ISSN: 04532198
Volume 62, Issue 03, April, 2020

The effect of changing the milling extraction rate on the flour properties

Zeyad Arif Ahmed[1*], Inas Abdulsattar Abduljabbar[2], Salah Mahdi Mousa[3], Shaimaa Ahmed Abed [1], Salah Thamer Owaid[1]

[1] General Company of Grain Processing, Ministry of Trade, Iraq
[2] Al-Furat Al-Awsat Technical University, Technical Collage\Al-Mussaib, Iraq
[3] Ministry of Industry, Iraq.
Email: ziadarif9@gmail.com , inasabdulsattar7@gmail.com , dr.inas.abdulsattar@atu.edu.com

Abstract— The purpose of this research is to investigate the influence of changing the milling extraction rate (MER) of Al-Dorah flour mill (Iraqi governmental mill), on the flour specifications. As it is the daily procedure in the mill, a mixture wheat of local Iraqi species, Australian and American wheat were tempered to 16% moisture content and milled after 32 hours over three levels of MER: 75%, 80% and 85% respectively. Flour samples were evaluated for a series of physical and chemical characteristics including particle size distribution, ash content, gluten content and flour whiteness. The highest ash content of flour was obtained with increasing the MER to 85%, while the highest gluten and the highest whiteness of the flour were found with decreasing the MER. There was a significant deference between the flour particles which stayed over the sieves in the experiment for the three levels of the milling extraction.

Keywords— Milling extraction rate, Particles size, Ash, Gluten, Whiteness.

1. Introduction

Wheat is the most important supply of food and calories for the human beings worldwide ever since the dawn of agriculture (Krasileva et al. 2017), wheat grain is used principally after turning the kernel components into dissimilar degrees of flour and other fractions, which is done by the roller mill through a gradual size-reduction process called wheat milling (Patwa et al. 2014). Increasing the flour extraction rate is affected by the degree of separating the starchy endosperm from the outer coat through the milling operation (Kong & Baik 2016). Likewise, the flour extraction rate is positively influenced by decreasing the gap between breaking and reduction rolls (Husain 2011). Generally, the flour produced in the mill is the key technical and a series economic indicator in the wheat milling operation (Posner & Hibbs 2005); indeed, it is a heterogeneous mixed of particles of diverse shapes and densities (Sonaye & Baxi 2012). On the other hand, the flour extracted in the mill and the dough behavior are necessary to match the costumer need. Wu & Cocks (2006) stated that particle size distribution has an enormous role in defining flour behavior as a powder. Furthermore, it is important to illustrate wheat bran particle size as a critical component in the whole wheat milling for it is significantly affects the dough specification and the final product quality like breads, noodles, pastas and cakes (Wang et al. 2016). Kalkan et al. (2014) represented that the design of a roller mill machine besides mechanical settings have an obvious impact on the particle size distribution of final product. Particle size distribution is a fundamental parameter which can lead researchers and millers to decide on adequately the milling process settings and chose the proper roller mill designs (Ta 2013). In fact, the normal particle size of the wheat endosperm (the major ingredient of the straight – standard flour) is less than 150 µm, and a higher percentage of bran particles are typically larger than 500 µm, before the further fine milling course (Rodriguez & Olivers 2007). The ash of flour is the inorganic residual which remains after incineration in a muffle furnace; it represents the content of mineral stuff of the flour (Posner 1991), for instance potassium, phosphorus, magnesium, calcium, iron, sodium, zinc, and copper (Aber 1989). Ash content in flour has been proposed as a key parameter of the grinding performance (Fadle 2010). Many literature works on ash content pay particular attention to its great effect on flour price, consequently, the wheat bran particles and ash content are considerable components in whole wheat flour production, for they have a great influence on dough properties and the quality of final products (Steglich et al. 2015, Liu et al. 2016). Wheat has a high protein content compared to other cereals such as maize and rice, that makes it the main supply of cereal protein in man's diet (Bhat et al. 2016). It has been assumed that the utmost percentage of protein content is located in the sub-aleurone region of wheat endosperm (Edwards et al. 2007). Anjum et al. (2007) showed that gluten is the main protein of wheat flour, mostly responsible for defining dough elasticity and positively correlated with high bread-making worth. The gluten content in grain involves dough viscosity and extensibility, as well, its cohesiveness and elasticity (Joye et al. 2009). Moreover, cake volume, crumb structure and gas retention depend to a great extent on the gluten content in the flour (Al-Dmoor 2013). Gluten test is a significant method to verify the wheat flour quality compared to other tests such us farinograph (Oikonomou et al. 2015) Bakery products are generally manufactured from white flour (Selimović et al. 2014). The whiteness degree of flour is very important quality character to produce different kinds of products (Blanco et al. 2011). Wheat milling performance could be tested by evaluating some factors connected with the flour quality such as flour whiteness (Ta 2013). In a major study, Campbell et al. (2007) concluded that the quality of the final product of the milling operation and in particular whiteness depended considerably on the properties of grain used. Moreover, machine design and operating settings of the milling machines were significant as well in this respect (Baasandorj et al. 2015).

2. Material and method

Investigations were conducted between December 2018 to January 2019 at the General Company for Grain Processing in Baghdad. Grain specific weight and the flour experiments were done at the laboratory of Al-Dorah flour mill (Buhler AG 600 ton/day).

2.1 Milling Setting

A mixture grains of 50% local Iraqi wheat cultivar and 35% Australian wheat in addition to 15% American wheat, were received at the mill according to the government plan to provide the people in Baghdad with a mixture wheat flour with high quality that enable them to bake it vertically by the Iraqi traditional way of baking. First, the grain were tested to evaluate the total specific weight which was 80%, (Easi-Way scale. KERN EMS laboratory Balance ISO 7971-3, UK), and the initial moisture content was 10-10.5% ±0.2 (Seedburo 1200D series moisture tester. MD7488 for USDA standards). The wheat were cleaned inside the mill by the cleaning section and tempered to 16% moisture content, then the tempered wheat were kept for 32 hours in the bins to ensure having the water inside the kernel for all the endosperm content, then the tempered wheat were moved to the first milling section and delivered to the first breaking roll. The milling rate during the experiment test was 12 ton/hour and the three levels of milling extraction rate (75%, 80% and 85%) were achieved by readjusting the roll clearance besides changing the direction of some grinded particles that moving down from the sifters floor in the milling section and let them pass with the flour production line. The samples of flour were taken from the flour production line subsequently to each level of milling extraction rate and kept it in an isolated bags, and the moisture content of the flour for all replications was (13-13.3)% (Inframatic 9500 NIR Grain Analyzer, SE-126 09 Hagersten Sweden).

2.2 Flour Experiments

The flour samples were kept in the laboratory in a sealed bags under normal temperature 25 ˚C and all the experiments were done within 48 hours after the milling operation.

2.2.1 Particle Size Distribution

For each treatment, the samples of the flour in the bags were mixed carefully and then 100 g of flour were subjected to the analysis of particle size distribution by the sieve shaker AS 200 (Retsch GmbH, Haan, Germany). The four sieves used in the experiment were put in descending order from top to bottom depending on the mesh size 1120 µm, 710 µm, 355 µm and 125 µm, followed by a gathering pan. The flour sample was shaken in the machine for 5 min, the weight of the materials on each sieve were recorded. Individually, the laboratory scale (Precisa XB-4200C, 4802 Glenwood Rd. Brooklyn, NY 11234, US) was used to measure the weight of material on each sieve in addition to the finest flour in the pan. The particle size distribution of each level of MER was indicated by the schedule representing the quantity of the five degrees of the flour samples as follows:

1- ≥1120 mm,
2- <1120 mm and ≥710 µm,
3- <710 µm and ≥355 µm,
4- <355 µm and ≥125 µm (310-500 µm),
5- <125 µm.

2.2.2 Ash Content

The ash content of the flour for each sample was determined according to AACC08-01.

2.2.3 Gluten

Gluten content was determined for AACC (38-12).

Whiteness L*

The whiteness of the flour (L*) for each treatment was determined by using Inframatic 9500 NIR Grain Analyzer, SE-126 09 Hagersten Sweden.

2.3. Statistical Analysis

The statistical analysis performed in the factorial design was the analysis of variance (ANOVA). The data was analysed statistically by utilizing the software package (Statistical Package for Social Scientists) IBMSPSS version 23.0 (IBM 2016). A one-way and two-way ANOVA were used to compare between the means of the treatments. The significant difference was tested using tukey and LSD test ($P \leq 0.05$).

3 Results and Discussion

3.1 Particle Size Distribution

Generally, milling the grain with 16% moisture content leads to get a wide range of particle sizes and increases the average dimension of middling particles (Warechowska et al. 2016). The most obvious finding to emerge from the analysis is that there is a difference between the particle size distribution of the flour produced from each level of MER, especially between 75% and 85%.

The data of the particle size distribution investigation in table 1 showed that the increase in the quantity of the flour that passed through 125 µm sieve was found as the MER decrease to 75%. On the other hand, particles that larger than 355 µm were clearly more with the higher MER, at the same time as the particles size which are less than 355 µm were found to be more with 75% MER, these observations are likely to be related to the different settings which made in the mill that allowed to pass more bran fractions and big semolina parts with the production line in case of 85% MER. In addition, tighten the milling rolls and decrease the clearance between them possibly will reduce the particles dimension that allowed to go along with the finest ones. Moreover, the percentage of the big particles <1120 µm and ≥355 µm in the flour which produced under 85% MER were higher than the percentage of big particles which found under the other levels of extraction rate, this result might be connected with the special settings inside the mill which allowed to pass more particles of bran with the produced flour compared to the different settings for 75% MER, which concentrated to pass the finest particles with the flour production line. These findings confirm those of (Danciu and Danciu 2010), who also demonstrated that milling roll clearance has a clear effect on determining the particle size distribution of the end product.

It is extremely important to clarify wheat bran particle size as a serious element in the whole wheat milling and its negative effect on net gluten performance and rheological characteristics of dough, such as water absorption, thus, it has a considerable effect on dough specification and quality of final products, like breads, pastas and noodles (Niu et al. 2014, Wang et al. 2016). Although the amount of the over-sieves > 355 µm were significantly different between the three levels of MER in this study as it is shown in Table 1, there might be no significant effect on dough behavior and further backing tests, because of the tiny amounts of the bran particles that allowed to pass with the flour production line to get the higher MER.

Table 1. The effect of MER on the particle size distribution of the produced flour

Sieve size (µm)	Milling extraction rate		
	75%	80%	85%
1120	0.04 [a]	0.09 [b]	0.22 [c]
710	0.13 [a]	0.25 [b]	0.39 [c]
355	0.19 [a]	0.34 [b]	0.45 [c]
125	45.19 [a]	45.32 [a]	45.17 [a]
Pass	53.37 [a]	52.98 [b]	53.1 [c]

3.2 Ash Content

What we can observe from the obtained results is: there was a significant difference in the mean values of the flour ash content between 85%, 80% and 75% MER. Generally, reducing ash content in flour should point toward better separation of aleurone from the flour and less bran contamination.

Fig 1 confirmed that the lowest ash content (0.72) was found with the lowest level of MER. However, the results of the ash content showed that tighten the milling rolls is extensively responsible for producing the highest percentage of the ash in the produced flour, this must have something to do with the influence of crushing more bran particles of the kernels skin and minimizing their size to allow them pass with the flour production line (in case of the closest roll clearance).

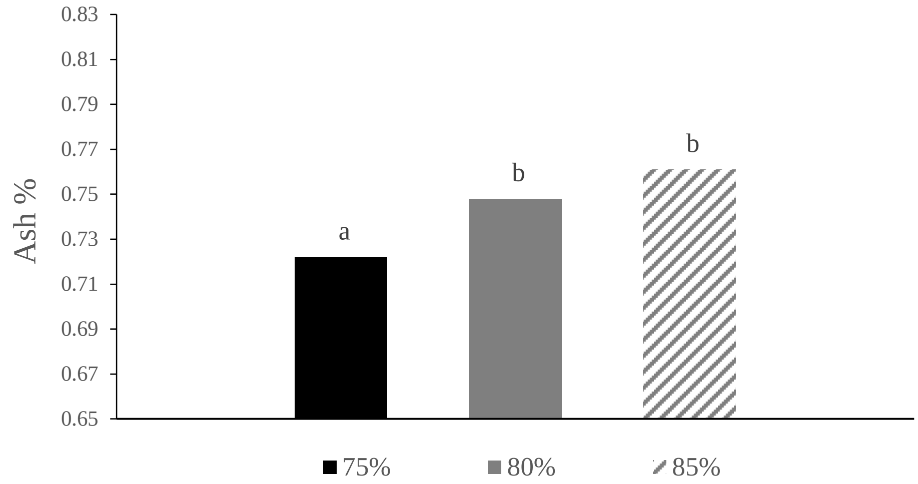

Figure 1. The effect of MER on the ash content of flour.

In general, The minimum ash content in the flour is mostly coming from the first breaking rolls and the first reduction passages in the milling section. Moreover, the flour ash content was increased in the conduct test with increasing the flour extraction rate by having more flour from the last reduction rolls, this observed positive relationship might be explained in this way: the ash content in the wheat kernel exists mainly far from the endosperm center and increases from the inside to the outer layers, which have more ash content than the kernel heart (Fišteš & Vukmirović 2009), for that reason, the higher the flour extraction, the more kernel skin will be grinded, and additional bran ingredient contamination (ash) will be present in the end-product (Sakhare & Inamdar 2014). likewise, through the test, the changes that settled in the milling section to get 80% and 85% MER, were responsible for allowing the materials which pass inside two pipes in the milling section and have small parts of kernels coat, to be delivered to the production line (with the smaller particles of the endosperm flour). From the results in the figure 2 it was clear that MER influences flour ash content, since it indicates to a significant extent, the tiny bran fractions in the final flour (Arendt & Zannini 2013).

3.3. Gluten

There was a very parallel and interesting behavior observed for the percentage of the flour extraction and the value of the flour gluten for all the repetitions (Figure 1). The observed correlation between the flour protein content and the flour milling extraction could be explained in this way: the high flour extraction from the grain means there will be more protein content in the flour (which is very important for nutritional topic and human digestive system), but with less gluten, for the protein cells are located mainly in the sub-aleurone area of wheat endosperm; which will be higher than the percentage of protein content in the central endosperm regions, consequently, the higher the flour extraction rate, the less gluten content in the flour, this is represented by (Edwards et al. 2007). These results were consistent with the work of Wieser et al. (2014) who showed that gluten quantity is decreasing along with increasing the flour extraction rate, because the gluten content is determined as it is storage proteins and located essentially in the starchy endosperm of the kernels; additionally, they represented around 70-80% of total grain proteins. On the other hand, the larger particle that found with the flour could also be a reason to affect positively the gluten network of the dough and starch gelatinization, which affects later the bread making quality.

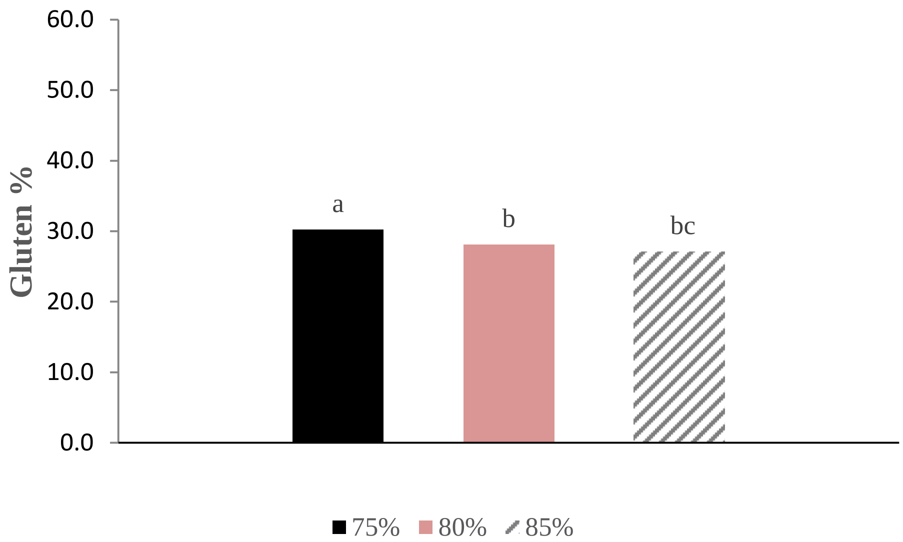

Figure 2. The effect of MER on the gluten.

3.4. Whiteness

The most significant finding for the flour whiteness in Figure 3 is the evident effect of the ash content on the flour whiteness and the positive relationship between them. Many factors could explain this observation. Firstly, the flour extraction, since the high percentage of the ash content in the flour may lead practically to producing flour with low whiteness (Alsamahy et al. 2011). Flour contaminated with more particles of the bran (which are already darker than the endosperm particles) must lead to lower whiteness for the produced flour. The ash content gradient in wheat kernels increases from the center to the outer layers, aleurone cells, in particular, are extremely rich in micro- and macro-elements, thus the more the grinding of kernel coat, the more the ash impurities will be in the produced flour and the low flour whiteness we get, this results were noticed by (Posner, 2009). The small parts of bran were permitted to be with the final flour to get the higher MER, thus the highest ash content for all the replications were found only with the highest MER.

Another relation might be notice between the flour whiteness and the degree of wheat grinding because of the affect of particle size distribution which has a remarkable influence on flour color (increasing the flour granulometry lead to decrease the whiteness), this relation is defined by (Hidalgo et al. 2014). The correlation between flour granulometry and the value of whiteness could explain in this way: higher absorbance affects by bigger flour granules for the increasing in particle dimension expands the length of spectral path in the samples, thus resulting in higher absorbance and lower reflectance. This explanation was determined by Oliver et al. 1992.

The current study represents a clear effect of the wheat grain moisture content on the flour whiteness, the lower moisture content in the grain would increase the flour extraction by grinding some parts of the bran particles, in addition to the endosperm, thus the flour will get darker and have an increased ash content (Kweon et al. 2009, Hourston et al. 2017). On the contrary, milling wheat with ideal moisture content 16% will lead to get low ash content and ideal whiteness.

ISSN: 04532198
Volume 62, Issue 03, April, 2020

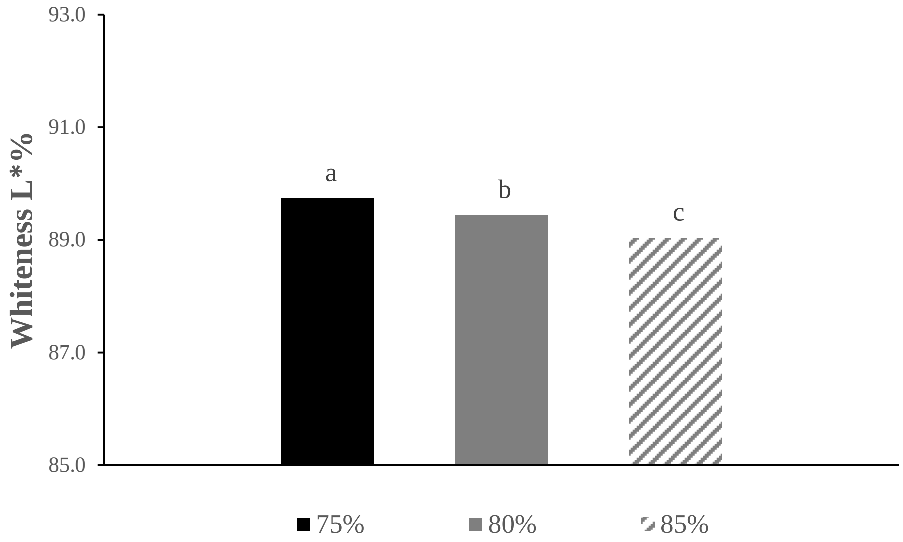

Figure 3. The effect of MER on the flour whiteness.

Conclusion

The point of this study is to evaluate the flour properties under three different levels of milling extraction rate which might describe as:

1- There was a difference between the particle size distribution of the flour produced from each level of MER.
2- The flour ash content was varied and affected significantly between the levels of 85%, 80% and 75% MER.
3- The gluten quantity was decreased when the flour extraction rate is increased.
4- Like the flour ash content, the flour whiteness was very clear indicator of the effect of the lower MER on having the higher flour whiteness.

5. References

[1]. Aber, B., 1989. Wheat, Flour and Bread. French Symex Institution, Dar Arab World, Egypt.

[2]. Al-Dmoor, H.M., 2013. Cake flour: functionality and quality. *European Scientific Journal, ESJ, 9*(3), PP. 166-180.

[3]. Alsamahy, S.K., Adel, Abobaker Shatta and Khaled, Mohammed Yusof., 2011. *Foods Technology* (First edition). Dar Almaseera. Amman.

[4]. Anjum, F.M., Khan, M.R., Din, A., Saeed, M., Pasha, I. and Arshad, M.U., 2007. Wheat gluten: high molecular weight glutenin subunits—structure, genetics, and relation to dough elasticity. *Journal of Food Science*, 72(3), pp. 56-63.

[5]. Arendt, E. K., and Zannini, E. 2013. Cereal Grains for the Food and Beverage Industries (1st ed.). Woodhead Publishing. ISBN: 978-0-85709-413-1, p. 512.

[6]. 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*(1), pp. 81-87.

[7]. Bhat, N.A., Wani, I.A., Hamdani, A.M., Gani, A. and Masoodi, F.A., 2016. Physicochemical Properties of Whole Wheat Flour as Affected by Gamma Irradiation. *LWT-Food Science and Technology*, *71*, pp. 175-183.

[8]. Blanco, A., Colasuonno, P., Gadaleta, A., Mangini, G., Schiavulli, A., Simeone, R., Digesù, A.M., De Vita, P., Mastrangelo, A.M. and Cattivelli, L., 2011. Quantitative Trait Loci for Yellow Pigment Concentration and Individual Carotenoid Compounds in Durum Wheat. *Journal of Cereal Science*, *54*(2), pp. 255-264.

[9]. Campbell, G.M., Fang, C. and Muhamad, I.I., 2007. On Predicting Roller Milling Performance VI: Effect of Kernel Hardness and Shape on the Particle Size Distribution From First Break Milling of Wheat. *Food and Bioproducts Processing, 85*(1), pp. 7-23.

[10]. Danciu, I. and Danciu, C., 2010. Assessment of the energy consumption for the first breaking step, depending on the break adjustment in the wheat milling process. Proceedings of the 2nd International Conference on Manufacturing Engineering, Quality and Production Systems, pp. 235-238

[11]. Edwards, M.A., Osborne, B.G. and Henry, R.J., 2007. Investigation of the Effect of Conditioning on the Fracture of Hard and Soft Wheat Grain by the Single-Kernel Characterization System: A Comparison with Roller Milling. Journal of Cereal Science, 46(1), pp. 64-74.

[12]. Fadle, J.A., Shaiban, M.S. and Obadi, M.A., 2010. Comparison of Physical Chemical Rheological and Baking Properties of Some Local and Imported Wheat Varieties. Assiut University Bulletin for Environmental Researches, 13(2), pp. 37-51.

[13]. Fišteš, A.Z. and Vukmirović, Đ.M., 2009. Reduction of Wheat Middlings Using a Conventional and Eight-Roller Milling Systems. Acta Periodica Technologica, 40, pp. 25-34.

[14]. Hidalgo, A., Fongaro, L. and Brandolini, A., 2014. Wheat Flour Granulometry Determines Colour Perception. Food Research International, 64, pp. 363-370.

[15]. Hourston, J.E., Ignatz, M., Reith, M., Leubner-Metzger, G. and Steinbrecher, T., 2017. Biomechanical Properties of Wheat Grains: The Implications on Milling. Journal of The Royal Society Interface, 14(126), pp. 1-12.

[16]. Husain, A. H., 2011. The Scientific Book of Grain Processing. Aldar Aljamiea for Translating Publishing and Distribution, Baghdad. p. 113.

[17]. Joye, I.J., Lagrain, B. and Delcour, J.A., 2009. Endogenous Redox Agents and Enzymes that Affect Protein Network Formation During Bread Making-A review. Journal of Cereal Science, 50(1), pp. 1-10.

[18]. Kalkan, F., Singh, A., Vanga, S.K.K., Raghavan, V. and Kara, M., 2014. Effects of Tempering Moisture and Roll Differential on Wheat Size Reduction Process During the First Break Rollers. Transactions of the ASABE, 57(5), pp. 1425-1429.

[19]. Kong, L. and Baik, B.K., 2016. Degree of starchy endosperm separation from bran as a milling quality trait of wheat grain. Jour*nal of Cereal Science, 69*, pp. 49-56.

[20]. Krasileva, K.V., Vasquez-Gross, H.A., Howell, T., Bailey, P., Paraiso, F., Clissold, L., Simmonds, J., Ramirez-Gonzalez, R.H., Wang, X., Borrill, P. and Fosker, C., 2017. Uncovering Hidden Variation in Polyploid Wheat. *Proceedings of the National Academy of Sciences, 114*(6), pp. 913-921.

[21]. Kweon, M., Martin, R. and Souza, E., 2009. Effect of tempering conditions on milling performance and flour functionality. *Cereal Chemistry*, 86(1), pp.12-17.

[22]. Liu, T., Hou, G.G., Lee, B., Marquart, L. and Dubat, A., 2016. Effects of Particle Size on the Quality Attributes of Reconstituted Whole-Wheat Flour and Tortillas Made From it. *Journal of Cereal Science,* 71, pp. 145-152.

[23]. Niu, M., Hou, G., Lee, B. and Chen, Z., 2014. Effects of Fine Grinding of Millfeeds on the Quality Attributes of Reconstituted Whole-Wheat Flour and its Raw Noodle Products. *LWT-Food Science and Technology, 57*(1), pp. 58-64.

[24]. Oliver, J. R., Blakeney, A. B., & Allen, H. M. 1992. Measurement of flour color in color space parameters. Cereal Chemistry, 69, 546-551.

[25]. Oikonomou, N. A., Bakalis, S., Rahman, M. S., & Krokida, M. K. 2015. Gluten index for wheat products: Main variables in affecting the value and nonlinear regression model. *International Journal of Food Properties, 18*(1), 1-11.

[26]. Patwa, A., Malcolm, B., Wilson, J. and Ambrose, K.R., 2014. Particle Size Analysis of Two Distinct Classes of Wheat Flour by Sieving. *Transactions of the ASABE, 57*(1), pp. 151-159.

[27]. Posner, E. S. 2009. Wheat flour milling. In K. Khan, &P. R. Shewry (Eds.) wheat chemistry and technology (pp. 119-152) (4^{th} Ed.). St Paul , MN, USA:AACC International.

[28]. Posner, E.S. 1991. Wheat and Flour Ash as a Measure of Malleability. *Cereal Food World*. (36), pp. 626-629.

[29]. Posner, E.S. and Hibbs, A.N., 2005. Wheat Flour Milling (Ed. 2). American Association of Cereal Chemists (AACC), St Paul, USA, ISBN: 978-1-891127-40-3, pp. 1-46.

[30]. Rodriguez, F.B.C. and Olivares, G.S. 2007. U.S. Patent Application No. 12/003.072.

[31]. Sakhare, S.D. and Inamdar, A.A., 2014. The Cumulative Ash Curve: A Best Tool to Evaluate Complete Mill Performance. *Journal of Food Science and Technology, 51*(4), pp. 795-799.

[32]. Selimović, A., Miličević, D., Jašić, M., Selimović, A., Ačkar, Đ. and Pešić, T., 2014. The Effect of Baking Temperature and Buckwheat Flour Addition on the Selected Properties of Wheat Bread. *Croatian Journal of Food Science and Technology, 6*(1), pp. 43-50.

[33]. Sonaye, S.Y. and Baxi, R.N., 2012. Particle Size Measurement and Analysis of flour. *International Journal of Engineering Research and Applications*, *2*(3). pp. 1839-1824.

[34]. Steglich, T., Bernin, D., Moldin, A., Topgaard, D. and Langton, M., 2015. Bran Particle Size Influence on Pasta Microstructure, Water Distribution, and Sensory Properties. *Cereal Chemistry*, *92*(6), pp. 617-623.

[35]. Ta, P.D.E.E., 2013. Researches on Variation of Grist Particle Size Parameters According to Constructive Characteristics of Grinding Rolls. *Inmateh*,*40*(2), pp. 5.

[36]. Wang, N., Hou, G.G., Kweon, M. and Lee, B., 2016. Effects of Particle Size on the Properties of Whole-Grain Soft Wheat Flour and Its Cracker Baking Performance. *Journal of Cereal Science*, (69), pp. 187-193.

[37]. Warechowska, M., Markowska, A., Warechowski, J., Miś, A. and Nawrocka, A., 2016. Effect of Tempering Moisture of Wheat on Grinding Energy, Middlings and Flour Size Distribution, and Gluten and Dough Mixing Properties. *Journal of Cereal Science*, (69), pp. 306-312.

[38]. Wieser, H., Koehler, P. and Konitzer, K., 2014. Celiac Disease and Gluten: Multidisciplinary Challenges and Opportunities (1st ed.), Academic Press Elsevier, London, Waltham, San Diego, pp. 53-75.

[39]. Wu, C.Y. and Cocks, A.C., 2006. Numerical and Experimental Investigations of the Flow of Powder into a Confined Space. *Mechanics of Materials*, *38*(4), pp. 304-324..