRC is mainly associated with solvent-accessible pentosans, while W-SRC gives an indication about the overall contribution of all constituents.

Increased addition of rye and hulled barley in the blends increased the W-SRC, SC-SRC and S-SRC, and decreased the LA-SRC. The evolution of S-SRC values is mainly determined by the contribution of arabinoxylans, which come from rye and barley present in the blends (Drakos *et al.*, 2017), while the evolution of LA-SRC can be explained by the dilution effect of gluten proteins (Collar and Angioloni, 2014). Concerning the influence of the type of experimental mill on the SRC profiles, one can see from Table 4 that the flours delivered by the Buhler MLU had higher values of SRC compared to the flours resulted from the SK mill. An important difference between the flours obtained from grain blends with similar amounts of rye and hulled barley, and processed through the two experimental mills, consists on the particle size distribution. These differences are generated by the way the flours are formed, particularly by the number of break rolls and the presence of reduction passages. According to Gomez *et al.* (2009) the streams produced in the break rolls suffer a decrease of particle size on the reduction passages, and as far as the distance between rollers decrease, the damaged starch and fibre contents increase. In our study, the flours delivered by the Buhler MLU had higher percentages of particles with size ranging from 125 to 180 μm, while the flours from the SK mill had higher percentages of particles with size lower than 90 μm. The lower sized particles (<90 μm) resulted from the two break rolls and contained starch endosperm with less damaged starch and pentosans, while the particles with size from 125 to 180 μm delivered by the Buhler MLU resulted from both break rolls and reduction rolls and contained more damaged starch and pentosans. As a consequence, W-SRC and S-SRC of flours from the Buhler MLU were higher than those from the SK mill. Moreover, significant negative correlations were found between the particles with size lower than 125 μm and W-SRC -0.84 ($P<0.05$) or S-SRC -0.83 ($P<0.05$). A similar observation was reported by Guttieri *et al.* (2011) when studying the influence of experimental milling systems with short and long flow on SRC of wheat flours. In the same study, Guttieri *et al.* (2011) found higher SC-SRC values for flours resulting from a long-flow system compared to a short-flow system. In agreement with Guttieri *et al.* (2011), our results indicated higher SC-SRC values for flours obtained from the Buhler MLU. Regarding the trend registered in LA-SRC values (Table 4), one should take into account that, in case of milling on the SK mill, the particles of wheat endosperm and high amounts of gluten get to be refused into the shorts based on their size, while in case of the Buhler MLU the same particles have small size and are passed to the flour.

Thermo-mechanical properties of multigrain flours

The rheological behaviour of the doughs prepared with multigrain flours determined with Mixolab device is presented in Supplementary Figure S2. The main thermo-mechanical properties registered using Chopin+ protocol are shown in Table 4. As expected, higher WA values were obtained for the multigrain samples with increasing

Table 4. Solvent retention capacity profiles and thermo-mechanical properties of the multigrain flours.[1,2]

Multigrain flours	Solvent retention capacity			
	W-SRC, %	SC-SRC, %	LA-SRC, %	S-SRC, %
100W_SK	62.41±0.14^{a}	80.01±0.48^{a}	78.41±0.57^{ab}	78.15±0.17^{b}
80W+10R+10B_SK	66.10±0.14^{a}	95.01±0.64^{a}	85.74±0.12^{ab}	76.16±0.17^{b}
70W+15R+15B_SK	72.46±0.12^{a}	96.42±0.57^{a}	82.99±0.12^{ab}	85.59±0.21^{b}
60W+20R+20B_SK	73.10±0.15^{a}	99.26±0.61^{a}	79.48±0.17^{ab}	95.84±0.14^{b}
100W_Bu	73.17±0.14^{a}	95.64±0.67^{a}	93.27±0.14^{ab}	95.84±0.14^{b}
80W+10R+10B_Bu	74.94±0.21^{a}	96.81±0.57^{a}	87.47±0.21^{ab}	94.91±0.21^{b}
70W+15R+15B_Bu	76.45±0.21^{a}	98.82±0.61^{a}	84.29±0.21^{ab}	95.68±0.21^{b}
60W+20R+20B_Bu	77.29±0.14^{a}	101.31±0.69^{a}	81.50±0.14^{ab}	97.28±0.14^{b}

Multigrain flours	Thermo-mechanical properties					
	WA, %	C2, Nm	C3, Nm	C4, Nm	C5, Nm	S, min
100W_SK	57.7±0.01^{a}	0.56±0.012^{ab}	2.42±0.01^{ab}	2.11±0.00^{abc}	3.82±0.01^{abd}	9.24±0.07^{abcd}
80W+10R+10B_SK	54.2±0.01^{a}	0.59±0.02^{ab}	2.63±0.01^{ab}	2.49±0.00^{abc}	3.82±0.01^{abd}	10.97±0.11^{abcd}
70W+15R+15B_SK	54.3±0.00^{a}	0.55±0.02^{ab}	2.59±0.02^{ab}	2.40±0.01^{abc}	3.63±0.02^{abd}	9.03±0.06^{abcd}
60W+20R+20B_SK	54.8±0.01^{a}	0.51±0.01^{ab}	2.46±0.02^{ab}	2.30±0.01^{abc}	3.52±0.02^{abd}	9.08±0.06^{abcd}
100W_Bu	59.6±0.01^{a}	0.44±0.01^{ab}	2.01±0.01^{ab}	1.83±0.00^{abc}	2.86±0.01^{abd}	2.88±0.07^{abcd}
80W+10R+10B_Bu	55.1±0.00^{a}	0.44±0.01^{ab}	2.27±0.01^{ab}	1.97±0.00^{abc}	3.11±0.01^{abd}	2.40±0.02^{abcd}
70W+15R+15B_Bu	55.4±0.01^{a}	0.41±0.01^{ab}	2.17±0.01^{ab}	1.96±0.00^{abc}	3.08±0.01^{abd}	3.00±0.02^{abcd}
60W+20R+20B_Bu	55.7±0.00^{a}	0.36±0.01^{ab}	2.03±0.01^{ab}	1.86±0.00^{abc}	2.84±0.01^{abd}	4.54±0.07^{abcd}

[1] The values are mean ± standard deviation. Values followed by the same superscript, within flour, short and bran group of results, are significantly different ($P<0.05$).

[2] Multigrain samples given as percentages. W = wheat, R = rye, B = hulled barley; Bu = Buhler MLU mill; SK = SK mill.

contents of rye and hulled barley because of the increase in fibre content (Table 3). Instead, lower WA values were obtained for the multigrain flours resulting from the SK mill, although they had higher fibre contents with respect to the corresponding flours produced with the Buhler MLU. This trend registered in the WA results might be due to the differences in the particle size distribution of the investigated flours; those generated by the SK mill having larger particle sizes. Moreover, the doughs prepared with flours delivered by the SK mill were more resistant to kneading; the dough stability was high, S ranging between 10.97 and 9.08 min, as well as the minimum torque, C2 values ranging between 0.59 and 0.51 Nm. The flours delivered by the Buhler MLU had lower C3 values than flours produced with the SK mill, most probably because of the higher content of damaged starch that is easier hydrolysed by α-amylase. In case of the flours delivered by both experimental mills, the C3 and C4 values decreased with an increase in added rye and barley in the cereal blends, and this is due the fact that rye and barley are known for having higher amylase activity than wheat (Dubat and Boinot, 2012).

The torque values that define starch behaviour during heating and cooling (C3, C4, C5) were higher in case of flours from the SK mill, compared to the flours from the Buhler MLU. Dubat and Boinot (2012) reported similar differences between flour produced with two experimental mills, suggesting that, in case of the low-flow mill, the increase of C3, C4 and C5 together with lower WA can be related to the lower content of damaged starch and additionally, to the lower amounts of fine bran particles rich in α-amylase.

Characteristics of bread

The baking test indicated significant differences between bread samples obtained out of the investigated multigrain flours (Table 5). Regardless of the type of experimental mill used to obtain the flours, increasing the levels of rye and hulled barley in the blends caused a significant decrease ($P<0.05$) in the specific volume of the bread samples, due to the gluten dilution effect, and consequently to the reduced retention of CO$_2$ gas (Sullivan *et al.*, 2011). Moreover, the firmness of the crumb increased with increasing substitution level of wheat by rye and hulled oat (Table 5).

Table 5. Specific volume and firmness of bread.[1,2]

Multigrain flours	Specific volume, cm^3	Firmness, g force
100W_SK	2.86±0.07^a	1,252.5±21.6^a
80W+10R+10B_SK	2.48±0.07^a	1,657.5±24.1^a
70W+15R+15B_SK	2.33±0.06^a	1,788.0±23.4^a
60W+20R+20B_SK	2.12±0.06^a	1,846.9±21.6^a
100W_Bu	2.99±0.07^b	1,179.8±19.6^b
80W+10R+10B_Bu	2.70±0.07^b	1,536.0±23.1^b
70W+15R+15B_Bu	2.54±0.06^b	1,638.8±19.8^b
60W+20R+20B_Bu	2.26±0.11^b	1,778.0±25.3^b

[1] The values are mean ± standard deviation. Values followed by the same superscript, within flour, short and bran group of results, are significantly different ($P<0.05$).

[2] Multigrain samples given as percentages. W = wheat, R = rye, B = hulled barley; Bu = Buhler MLU mill; SK = SK mill.

The breads prepared with flours produced with the Buhler MLU had higher specific volume and lower firmness compared with the bread samples prepared with equivalent flours produced with the SK mill. These results are in good agreement with the LA-SRC values that are associated to the gluten properties (Drakos *et al.*, 2017). Our study indicated a significant positive correlation between LA-SRC of flours and specific volume of bread (0.97, $P<0.05$), which is in good agreement with the results reported by Kweon *et al.* (2011). Anyway, a significant negative correlation was found between LA-SRC of flours and crumb firmness (-0.95, $P<0.05$).

4. Conclusions

The study showed the influence of the type of experimental roller mill on the technological performance at milling multigrain blends. Flour yield, particles size and distribution of the main chemical components among the mill products depended by the number of technological passages. The type of experimental mill also influenced flour functionality, thermo-mechanical behaviour of the doughs and bread quality. The number of technological passages influenced the functionality of the flours in terms of water absorption and starch behaviour during heating and cooling, due to lowering the starch damage and the amount of fine bran particles rich in α-amylase.

Supplementary material

Supplementary material can be found online at https://doi.org/10.3920/QAS2018.1351.

Figure S1. Schematic representation of the milling process performed with the Buhler laboratory mill MLU and laboratory four-roller mill SK.

Figure S2. Mixolab curves of multigrain flours obtained through milling with the Buhler laboratory mill and laboratory four-roller mill type SK.

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