Quality Assurance and Safety of Crops & Foods, 2019; 11 (5): 459-464

Effects of wheat kernel size on hardness and various quality characteristics

O. Acar[1*], T. Sanal[1] and H. Köksel[2]

[1]Food Technology Department, Field Crops Central Research Institute, Şehit Cem Ersever Cad. 9, Yenimahalle, 06170 Ankara, Turkey; [2]Food Engineering Department, Hacettepe University, Beytepe, 06510 Ankara, Turkey; oguz.acar@tarimorman.gov.tr

Received: 20 January 2019 / Accepted: 9 May 2019

RESEARCH ARTICLE

Abstract

Kernel size and hardness are important for millers and they should be controlled prior to milling. The kernel hardness also determines end-use quality of wheat. The objective of this study was to determine the effect of kernel size on wheat kernel characteristics, especially kernel hardness, milling yield and various flour quality properties. Three bread wheat varieties (Bayraktar 2000, Demir 2000 and Ikizce 96) were used after separating them into three kernel size groups. As expected, 1000 kernel weight significantly ($P<0.05$) decreased with decreasing kernel size. Results of three hardness tests (single kernel characterisation system, pearling index and particle size index) were parallel and hardness of the samples significantly increased ($P<0.05$) as the kernel size decreased. Flour yields were generally lower in the smaller kernels. However, the decrease in flour yield was not significant for cv Bayraktar 2000. In two cultivars protein content and wet gluten had a significant ($P<0.05$) decreasing tendency with decreasing kernel size while those of the third cultivar were not affected by kernel size. Sedimentation values of the samples were not affected by kernel size. Overall, small kernels did not seem to influence flour quality while they generally had a detrimental effect on milling yield.

Keywords: kernel size, hardness, SKCS, pearling index, particle size index

1. Introduction

Kernel size is an important quality criterion for millers and milling properties are reported to generally deteriorate with decreasing kernel size (Li and Posner, 1987). Kernels with smaller size are expected to have poorer flour yield. Smaller kernels in a mill mix also tend to lower the flour yield. Therefore, larger and uniform kernel size is desirable in milling. Morgan *et al.* (2000) indicated that flour yield, ash content and colour are generally negatively influenced as the kernel size decreased. Grain size varies depending on wheat variety, weather and growing conditions. The homogeneity of grain size is also important in grain cleaning and to ensure even distribution of the water during tempering prior to milling. There are a number of publications investigating the effects of wheat kernel size on its milling properties (Baasandorj *et al.*, 2015; Dziki and Laskowski, 2004; Morgan *et al.*, 2000; Ohm *et al.*, 1998). On the other hand, the studies investigating the effects of wheat kernel size on kernel hardness and quality of flour produced from differently sized kernels are quite limited.

Although, the reasons for differences in wheat hardness are not clearly understood, there are several factors claimed to influence it. One of them is the cell wall thickness which varies among hard and soft cultivars of bread wheat (*Triticum aestivum*). Hard wheats have been selected for high water absorption. The arabinoxylan component in cell walls absorbs high levels of water and hence when a breeder selects for high water absorption he/she also selects for thick endosperm cell walls. On the contrary, high water absorption is not desired in soft wheat flour. Accordingly, soft wheats have been selected for low water absorption and thus for thin endosperm cell walls. Another major difference in wheat hardness is related to existence, lack or the amount of the proteins puroindolins a and b. These proteins seem to control the interaction between starch and protein matrix and hence controls wheat hardness (Delcour and Hoseney, 2010).

Wheat kernel hardness is a significant factor in determining the functionality of wheat. The variation in grain hardness is the most important characteristic that determines the end-use quality of wheat. Baljeet *et al.* (2017) reported that the hard wheat cultivars could be characterised by higher dough stability and lower dough softening. Hard bread wheat varieties are the main source for bread flour and harder wheats are commonly used for breads with higher quality requirements. Soft wheat varieties are a good raw material for the production of flour to be used for cookies and cakes (Delcour and Hoseney, 2010). Besides determining end-use quality of wheat, kernel hardness in fact has a critical impact on the milling process and it should be determined before milling. Kernel hardness affects power utilisation during wheat milling. Hard wheat cultivars consume more power than do soft wheat cultivars during grinding. In addition, kernel hardness is an important parameter for estimating the flour yield (Dziki and Laskowski, 2005).

There are several methods commonly used for determining kernel hardness. Particle size index (PSI) is based mainly on the particle size distribution of ground wheat (Morris, 2002). On the other hand, the pearling index (PI) method is based on pearling off the outside of kernels while the single kernel characterisation system (SKCS) determines the resistance of kernels to crushing (Szabó *et al.*, 2016). Besides determining hardness, SKCS also measures weight, size, and moisture content of grains. It takes 300 individual kernels, weighs and crushes them, then measures the conductivity of crushed kernels to determine the moisture content (Gaines *et al.*, 1996; Ohm *et al.*, 1998; Osborne and Anderssen, 2003; Osborne *et al.*, 1997; Sissons *et al.*, 2000). Hence, these three methods are based on different principles. Since these three methods are based on different principles, the capabilities of these methods might vary in differentiating wheat samples in terms of kernel hardness.

The objective of this study was to determine the effect of kernel size on wheat kernel characteristics, especially kernel hardness as well as milling yield and flour characteristics such as protein content, Zeleny sedimentation value, wet gluten content and gluten index.

2. Materials and methods

Three different bread wheat varieties (cv. Bayraktar 2000, Ikizce 96, and Demir 2000) of Field Crops Central Research Institute (Ankara, Turkey) were used. Bayraktar 2000 is a white soft wheat with medium strong gluten properties while Ikizce 96 and Demir 2000 are hard red winter wheat varieties with medium strong gluten properties.

Firstly, wheat samples were cleaned to remove broken and severely damaged kernels by using a laboratory type wheat cleaning equipment (Labofix 90, Brabender, Beilngries, Germany). The samples were kept in an air circulation cabinet (Protech, Ankara, Turkey) at 30 °C for 24 hours for moisture equilibration to eliminate the effect of moisture content on kernel hardness.

After taking a representative specimen (unsorted; US), the sample was fractionated into three groups according to the kernel size (KS) by shaking 100 g sample using sieve analysis equipment (Pfeuffer Sortimat, Kitzingen, Germany) for 180 s. This was repeated several times to obtain enough sample from each fraction for the analyses. The three KS groups were KS-1 (>2.8 mm); KS-2 (2.5-2.8 mm) and KS-3 (2.2-2.5 mm).

The samples were analysed by SKCS 4100 (Springfield, IL, USA) for determining weight, size, moisture content and hardness properties according to the Approved Method 55-31.01 (AACC, 2000). PI was determined on 20 g sample by grain pearling equipment (Strong Scott, New Prague, MN, USA). The sample was pearled for 60 s and the fine particles were removed by sifting through 1.2 mm sieve. The PI was calculated by using the following formula:

$$PI(\%) = 5 \times (20 - \text{amount of pearled wheat})$$

PSI was determined according to AACC Approved Method 55-30.01 (AACC, 2000). 10 g ground sample was sifted on a 75 µm sieve using a laboratory shaker (Retsch As200 Tap, Rotap Shaker, Germany).

Wheat samples were tempered to 15.5% moisture for 18 h before milling and milled into flour in replicates using Brabender Quadrumat Jr. laboratory mill (Brabender Instruments, Hackensack, NJ, USA). Flour yield was determined as a percentage of total products. Protein content, wet gluten and gluten index values of the samples were determined according to Approved Method 46-30 and 38-12A (AACC, 2000), respectively. Zeleny sedimentation values were determined according to the Standard Method No 116/1 (ICC, 2008).

Data were analysed using one-way analysis of variance (ANOVA). When significant ($P<0.05$) differences were found, the LSD test was used to determine the differences among means.

3. Results and discussion

Three different bread wheat varieties (cv. Bayraktar 2000, Ikizce 96 and Demir 2000) were used in this study. The samples were sorted into three groups according to their kernels size (KS; KS-1 >2.8 mm, KS-2 2.5-2.8 mm, KS-3 2.2-2.5 mm). The kernel size distribution (%) and thousand kernel weight of wheat samples are presented in Table 1.

The results indicated that all of the wheat varieties had a relatively large kernel size. Amounts of kernels bigger than 2.8 mm (KS-1) were 54.6, 67.8, and 66.5% for the cultivars Bayraktar 2000, Demir 2000 and Ikizce 96, respectively while corresponding total amounts of the kernels bigger than 2.5 mm (KS-1+KS-2) were 88.4, 90.4 and 94.7% for

Table 1. Kernel size distribution and 1000 kernel weight of bread wheat samples.[1]

Sample[2]	Kernel size distribution (%)			1000 kernel weight (g)		
	Bayraktar 2000	Demir 2000	Ikizce 96	Bayraktar 2000	Demir 2000	Ikizce 96
US	100.0	100.0	100.0	33.8 b	32.5 b	32.1 b
KS-1	54.6	67.8	66.5	40.2 a	38.6 a	36.6 a
KS-2	33.8	22.6	28.2	33.2 b	29.9 c	29.4 c
KS-3	11.7	8.6	5.3	26.4 c	24.9 d	23.1 d

[1] Means with different letters within each column are significantly different (P<0.05).
[2] KS: kernel size; KS-1: >2.8 mm; KS-2: 2.5-2.8 mm; KS-3: 2.2-2.5 mm; US: unsorted.

the same cultivars. Dizlek and Özer (2016) reported that total amounts of KS-1+KS-2 were 42.2 and 80.0% for the non-damaged samples of cultivars Golia and Sagittario, respectively. It is reported in another study that total amount of the kernels bigger than 2.5 mm (KS-1+KS-2) was 69.0% for the non-damaged sample of cultivar Sagittario (Dizlek and Özer, 2017). Hence, kernel size seems to be affected by genotype and growing conditions. However, further studies are needed to confirm this finding.

As expected, thousand kernel weight of the samples significantly (P<0.05) decreased as the kernel size of the samples decreased (Gaines *et al.,* 1997). It is reported that the percentage of endosperm increases as the grain size increases, thus, larger kernels have the potential to provide higher flour yield than smaller ones (Posner and Hibbs, 1997; Sutton *et al.,* 1992). Therefore, in the present study, flour yield is expected to decrease with decreasing kernel size/thousand kernel weight.

As for the hardness data of the wheat samples, SKCS and PI values are presented in Table 2, whereas PSI values are presented in Table 3. For each variety, SKCS Hardness index of the sample with the largest kernel size (KS-1) was lower than that of the unsorted sample. However, the differences were not significant. In addition, SKCS hardness index of the samples increased as the kernel size decreased. In each variety, the hardness index value of KS-3 was significantly higher than those of the samples with larger kernel size (KS-1, KS-2) and the unsorted one.

A higher SKCS hardness index value indicates that the wheat sample is harder while a higher PI value means the sample is softer. PI values of the samples with the largest kernel size (KS-1) were higher than that of the unsorted one. The differences were significant (P<0.05) for cv. Bayraktar 2000 and Demir 2000. In addition, PI of the samples significantly decreased (P<0.05) as their kernel size decreased, indicating increased kernel hardness. Both SKCS hardness index and PI results indicated that hardness increased as the kernel size decreased for all wheat cultivars.

PSI is another method commonly used for determination of wheat hardness (Table 3) In general, Bayraktar 2000 samples had higher PSI values indicating that it is a soft wheat cultivar. Demir 2000 and Ikizce 96 samples had lower PSI values indicating that they are harder than Bayraktar 2000 cultivar. Therefore, the results of all three tests (SKCS hardness index, PI and PSI) seem to be supporting each other.

Table 2. Kernel hardness index values of bread wheat samples.[1]

Sample[2]	SKCS hardness index (%)			Pearling index (%)		
	Bayraktar 2000	Demir 2000	Ikizce 96	Bayraktar 2000	Demir 2000	Ikizce 96
US	22.5 b	58.6 bc	49.4 b	31.2 b	23.0 b	26.8 ab
KS-1	21.4 b	55.3 c	47.1 b	33.1 a	24.5 a	27.4 a
KS-2	22.1 b	60.1 b	49.1 b	31.2 b	23.2 b	25.4 b
KS-3	26.7 a	63.7 a	56.9 a	27.8 c	21.6 c	23.1 c

[1] Means with different letters within each column are significantly different (P<0.05).
[2] KS: kernel size; KS-1: >2.8 mm; KS-2: 2.5-2.8 mm; KS-3: 2.2-2.5 mm; US: unsorted.

Table 3. Particle size index values of bread wheat samples.[1]

Sample[2]	Bayraktar 2000	Demir 2000	Ikizce 96
US	17.7 a	12.5 b	11.6 c
KS-1	16.8 b	12.6 b	12.0 bc
KS-2	17.0 b	12.9 b	12.7 a
KS-3	17.9 a	13.7 a	12.5 ab

[1] Means with different letters within each column are significantly different (P<0.05).
[2] KS: kernel size; KS-1: >2.8 mm; KS-2: 2.5-2.8 mm; KS-3: 2.2-2.5 mm; US: unsorted.

Table 4. Flour yield values (%) of bread wheat samples.[1]

Sample[2]	Bayraktar 2000	Demir 2000	Ikizce 96
US	55.8	51.0 a	52.3 a
KS-1	56.4	51.3 a	52.8 a
KS-2	55.9	48.8 b	52.3 a
KS-3	55.8	46.7 c	49.8 b

[1] Means with different letters within each column are significantly different (P<0.05).
[2] KS: kernel size; KS-1: >2.8 mm; KS-2: 2.5-2.8 mm; KS-3: 2.2-2.5 mm; US: unsorted.

Although KS-1 groups of all wheat varieties had the lowest PSI values, they did not change to a considerable extent within each cultivar as the kernel size changed. This is consistent with the results reported by Dziki and Laskowski (2004). The difference in the PSI values of the largest and smallest kernel sized samples were around 1%. This is not a considerable difference in terms of differentiating wheat hardness based on their PSI values. Based on the PSI hardness classification by Williams *et al.* (1988), all of the samples of Demir 2000 and Ikizce 96 with different kernel size belong to 'hard' group and KS-1 and KS-2 samples of Bayraktar 2000 belong to the 'medium hard' group. PSI value of Bayraktar 2000 KS-3 sample was also very close to 'medium hard' group. Therefore, it can be concluded that PSI test does not seem to be very effective in discriminating the hardness of different sized kernels of the same cultivar.

The PI method is based on pearling off the outside of kernels while the SKCS Hardness Index determines the crushing force required for kernels. On the other hand, PSI is applied on the ground sample. Hence, they are based on different principles. Although, all of the tests gave parallel results in the samples with diverse hardness, their results were not parallel in the different sized kernels of the same cultivar, which have minor differences in terms of hardness. As indicated above, the difference in the PSI values of the largest and smallest kernel sized samples (1%) were not high enough for differentiating the different sized kernels of the same cultivar in terms of their hardness.

The flour yields of the wheat samples are presented in Table 4. Flour yields of the samples decreased as the kernel size decreased for all cultivars. The differences between the kernel size groups in flour yield was significant (P<0.05) for cv. Demir 2000 while that of cv. Bayraktar 2000 was not significant. For cv. Ikizce 96, the flour yield of KS-3 sample was significantly (P<0.05) lower than other size groups of the same cultivar. Dziki and Laskowski (2005) also reported that kernel size had an influence on the total flour yield and ash content. The highest flour yield with the lowest ash content was obtained for the large kernels.

The samples with different kernel size had a similar decreasing trend in terms of flour yields. The results are consistent with the studies by Gaines *et al.* (1997), Morgan *et al.* (2000) and Baasandorj *et al.* (2015). Similar to the present study, in the studies cited above, some of the decreases in flour yield with decreasing kernel size were significant while some of them were not.

Flour yields of the unsorted sample in each cultivar gave lower results than KS-1 of the same cultivar. However, the differences were not significant. In addition, the difference in flour yield between unsorted and KS-2 samples of cv. Demir 2000 was significant, while the flour yields of unsorted and KS-2 samples of cv. Bayraktar 2000 and Ikizce 96 were not significant.

Li and Posner (1987) reported that small kernels had low flour yield potential. In the present study, the samples with the smallest kernel size (KS-3) also had the lowest flour yield in all cultivars, however, the difference between flour yield of different kernel size groups was significant (P<0.05) only for cv. Demir 2000.

The protein contents and Zeleny sedimentation values of the samples are given in Table 5. Protein content of the samples decreased as the kernel size decreased except for cv. Demir 2000. Protein content of cv. Demir 2000 did not considerably change depending on the kernel size. Protein contents of the unsorted sample, KS-1 and KS-2 of cv. Bayraktar 2000 were comparable while that of KS-3 was significantly lower as compared to unsorted one and KS-1. Protein contents of the unsorted sample and KS-1 of cv. Ikizce 96 were comparable; however, their protein content was significantly higher than protein content of KS-2 and KS-3. The results of the present study are consistent with Sutton *et al.* (1992) and Morgan *et al.* (2000) who also reported that as the wheat kernel size increased as the protein content increased. However, the

Table 5. Protein content and Zeleny sedimentation values of bread wheat samples.[1]

Sample[2]	Protein content (N×5.7, dry weight basis, %)			Zeleny sedimentation (ml)		
	Bayraktar 2000	Demir 2000	Ikizce 96	Bayraktar 2000	Demir 2000	Ikizce 96
US	11.7 ab	10.1	11.9 a	21.0	21.0	22.0
KS-1	11.9 a	10.0	12.0 a	22.0	21.0	22.5
KS-2	11.4 bc	10.1	11.4 b	21.5	21.0	21.5
KS-3	11.2 c	10.1	11.2 c	22.0	21.0	21.0

[1] Means with different letters within each column are significantly different (*P*<0.05).
[2] KS: kernel size; KS-1: >2.8 mm; KS-2: 2.5-2.8 mm; KS-3: 2.2-2.5 mm; US: unsorted.

results by Baasandorj *et al.* (2015) are in contradiction with the present study and protein content decreased as the wheat kernel size increased. Inconsistent results might be due to the differences in the materials utilised in these studies. The smallest kernel size in the study by Baasandorj *et al.* (2015) was in the range of 1.65-2.24 mm while the smallest kernel size in the present study was 2.20-2.50 mm.

Although small variations were observed in the Zeleny sedimentation values within each cultivar, the differences were not significant. It is well accepted that the Zeleny sedimentation value is affected by protein content and quality. Although there were some significant differences in the protein contents of the cultivars based on their kernel size, the differences were not very high. Furthermore, we do not expect any difference in terms of protein quality within each cultivar as the kernel size change, since they have the same genetic makeup. Hence, as expected, Zeleny sedimentation values of the samples within each cultivar were similar and did not change based on the kernel size.

The wet gluten and gluten index values of the samples are given in Table 6. Wet gluten contents of the samples decreased as the kernel size decreased. The decrease in wet gluten content of cv. Demir 2000 was not significant. As indicated earlier, a similar trend was also observed in the protein contents of cv. Demir 2000 and protein content of this cultivar was not affected by the kernel size (Table 5). In cv. Bayraktar 2000 and Ikizce 96 the samples with the lowest kernel size had the lowest gluten content. In other words, the samples with different kernel size had a similar trend in terms of wet gluten and protein contents.

Although, gluten content is largely affected by growing conditions, a large variation is not expected in the gluten quality within the same cultivar. Gluten index value is commonly used for the evaluation of gluten quality and determined by centrifuging wet gluten on a certain size sieve and expressed as the percentage of wet gluten remaining on the sieve. It is clear that the centrifugal force will be larger as the amount of wet gluten on the sieve is increased, resulting in a lower gluten index value. In the present study, gluten index values of all cultivars increased as the kernel size decreased and some of the increases were significant (*P*<0.05). There seems to be a close negative correlation between gluten index value and wet gluten content. A possible explanation for the higher gluten index value of the kernels with smaller size might be their lower gluten content which encounters a lower centrifugal force, thus a higher percentage of wet gluten remained on the sieve.

Table 6. Wet gluten and gluten index values of bread wheat samples.[1]

Sample[2]	Wet gluten (%)			Gluten index (%)		
	Bayraktar 2000	Demir 2000	Ikizce 96	Bayraktar 2000	Demir 2000	Ikizce 96
US	20.3 b	22.9	27.9 b	98.0 a	82.0 ab	47.0 b
KS-1	25.6 a	21.8	29.9 a	70.5 b	68.0 b	40.0 b
KS-2	20.7 b	20.8	26.8 b	94.0 a	94.0 a	55.5 b
KS-3	19.2 b	18.8	22.4 c	98.0 a	94.0 a	80.5 a

[1] Means with different letters within each column are significantly different (*P*<0.05).
[2] KS: kernel size; KS-1: >2.8 mm; KS-2: 2.5-2.8 mm; KS-3: 2.2-2.5 mm; US: unsorted.

4. Conclusions

Kernel size is an important descriptor of milling properties for millers. Furthermore, kernel hardness is a significant factor in determining the end-use properties of wheat. The present study showed that the decrease in the kernel size resulted in significant ($P<0.05$) increases on the hardness of the wheat cultivars which were determined by SKCS, PI and PSI methods. The results of all three tests seem to be supporting each other. However, the differences in the PSI values of the kernel size groups was not large to adequately differentiate the wheat hardness according to the PSI hardness classification by Williams *et al.* (1988), because the PSI values of the largest and smallest kernel sized samples were around 1%. In addition, flour yields of all cultivars had a decreasing trend with decreasing kernel size, but, the difference in the flour yield of all kernel size groups was significant only for one of the cultivars used (Demir 2000). The flour yield of the sample with the smallest kernel size was also significantly $P<0.05$) lower than those of other size groups in another cultivar (Ikizce 96). Although, protein and wet gluten contents of two cultivars had a similar significant ($P<0.05$) decreasing tendency when the kernel size decreased, the values of the third cultivar was not affected (Demir 2000). Although, some significant differences were observed in the protein contents of various kernel size groups, their Zeleny sedimentation values were not affected. This might be due to the same genetic make-up of the kernel size groups within each cultivar.

It can be concluded that, small kernels did not seem to influence flour quality while they generally had a detrimental effect on milling yield. Hence, breeders can select genotypes which have kernels with the lowest KS-3 content. However, further work is required to expand the information obtained in the present study using a large number of wheat cultivars grown in different locations and additional research should be carried out to determine the rheological properties of flours obtained from different kernel size groups.

References

American Association of Cereal Chemists (AACC), 2000. Approved methods, 10th edition. Method No: 38-12A, 46-30, 55-30.01. AACC, St. Paul, MN, USA.

Baasandorj, T., Ohm, J.B., Manthey, F. and Simsek, S., 2015. Effect of kernel size and mill type on protein, milling yield, and baking quality of hard red spring wheat. Cereal Chemistry 92: 81-87.

Baljeet, S.Y., Yogesh, S. and Ritika, B.Y., 2017. Physicochemical and rheological properties of Indian wheat varieties of *Triticum aestivum.* Quality Assurance and Safety of Crops & Foods 9: 369-381.

Delcour, J.A. and Hoseney, C., 2010. Principles of cereal science and technology, 3rd edition. American Association of Cereal Chemists, St. Paul, MN, USA, 270 pp.

Dizlek, H. and Özer, M.S., 2016. Effects of sunn pest (*Eurygaster integriceps*) damage ratio on physical, chemical, and technological characteristics of wheat. Quality Assurance and Safety of Crops & Foods 8: 145-156.

Dizlek, H. and Özer, M.S., 2017. Improvement of physical, physicochemical, and rheological characteristics of sunn pest (*Eurygaster integriceps*) damaged wheat by blending. Quality Assurance and Safety of Crops & Foods 9: 31-39.

Dziki, D. and Laskowski, J., 2005. Wheat kernel physical properties and milling process. Acta Agrophysica 6: 59-71.

Dziki, D. and Laskowski, J., 2004. Influence of kernel size on grinding process of wheat at respective grinding stages. Polish Journal of Food and Nutrition Science 13(54): 29-33.

Gaines, C.S., Finney, P.F., Fleege, L.M. and Andrews, L.C., 1996. Predicting a hardness measurement using the single-kernel characterisation system. Cereal Chemistry 73: 278-283.

Gaines, C.S., Finney, P.L. and Andrews, L.C., 1997. Influence of kernel size and shriveling on soft wheat milling and baking quality. Cereal Chemistry 74: 700-704.

International Association for Cereal Science and Technology (ICC), 2008. ICC standards, standard no116/1. ICC, Vienna, Austria, 129 pp.

Li, Y.Z. and Posner, E.S., 1987. The influence of kernel size on wheat millability. Association of Operative Millers Technical Bulletins, November, 5089 pp.

Morgan, B.C., Dexter, J.E. and Preston, K.R., 2000. Relationship of kernel size of flour water absorption for Canada Western Red Spring wheat. Cereal Chemistry 77: 286-292.

Morris, C.F., 2002. Puroindolines: the molecular genetic basis of wheat grain hardness. Plant Molecular Biology 48: 633-647.

Ohm, J.B., Chung, O.K. and Deyoe, C.W., 1998. Single-kernel characteristics of hard winter wheats in relation to milling and baking quality. Cereal Chemistry 75: 156-161.

Osborne, B.G. and Anderssen, R.S., 2003. Review: single kernel characterization principles and applications. Cereal Chemistry 80: 613-622.

Osborne, B.G., Kotwal, Z., Blakeney, A.B., O'Brien, L., Shah, S. and Fearn, T., 1997. Application of the single-kernel characterisation system to wheat receiving testing and quality prediction. Cereal Chemistry 74: 467-470.

Posner, E.S. and Hibbs, A.N., 1997. Wheat: the raw material. Wheat flour milling, 2nd edition. American Association of Cereal Chemists, St. Paul, MN, USA, pp. 1-46.

Sissons, M.J., Osborne, B.G., Hare, R.A., Sissons, S.A. and Jackson, R., 2000. Application of the single-kernel characterization system to durum wheat testing and quality prediction. Cereal Chemistry 77: 4-10.

Sutton, K.H., Hay, R.L. and Mouat, C.H., 1992. The effect of kernel weight on the assessment of baking performance of wheats by RP-HPLC of glutenin subunits from single grain. Journal of Cereal Science 15: 253-265.

Szabó, B.P., Gyimes, E., Véha, A. and Horváth, Z.H., 2016. Flour quality and kernel hardness connection in winter wheat. Acta Universitatis Sapientiae Alimentaria 9: 33-40.

Williams, P., El-Haramein, F.J., Nakkoul, H. and Rihavi, S., 1988. Crop quality evaluation methods and guidelines. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria, 145 pp.