STONE MILLING OF HARD RED SPRING WHEAT: EFFECT OF SETTINGS ON FLOUR, DOUGH AND BREAD QUALITY

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MASTER OF SCIENCE

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ABSTRACT

Stone milling is an ancient method for grinding without separation of the wheat constituents to produce flour. This study evaluated the effect of three different stone gaps (setting wide, medium, and narrow) and 200 and 400 revolutions per minute (rpm) on the particle size distribution of whole wheat flour and its effect on baking, and dough rheological properties. Gap settings wide and medium at 200 rpm produced higher amount of small particles (<250 μm), resulting in a greater angle of repose, starch damage, loaf volume, lighter flour, and bread color. Water absorption and rheological parameters were significantly different from the other flours ($P<0.05$). This study showed an effect of the stone mill settings on the particle size distribution of whole wheat flour and its subsequent impact on bread quality.

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Special thanks to my family, for always believing in me and supporting my goals. I cannot thank you enough for everything. To my parents Ramon Alava and Teresa Vargas, my siblings Olga, Angel, and Laura, whom in the distance have been my rock. And also, Edgar for been always the special person that encourages me to pursue my dreams and reminds me that everything is possible.

Finally, my most special thanks to God for always been my guidance, strength and help me accomplish this goal.

DEDICATION

I would like to dedicate this thesis to God and my parents Ramon and Teresa.

God’s timing is always perfect, and with Him everything is possible.

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INTRODUCTION

Milling (grinding) is a common operation for the reduction of particle size of different grains for the creation of many food products. One of the most ancient mills is the stone mill, where millstones were first used for grinding flour 2,600 B.C (Cappelli et al. 2020). The stone mill usually has the millstones horizontally, and the upper millstone is the one running and the lower stone standstill. Milling is the breakage of the bran, germ, and endosperm of the wheat ground into smaller particles. Before 1870, wheat flour was mostly ground by millstones until the roller process was introduced to the milling industry (Synder 2007). Flour milling is a mechanical process where the wheat can be separated to obtain different products or milled in a single stream mill.

Stone mill is a single stream mill where the wheat kernel constituents are never separated and milled together through the whole process, having as the end product whole wheat flour. Stone mill’s settings are mostly changed depending on the miller’s experience and the desired product characteristics (O’Connell 2019). There is limited information available concerning the most efficient configurations for stone milling wheat. The mill’s capacity and the fineness of the whole wheat flour depend on the stones diameter, the revolutions per minute (rpm), gap, the load, and the horsepower of the motor (Posner and Hibbs 2005). Stone mill whole wheat flour has shown a theoretical extraction of a 100% and a higher value for health such as protein, fiber, carotenoids, and macro and micronutrient elements (Ficco et al. 2016).

In the last decades, more consumers are looking for products that can increase health benefits, and whole wheat flour and bread are examples. The sensory attributes of whole wheat bread are different from white bread and some consumers like it while others do not. Besides its positive features, there are some other considerations to take when breadmaking whole wheat bread. Whole wheat flour weakens the dough and gas cells' framework resulting in lower gas retention and consumer acceptance of the bread taste than white flour (Li et al. 2012; Li et al. 2017; Posner and Hibbs 2005; Wang et al. 2017). Also, not just the flour particle size but also the bran particle size directly affects the loaf volume, crumb firmness and color, and other bread quality parameters.

The particle size of wheat flour affects the dough extension and resistance, water absorption, and dough stability. In whole wheat flour, the bran particle size also affects the bread quality and parameters such as the crumb firmness, water absorption, starch retrogradation, and the release of nutritional components;(Cai et al. 2014; Doblado-Maldonado et al. 2012; Rosell et al. 2010). The particle size distribution can affect the dough rheology and, therefore, the bread quality. The viscoelastic properties will affect the dough development, resistance, extension, and this will directly affect the loaf volume. The starch viscosity can also be affected by the flour's particle size, which affects its water holding capacity, cooking stability, strength, viscosity, and ending in the quality of the bread and its crumb structure.

Knowing how the settings configuration in a stone mill affects the particle size distribution can help millers achieve the product bakers need. The stone gap, stone speed, and feed rate have different effects on the flour particle size; lower feed rate and closer stone gaps can result in more refined flours and, depending on their median particle size, a better bread quality. The aim of this research was as follows,

To determine the influence of the stone gap, feed rate, and revolutions per minute on the whole wheat flour particle size and distribution.

To compare the effect of the particle size distribution of the flour on the flour physical and chemical properties and, therefore, the bread quality.

1. LITERATURE REVIEW

1.1. Hard red spring wheat

In bread-making, hard red wheat (Triticum aestivum L.) typically is used. Hard red spring (HRS) wheat breeding programs often put effort towards improving traits that allow the varieties to produce superior flour quality (Bruckner et al. 2001). There are eight classes of wheat according to the official standards: durum, hard red spring, hard red winter, soft red winter, hard white, soft white, unclassed, and mixed wheat. There are three subclasses in the hard red spring wheat class: dark northern spring, northern spring, and red spring wheat (Matz 1991).

Kernel characteristics such as protein content and quality, vitreousness, falling number, and kernel size and distribution are needed to ensure a good quality whole wheat flour. Kernel characterization has many tests that help to evaluate these characteristics in the grain. One of the trials of kernel characterization measures the size and distribution of the grains in the sample. Wheat grains with a more homogenous size distribution milled better since they get the same shear and breakage inside the mill (Mosleth Færgestad et al. 2004).

Another test from kernel characterization is the weight of 1000 kernels. The central part of wheat flour is comprised of the grain endosperm. Larger wheat grains have a more substantial portion of endosperm that results in higher flour yield for refined flours. This test is used mostly for trading characteristics (Mosleth Færgestad et al. 2004).

Protein content and quality in the wheat kernel are essential and will determine the protein content of the flour. This parameter has proved to be crucial for bread-making quality (Mosleth Færgestad et al. 2004). Wheat proteins affect doughs' viscoelasticity, which will determine the final bread quality (Mosleth Færgestad et al. 2004). Milling also has a significant role in protein content. Under high temperatures, it can denature proteins (Prabhasankar and Haridas 2001).

Vitreous kernel content is another parameter that tests the quality of the wheat kernel. Kernel vitreousness affects the milling performance and the end product quality, resulting in flour with high water absorption and loaf volume potential (Dexter and Edwards 1998).

1.2. Whole wheat flour

Over the years, eating healthier food has increased due to the different diseases attributed to inadequate or lack of nutritional foods. Whole wheat flour is one of the foods people have included in their daily diet to have a higher intake of fiber, protein, micronutrients, vitamins, and phytochemicals (Li et al. 2017; Miller Jones et al. 2015). Figure 1 shows in detail the composition of whole wheat flour. Whole wheat bread has a higher nutritional value than white bread, but coarser particles in this flour can also decrease digestibility, thus obtaining less protein and energy. The flour's digestibility can be associated with grinding's mechanical conditions, were finely ground flour has showed a higher digestibility (Synder 2007).

There is an increase in demand for whole-grain products due to their health benefits (Li et al. 2012). By 2005, 45% of the shoppers increased their consumption of whole grains (Sloan 2005), and research by the Food Information Council stated that almost 64% of the consumers are interested in eating whole-grain foods (Insight 2019). Even with whole wheat flour's nutritional benefits, consumers are not accepting it as much as they do refined white flour. Other problems faced are including other constituents of the grain and not only the endosperm that affects its taste and rheological properties of the dough and, therefore, the bread quality (Li et al. 2012). The germ and bran that whole wheat flour contains have a dilution effect on the gluten network, weakening the dough and the framework of gas cells lowering the gas retention and the consumer acceptance of the bread taste (Li et al. 2012; Li et al. 2017; Posner and Hibbs 2005; Wang et al. 2017). Whole wheat dough shows lower baking qualities than white flour dough in loaf volume, specific volume, and interior structure (Li et al. 2012).

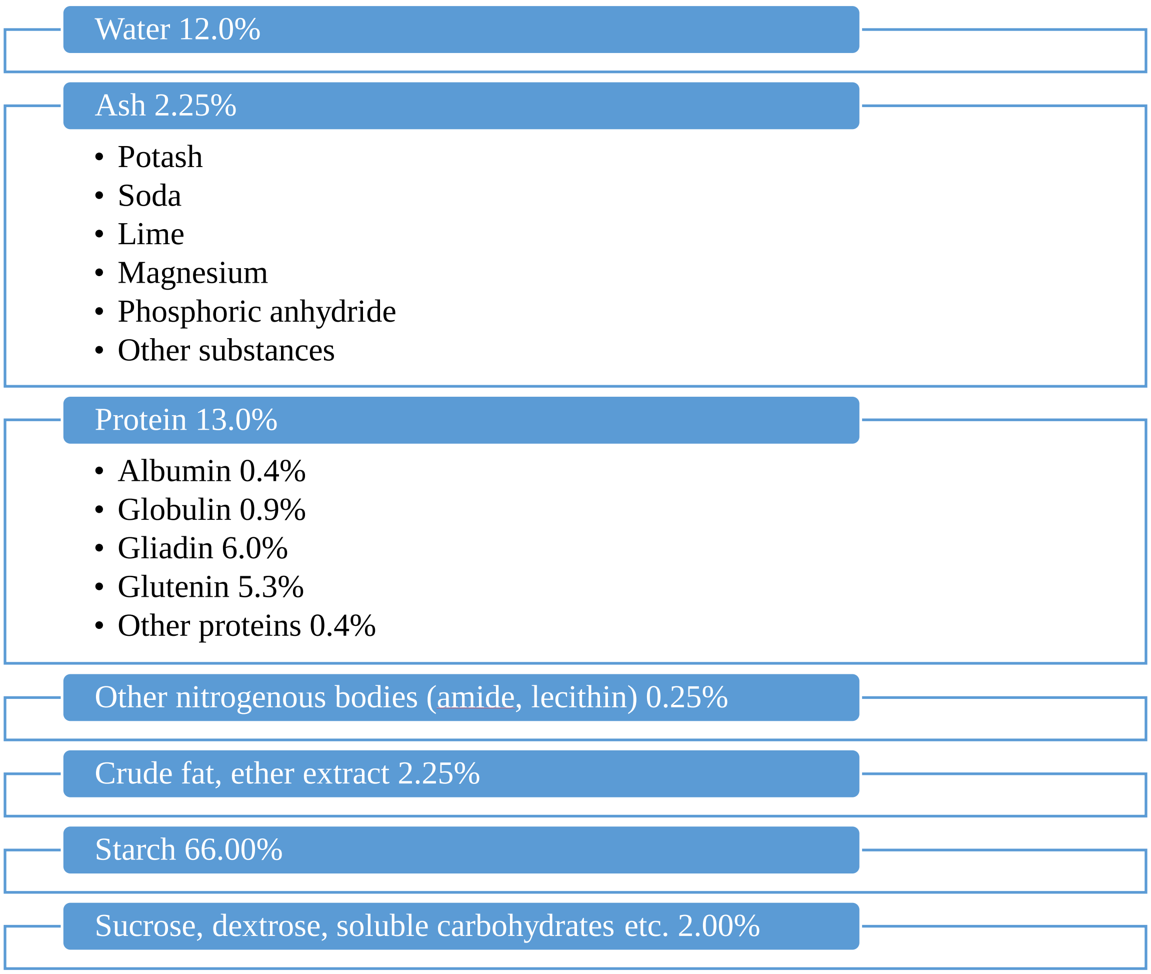

Figure 1. Summary of the composition of wheat flour and the percentages of its components (Synder 2007).

1.3. Stone milling

Before 1870, the stone mill was the primary mill for grinding wheat into flour and is considered might be the oldest type of mill in the world (Figure 2) (Cappelli et al. 2020). The stone mill produces a single stream in which flour is ground by two millstones and has almost 100% flour yield, making it attractive for a business feature (Synder 2007). Stone mills grind the wheat kernels by abrasion, compression, and shear where the bedstone is stationary, and the turning runner stone is on top and is the one crushing (Doblado-Maldonado et al. 2012).

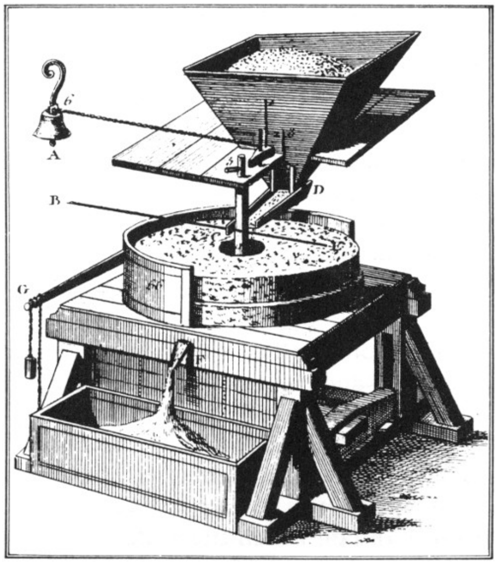

Figure 2. An 18th century stone mill with an upper runner stone and below and stand stone with a feeder and a bell rings when the hopper has been empty—source: (Ford 2018).

The milling technique has a significant influence on the quality of the final product and for this is vital to consider the settings in the mill. It has shown an effect on the physicochemical and functional properties of wheat flour (Cappelli et al. 2020). The amount of force applied to the kernel changes by adjusting the gap between stones and surfaces. The contact of both surfaces causes the breakage in the grain. The stones can be made of different materials such as composition stone and metal plates and is important to sharpen the stones surface to mantain an efficient grinding action. The stone surface will have a different grinding effect depending on its stone surface and it can be adapted depending on the produc desired. Two of the main types of stone surface are the ‘quarter’ dress and the ‘sickle’ dress (Posner and Hibbs 2005) (Figure 3). Also, their capacity will determine the fineness of the ground material. The number of kernels ground by the stones depending on the feed rate affects its rupture. Besides, the upper stone moved by a motor, and the speed settled affects this breakage (Bayram and Durdu 2005).

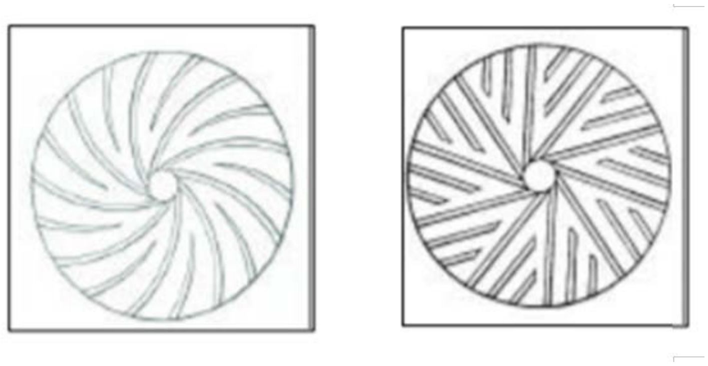

Figure 3. Two main types of millstone dress, left picture the ‘sickle dress’ and right ‘quarter’ dress (Posner and Hibbs 2005).

Stone mill breaks the kernels in different particle sizes, and it has become popular because of its nutrition retaining the germ and the bran of the wheat and been suited for making whole wheat flour (Doblado-Maldonado et al. 2012). In stone mill flour, its particle size has been found more homogenous than with the roller mil and improving the particles’ appearance been opaquer and less glassy. Smaller bran particles can facilitate the reactivity of the phenolic compounds (derivatives of benzoic acid, ferulic acid, resorcinol, aromatic amines, phytates, folates, and sterols), affecting the intensity of the taste (Cappelli et al. 2020).

Some studies found that stone mills had little effect on the loss of macroelements (sodium, magnesium, potassium, calcium, and phosphorus) and no effect in microelements (manganese, iron, copper, zinc and selenium) compared to the roller mill (Cappelli et al. 2020). The milling technique can affect the color, particle size, surface area, damaged starch, bulk density, and potentially reduced mycotoxins in flour. Bakers sometimes prefer stone mill flour because the texture and taste flavor is characterized as sweet and nutty (Cappelli et al. 2020). Stone milling can generate heat due to friction leading to a denaturation of protein, damage to starch, and oxidation of unsaturated fatty acids (Cappelli et al. 2020; Doblado-Maldonado et al. 2012). Stone mill flour has shown a higher water holding capacity, antioxidant activity and an increase in the amylose content caused by the heat of the stones. In stone milling, grinding temperatures of 63°C of hard and soft wheat have shown a reduced loaf volume by 15% compared to a milling temperature of 40°C (Posner and Hibbs 2005).

1.3.1. Craft milling

Craft milling mostly refers to a more artful type of milling where the miller changes the settings and adapts it depending on their experience and the kind of flour they need (Ford 2018). This type of milling can often be related to small to medium scale production where they can blend different varieties and have trackable products. In the 1980s in the USA were mostly small flour mills and just a few extensive mills, now most of the small mills have disappeared (O'Connell 2019). The number of small to medium scale regional whole wheat flour mills have been increasing. These types of flour have become popular due to claims of freshly milled flour and the health benefits of fresh food (Ross 2018). Also, this type of milling can help the local grains' movements where organic, an ancient grain, and specialty flours can enter the market (O'Connell 2019).

1.3.2. Machine parameter/effect

Besides kernel characteristics, the flour is affected by the milling parameters. These parameters consider the effect of the stone's abrasion of the kernels to make flour. Stone gaps and speed set in the mill will directly affect the grinding surface's pressure in the kernel. The particle size and starch damage are affected by the type of mill, affecting absorption and flour functionality (Ghodke et al. 2008).

Feed rate setting during stone milling directly affects the whole wheat flour and its end product. The feed rate consists of the number of grains getting in between the two stones milled simultaneously, and an optimum feed rate is needed to reduce the starch damage content and efficient use of the stone milling machine. The aperture of the stones and feed rate are essential machine-parameters affecting starch damage and dough stickiness. The increase of feed rate and the gap between the stones can lead to a decrease in starch damage content while reducing both parameters would increase it (Ghodke et al. 2008). The feed rate and the stone gap will have a direct effect on the severity of the grinding and, therefore, on the mechanically damaged starch. Starch damage can increase water absorption in the flour, leading to a stickier dough (Ghodke et al. 2008; Ross and Kongraksawech 2017).

Another effect besides the starch damage is the particle size distribution of the flour. The particle size distribution affects bread quality by modifying the bread palatability, loaf volume, and porosity (Ross and Kongraksawech 2017). There is a lack of information about the ideal particle size distribution in flour but still affects tests such as rapid visco analyzer, farinograph, and in general bread-making (Ross and Kongraksawech 2017). In other studies, the stone mill has shown to milled coarser particle size flour (Unal and Sacilik 2011), compared to the roller and centrifugal mills (Bayram and Durdu 2005).

Grinding temperature is another critical parameter in milling that is important. If the temperature rises above 60°C, the denaturation of proteins occurs, reducing amino acid content and slight losses of essential fatty acids in flour (Prabhasankar and Haridas 2001). Due to the effect of these machine-parameters, it is necessary to use it properly to avoid temperature increase above the ideal point and minimize the damage to chemical components of the grain (Prabhasankar and Haridas 2001). The milling room temperature and relative humidity affect the milling performance where the favorable room conditions are about 23.9°C and 65-70% relative humidity. The milling settings and the grain performance will also affect the temperature generated, taking in mind the grain’s initial temperature. In the stone mill, lower milling temperatures can be maintained by lower stone rotating speed and slowing its feed rate, but it will depend on the milling time, increasing the temperature function of the duration of milling (Di Silvestro et al. 2014).

1.4. Bread-making

The bread-making process takes into consideration at least three main ingredients: flour, water, and yeast. These ingredients are added together with optional components such as salt, sugar, milk solids, improver, and fat, depending on quality requirements or industrial needs in the formation of the dough and the bread, depending on what is the final goal (Sluimer 2005). In bread-making, its performance is directly affected by the gluten proteins. The gluten proteins allow the dough to hold the gas during the fermentation. It interacts with other flour components such as lipids, non-gluten proteins affecting rheological dough properties, and the final bread quality (Sluimer 2005; Veraverbeke and Delcour 2002). The protein quality is vital, so there could be a starch-gluten matrix that holds the gas cells for a better crumb structure and large loaf volumes of bread. Also, milling affects starch damage, which will impact the amount of sugar available to the yeast during dough formation (Lever et al. 2005). Some researchers have found that reducing the particle size in the flour can increase the damaged starch in whole wheat flour (Ghodke et al. 2008; Wang et al. 2017; Wang et al. 2020). Cavanaugh et al. (2010) suggested that dough stability during fermentation can vary depending on the variety (genetics), the environmental impact on the variety, and the fermentation process. It is essential for whole-meal bread recipes to know that the water absorption can be higher than with white flour, almost reaching 80%. The fermentation process, together with its ingredients, will affect the final bread quality and characteristics directly. Different types of fermentation processes will have results in the texture and flavor, which will be better with leavening the dough during fermentation than not having any fermentation or short fermentation (Sluimer 2005).

1.4.1. Sponge and dough

The sponge and dough method is one of the many ways of making bread. This method consists of two parts — first, creating the sponge comprising two-thirds of the total recipe and improving agents. The sponge is pre-fermented anywhere from one to six hours, and the time will depend on the amount of flour in the sponge, 1 to 3.5 hours if 75% of the flour mix, or 5 hours if its 50% of it, and depending on the flavor requirements (Cauvin 2003; Pyler 1973; Sluimer 2005). After fermentation, the sponge part is mixed with the rest to create the dough, then its mold, and let stand for a final fermentation before baking. Some advantages of this type of bread-making are that it softens the gluten, promotes yeast activation, ease of dough formation, superior aroma and flavor, soft and regular crumb, and more forgiving process in delays (Sluimer 2005).

1.4.2. Artisan baking

There is no exact definition for an artisan baker but is referred mostly to bakers who adapt their process to changing flour qualities. Consumers also refer to artisan bread when they do not have a standardized procedure, including extended fermentations, lean formulations, and sometimes unusual ingredients. Industrialization, high speed, high capacity, and continuous industrial processes are more common in the bread industry. To achieve this industrial goal, the ingredients' homogeneity and flexibility are fundamental characteristics, besides quality. On the other hand, the artisan process comes from well-trained bakers where the mixing, resting, scaling, molding, and proofing varies depending on the quality of the flour and the type of bread (Ross 2018). Bakeries with artisan bread will look for the process that best fits its needs and has a longer fermentation process, which gives a pleasant flavor and texture. Also, to find the flour they need most of the time, they need direct communication with the flour or grain producer.

Now, consumers and producers are more interested in knowing the story of where the food they are eating comes from, having products from ‘farm to table’ (O’Connell 2019).

1.4.3. Flour particle size

In bread-making, some studies show that the flour particle size can affect its quality. Whole wheat flour with smaller particle size showed higher resistance to extension, extensibility, water absorption, and dough stability than larger particles (Posner and Hibbs 2005; Wang et al. 2017). The dough stability can increase due to the increase in the number of hydrogen bonds formed with the hydroxyl groups that are in the fiber molecules (Rosell et al. 2010). In whole wheat bread, finer bran particles positively influence the gluten network formation having high resistance after long resting time, for example, 180 minutes. The improvement in extensibility could also help the air cells from collapsing and result in larger bread volume (Wang et al. 2017). There have been controversial studies showing that smaller bran particle size in the flour had a larger volume than with coarser bran flour (Doblado-Maldonado et al. 2012). Still, other studies contradicted this statement (Li et al. 2012) or state that bran particle size did not affect loaf volume (Cai et al. 2014). According to Li et al. (2012), whole wheat bread made with flour having a medium particle size (96.99µm) had a larger volume and specific volume than when made with flour having a coarser particle size (235µm) and refined group (50.21µm) but no significant difference ($P<0.05$) between the medium and coarser particle size. It is important to continue investigating the effect of the particle size flour on the baking quality.

1.4.4. Effect of bran in bread

Wheat bran is considered a rich source of dietary fiber that ranges between 36.5-52.4% and divided between soluble and insoluble dietary fiber (Ahmed Junejo et al. 2019). In the wheat dough, the dietary fiber interferes significantly with protein matrix formation and reduces the dough's extensibility, which limits the gas cell expansion and retention (Rosell et al. 2010; Wang et al. 2017). The dietary fibers' behavior affecting the protein matrix varies during the heating and cooling in bread-making (Cai et al. 2014). Also, adding fiber, which in some cases is by adding wheat bran, shows an increase in bread crumb firmness and starch retrogradation (Cai et al. 2014). Coarser bran particles form more discontinuos gluten network and reduced its capacity to retain the CO2 gas during baking resulting in an increase in bread texture (firmness) and lower loaf volume (Li et al. 2012). The bran particles affects the bread texture becoming less cohesive and with a harder crumb (Majzoobi et al. 2013). Larger bran particles have a higher water holding capacity than starch granules which can increase starch retrogradation and bread staling (Sun et al. 2015).

In whole wheat flour, bran friability can increase depending on the cultivar, which tends to reduce to smaller pieces and produce lower quality bread (Doblado-Maldonado et al. 2012). Bran particle size can also affect water absorption and the release of nutritional components and vitamins. According to Doblado-Maldonado et al. (2012) and Cai et al. (2014), coarse bran particles in flour can increase water retention while decreasing wheat bran particle size reduces its water-binding capacity (Wang et al. 2017). In fiber-rich flour, the water retention in dough increases due to the preferential water-binding capacity of fiber competing with starch (Rosell et al. 2010). In contrast, smaller particles can help release dietary elements, but the moderate particle size may be most desirable for whole wheat bread-making (Doblado-Maldonado et al. 2012).

2. EXPERIMENTAL APPROACH

2.1. Kernel characteristics

Blend of three different varieties of hard red spring wheat (Glenn, VitPro, and Linkert) from the 2018 harvest of Casselton, ND, USA, for analysis of kernel vitreousness, 1000 kernel weight, and moisture and test weight using a Dickey-John GAC 2100 (Dickey-John, Auburn, IL, USA). Full grade characterization will be realized with the official US standards for wheat grain in the category of hard red spring wheat and also followed by a single kernel characterization system (Model 4100; Perten, Springfield, IL USA). Also, there was a control sample (flour from the stone mill whole wheat flour from the North Dakota State mill) that was not part of the statistical analysis. Flour moisture content was measured using Near-Infrared Reflectance (NIR) in triplicate and protein content and ash content following the AACC international method (39-11.01; 08-21.01, respectively). The grain was cleaned and stored in a cold room at -18°C before milled. Each experimental unit will consist of 4 kg of grain, and before milling equilibrated to room temperature for 24 hours and homogenous moisture between 11-12%.

2.2. Whole grain flour milling

Wheat sample (4 kg) ground using a stone mill (Kombi mill model A 500 MSM, Osttiroler Getreidemuehlen) with it is own feeder (Figure 4). The mill consisted of two horizontal stones 50 cm diameter and an estimated surface area of 1955 cm^2. The bottom stone was stationary, while the top stone rotated at 200 and 400 rpm. Also, there were three stone gaps specified as setting wide, setting medium, and setting narrow (Figure 5). Setting wide had a higher aperture, and the aperture of the stones decreased from setting wide to setting narrow, setting medium been the intermediate gap and setting narrow the closest the stones.

Figure 4. Stone mill model A 500 MSM and produced by Osttiroler Getreidemuehlen

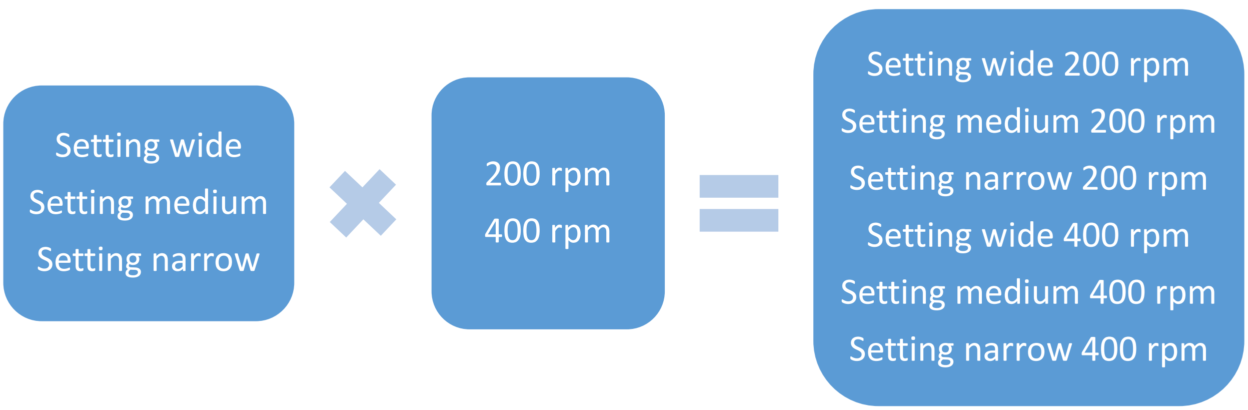

Figure 5. The three gap settings (wide, medium and coarse) and two stone speed (200 and 400 rpm) resulted from six different setting combinations, becoming six different flour samples.

The wheat kernel milling was by abrasion and impact between the two stones, the top one moving in a clockwise direction and the lower one standstill. The stone surface directs the flour outside of the stone mill without any sieve restriction. The feeder was attached to the stone mill and not controlled; it changed depending on the stone rotating speed and setting, where the higher the speed, the faster the feeder emptied. The feed rate was calculated using the feed time and was the same as the milling time. In each of the treatments, the milling time and action stopped simultaneously as the feeder was emptied; in that time frame, the flour sample was taken. The ambient milling conditions in the basement of Harris Hall during the spring season had a room temperature of 23.1-24.6°C and relative humidity of 69-80%. Flour temperature varied from 34-39°C right after milling, and stones were not directly exposed, it is covered as shown in Figure 4. The temperature of the stones over the wood cover was between 24-27°C while milling. Flour and stones temperatures were measured with a non-contact infra-red digital thermometer (VWR International, Radnor, PA, USA).

2.3. Whole wheat flour fractions

After milling, with the use of a cross-flow blender, the flour was homogenized in eight minutes. The particle size distribution was analyzed by placing the flour samples (100 gr) in a Ro-Tap vibratory sieve shaker (Model R-30050, W.S. Tyler, Mentor, OH, USA) with a stack of seven sieves (75 µm, 105 µm, 150 µm, 205 µm, 250 µm, and 500 µm). The moisture, ash, and protein content of whole wheat flour were measured with the Near Infrared (NIR) (AACI Approved Method 08-21.01, 39-11.01).

2.4. Flour and dough properties

The rheological behavior of flour was determined for every treatment using a farinograph (Farinograph-TS; Brabender GmbH & Co. KG, Duisburg, Germany) according to the AACCI method 54-21.02. The rapid visco analyzer (RVA 4500, Perten Instruments, Australia) evaluated the flour's pasting properties (AACCI Approved Method 76.21.02). It recorded the change in viscosity when heating and cooling the starch in water, determining the energy requirement for cooking and desired consistency and thickening effect. Each flour sample had a color analysis using the CIE LAB color space (Konica Minolta, Inc.) and starch damage (AACCI Approved Method 76.31.01). The angle of repose measured in the samples had a similar method as the one explained by Lumay et al. (2012). The funnel was placed 5cm from a rubber stopper that has 6 cm of diameter. The flour sample (25 g) poured in the funnel and fell onto the rubber stopper without any stop (Figure 6). Then the height of this flour pile was measured and the angle of repose of the sample calculated.

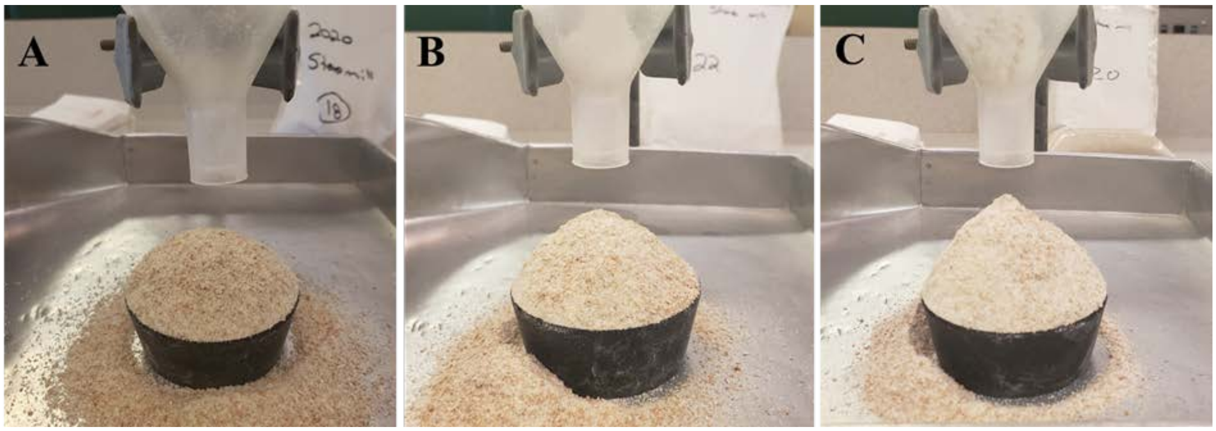

Figure 6. The angle of repose samples from 400 rpm setting narrow (A), 400 rpm setting wide (B), and 200 rpm setting medium (C).

2.5. Whole wheat bread-making

The bread was made using a sponge and dough AACCI 10-11.01 method for all the samples and control. In this procedure, two-thirds of the flour, yeast, and part of the water mixed to form a loose dough. The dough fermented up to 4 hours and then combined with the remaining ingredients and rest into a developed dough. After this, it was proofed 30 min and then molded and proofed for 1 hour at 25°C before baking (Figure 7). The bread loaf volume was measured by rapeseed displacement method (AACCI 10-05.01). Loaf weight was measured after the bread was cooled, and the crumb firmness was evaluated according to the AACCI approved method 74-09.01. The bread was sliced, and the middle slices were used to have a color analysis of the crumb using the CIE LAB color space.

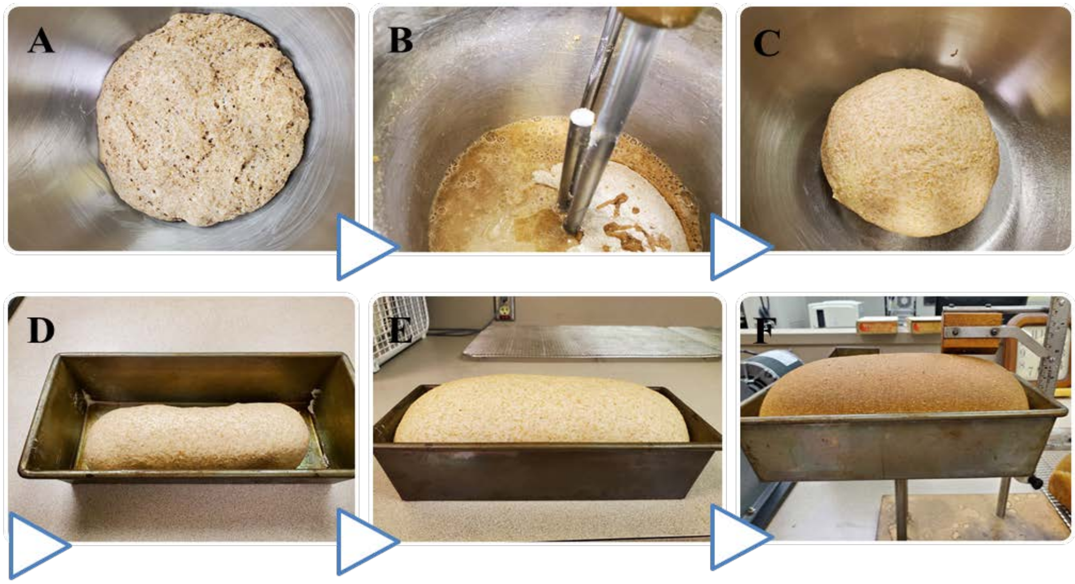

Figure 7. Sponge and dough AACCI 10-11.01 method of bread-making. First, the sponge fermentation (A), dough mixing (B), dough fermentation (C), then the dough is molded before proofing(D), after proofing (E), and finally, baking (F).

2.6. Scanning electron microscopy (SEM)

The bread was evaluated with scanning electron microscopy (SEM) to determine bran particles in the starch/protein matrix. Thin slices of bread were air dried at 22°C for 48 hours, then stored in zip top bags before analysis. The samples were broken to expose fresh surface before mounted on aluminum mounts using colloidal silver or carbon adhesive tabs and coated with gold using a Balzers SCD 030 sputter coater (BAL-TEC RMC, Tucson, AZ, USA). Images were obtained with a JEOL JSM-6300 SEM (JEOL USA, Peabody, MA, USA) using an accelerating voltage of 10 kV (Ovando-Martinez et al. 2011). This material is based upon work supported by the National Science Foundation under Grant No. 0619098, 0821655, 0923354, and 1229417. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

2.7. Experimental design and statistical analysis

The experimental design was a randomized complete block with two factors: stone speed (200 and 400 rpm) and stone gap (setting wide, setting medium, and setting narrow). All measurements were made in duplicates on three replicates, and data presented as the means. Data were analyzed using the SAS System for Windows (V 9.4, SAS Institute Inc., Cary, NC, USA). Also, the analysis of variance (ANOVA) was performed using the 'Mixed' procedure in SAS with treatment means separation by Fisher's protected Least Significant Difference (LSD) test at P=0.05. Pearson correlation coefficients were estimated between variables using CORR procedure in SAS. The non-linear relationships were shown between certain variables mean values and stone mill feed time. The variables were fitted to a logistic equation, y = a/(1 + b*e^(-c*x)), as a function of feed time. The constants in the equation were estimated using the Genetic algorithm and Direct simplex search functions in the MATLAB software (R2020b, The Mathworks, Inc. Natick, MA, USA). The fitness of the model was shown by the coefficient of determination (R^2) of the mean values of the variables.

3. RESULTS AND DISCUSSION

3.1. Flour and milling characteristics

The stone mill with the configuration at 200 and 400 rpm, and each one at gap setting wide, medium, and narrow, resulted in six different flour from the same bulk of grain (Table 1). The six different flours came from the same bulk of samples, and in Table 1 there is some information to ensure homogeneous samples. Table 1 shows that the samples were made with initial grain with the same characteristics, such as test weight and grain moisture. Also, the milling temperature was never greater than 29°C, but it was not measured directly to the stones but with wood cover, which could affect the temperature measurement. The flour temperature was below 40°C, and the milling room had a temperature of around 23-25°C and relative humidity between 69-80%. After milling, the moisture (not shown in the table), protein and ash content were measured to prove homogeneity between the samples.

The feed time was not controlled and varied for each stone mill configuration. Table 1 shows the feed time, which was the same as the milling time. The flour sample for each stone mill configuration was obtained until the feeder was emptied. Table 1 shows that the 400 rpm stone rotational speed was able to grind 4 kg of the sample around 1 minute for the stone gap setting medium and fine. On the other hand, the 200 rpm samples had a higher milling time because the feeder was emptied slower than with the 400 rpm. The gap setting wide at 200 and 400 rpm showed a higher milling time than in the settings where the stones were closer, showing that the stone gap settings also affected emptying the feeder and, therefore, the feed rate and milling time.

Table 1. Mean values of stone milling rates at different gap settings and characterization of the kernel samples.

Stone gap	Speed (rpm)	Feed time (minutes)		Grain moisture (%)		Test weight (lb/bu)		Flour protein (DM basis)		Flour ash (DM basis)	
Setting wide	200	10.8	±0.7	12.3	±0.2	63.3	±0.1	16.3	±0.0	1.6	±0.0
Setting medium	200	4.6	±0.4	12.3	±0.0	63.5	±0.1	16.4	±0.1	1.7	±0.0
Setting narrow	200	3.0	±0.3	12.3	±0.1	63.4	±0.1	16.3	±0.1	1.7	±0.0
Setting wide	400	3.3	±0.1	12.2	±0.2	63.2	±0.1	16.3	±0.0	1.6	±0.0
Setting medium	400	1.4	±0.1	12.2	±0.1	63.4	±0.2	16.3	±0.1	1.7	±0.0
Setting narrow	400	1.3	±0.2	12.3	±0.2	63.3	±0.2	16.1	±0.1	1.6	±0.1

3.2. Stone mill settings effect in flour

The mean values of the six flour samples' particle size distribution are shown in Figure 8 and Table 2. The statistical analysis showed a significant difference between 200 rpm and 400 rpm, at a 95% and 99% level of confidence in the fractions ≥500 µm, 250-500µm, 75-250 µm (for the statistical analysis, the values of the sieves 212 µm,150 µm, 105 µm and 75 µm were unified) and ≤75 µm. The stone gap and stone rotational speed interaction significantly affected (P<0.0001) the particle size distribution in the flour samples fractions ≥500 µm, 250-500 µm, 75-250 µm (Appendix Table A1). Also, for the fraction ≤75 µm, the ANOVA indicates a significant effect (p<0.0001) from the stone rotational speed and stone gap setting.

The feed rate and feed time have a significant influence on the particle size because of the amount of time the kernel exposed to the grinding surface, where the faster it is it can lower the percentage of fine particles (Deng and Manthey 2016; Ghodke et al. 2008; Hazila Khalid et al. 2016). As shown in Table 2, the flour with the finer particles had a slower feed rate and longer milling time than the others. The stone gap settings and their speed significantly impact the particle size of flour, wherein other studies, the closer and faster stones yield finer particles (Islam and Matzen 1994; Posner and Hibbs 2005).

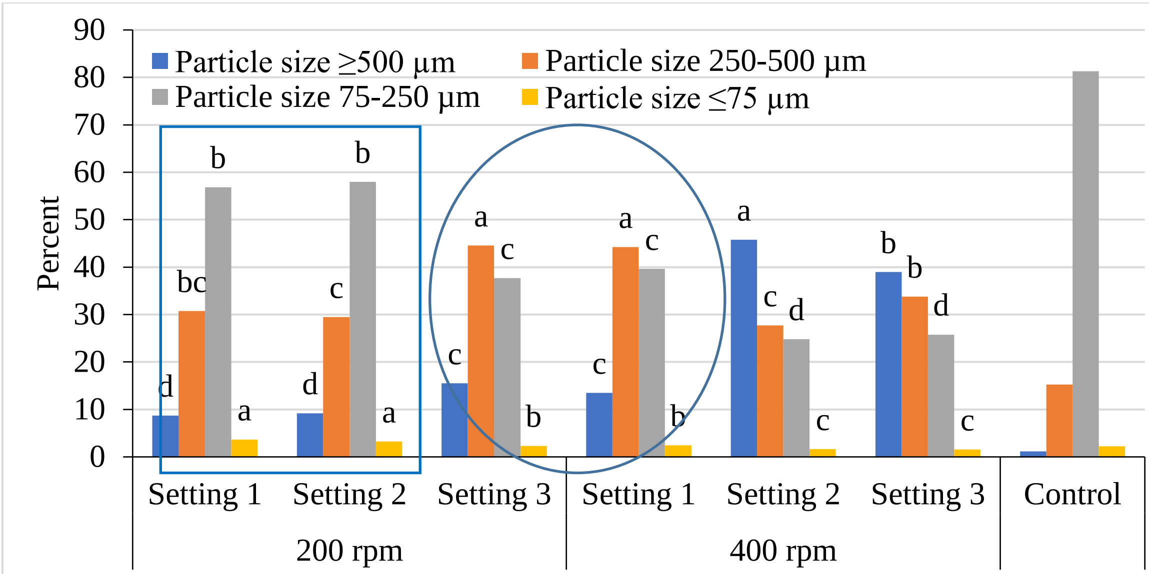

Figure 8. The particle size distribution of control, 200 rpm, and 400 rpm in settings wide, medium, and narrow in HRSW stone mill flour. The values are the mean percentages of each flour in the different fractions.
[a]If the same letter is on the top of the bars and in the same particle size, fractions are not significantly different (P=0.05). The control sample was not part of the LSD analysis (P=0.05).

There were no significant differences (P=0.05) between the 200 rpm with wide and medium gap and were the flours with the smallest particle size and lowest values in the coarse fraction besides the control. The control sample had the highest percentage of the fraction ≤250 µm and flours 200 rpm setting wide, and medium had the closest values. Flour particle size was not significantly different between 200 rpm narrow gap and 400 rpm wide gap. They had the second-highest mean values on the smallest particle size fractions followed by 400 rpm setting medium and at last, 400 rpm setting narrow as the flour with the highest coarse fraction. In Figure 9, the Scanning Electron Microscopic (SEM) imaging are shown for bran particles in flour with the highest fraction of smallest particles (A), followed by the flour with the medium particle size (B), and finally, the one with the coarser fraction (C). The bran particles appear in the dough system and these images show a visual evaluation of each flour's bran size.

Table 2. Mean values of feed rate, particle size fractions, angle of repose and starch damage of control, 200 rpm and 400 rpm in settings wide, medium, and narrow in hard red spring wheat stone mill flour.

Speed (rpm)	Settings	Feed rate		Particle size >500µm	Particle size 500-250µm	Particle size 250-75µm	Particle size <75µm	Angle of repose	Starch damage
		(g/min)		---------------------%-------------------				----α----	----%----
200 rpm	Setting wide	373	±23.7	8.7	30.74	56.86	3.69	22.28	4.44
200 rpm	Setting medium	877	±71.4	9.2	29.48	57.97	3.25	25.16	4.72
200 rpm	Setting narrow	1340	±112.0	15.51	44.57	37.71	2.34	23.98	3.98
400 rpm	Setting wide	1207	±41.2	13.52	44.25	39.62	2.42	21.2	3.69
400 rpm	Setting medium	2803	±236.9	45.8	27.74	24.81	1.64	20.79	2.81
400 rpm	Setting narrow	3067	±352.8	38.94	33.77	25.79	1.55	19.55	3.06
Control				1.18	15.28	81.29	2.22	27.18	4.3
LSD (P=0.05)				3.58	3.21	3.92	0.53	1.33	0.42

[a] Reported on 'As Is' moisture basis

[b] Control sample was not part of the LSD analysis (P=0.05).

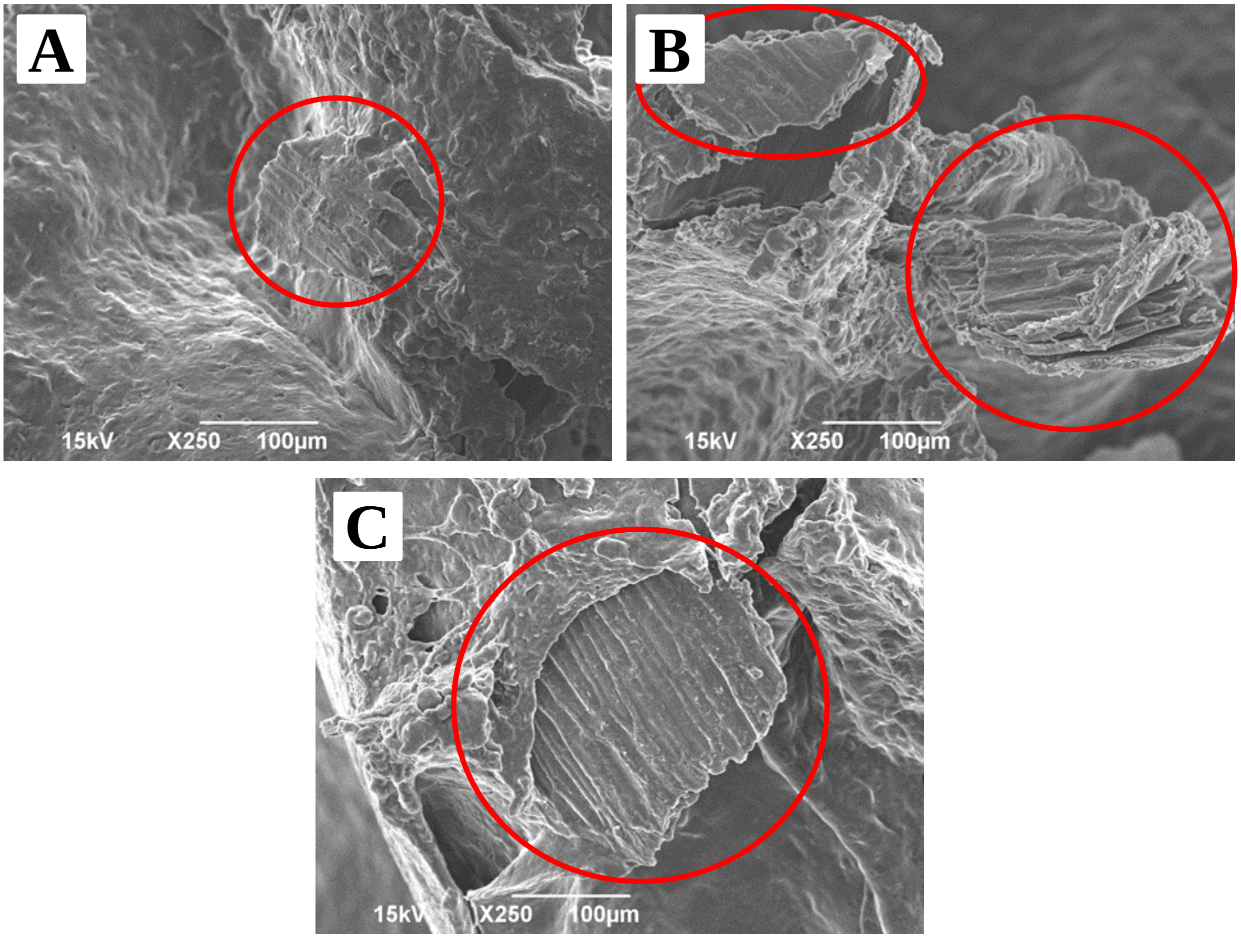

Figure 9. SEM images at 250x magnification level of bran particles of 200 rpm setting wide (A), 400 rpm setting wide (B), and 400 rpm setting narrow (C).

Table 3 shows the correlation between the stones' speed and the feed rate with the different particle size fractions. The feed rate had a positive linear correlation with the stones' speed (r:0.749; $p \leq 0.001$) and the particle size fraction ≥500 µm (r: 0.938; $p \leq 0.001$). Stones' speed and feed rate have a negative correlation with the particle size fractions <500 µm. Even though speed and feed rate affected the ≥500 µm and the ≤75-250 µm ($p \leq 0.001$) fractions significantly, feed rate showed a stronger correlation than the speed setting were lower feed rates outcome in flour with a higher fine particle size fraction.

Table 3. Correlation of the particle size distribution of flour on 200 rpm and 400 rpm at settings wide ,medium, and narrow with the feed rate, feed time, angle of repose and starch damage.

	Particle Size ≥500 µm		Particle Size ≤250-500µm		Particle Size ≤75-250 µm		Particle Size ≤75 µm	
Feed rate [b]	0.939	***	-0.162	NS	-0.888	***	-0.792	***
Feed time [b]	-0.666	**	-0.191	NS	0.784	***	0.639	**
Stones speed [b]	0.719	***	0.022	NS	-0.763	***	-0.673	**
Angle of repose [a]	-0.633	***	-0.023	NS	0.671	***	0.325	NS
Starch damage [b]	-0.912	***	-0.002	NS	0.951	***	0.47	*

NS, nonsignificant (p >0.05); **, $p \leq 0.01$; and ***, $p \leq 0.001$. [a] n=36; [b] n=18.

Figure 10 shows the linear correlation between the feed rate and the particle size ≥500 µm, where the percentage of the coarse particle size fraction increases with the feed rate. The coefficient of determination (R^2) in this model was 0.882, and for the particle size fraction 75-250 µm was the opposite; an increase in feed rate would decrease the percentage of this fraction (R^2= 0.789). The R^2 shows how much the data can fit the model presented in the figures considering the variance explained by the model/ total variance. The feed time showed a non-linear association with the particle size fractions, and this model is the result of a logistic equation. Figure 10 shows the model of the interactions between the increase in mill time results in a decrease of ≥500 µm fraction and how, after the 4th minute of milling, the curve starts to flat and get to a plateau when the milling time keeps increasing. For the ≤75-250 µm particle, size fraction occurs the opposite, where an increase in milling time will also increase its percentage, and after around six minutes, the curve changes and starts a plateau. The R^2 for this non-linear model is considerably high, being 0.938 and 0.930 for ≥500 µm and, respectively.

The mean values for the angle of repose and starch damage are shown in Table 2. The samples 200 rpm gap setting wide and medium did not differ significantly (P=0.05) and had the highest values in starch damage parameter, followed by 200 rpm setting wide, 400 rpm setting wide, 400 rpm setting medium, and the last one 400 rpm setting narrow. The control sample had its value close to the gap setting wide and medium at 200 rpm. The gap between stones and the feed rate shows a significant effect on the particle size and the damaged starch content. Higher feed rate and increase in the aperture show decreased starch damage in flour and the opposite with slower feed rate and the gap between stones closer (Ghodke et al. 2008). The severity of the grinding in the stone mill can increase the starch damage, where the increase in gap and the feed rate shows a decrease in damaged starch and the opposite increases it, as shown in Table 2 (Bayram and Durdu 2005; Ghodke et al. 2008; Prabhasankar and Haridas 2001; Wang et al. 2020). The amount of damaged starch is vital due to its impact on dough properties and baking quality in bread (Ghodke et al. 2008; Mulla et al. 2010; Ross and Kongraksawech 2017; Wang et al. 2020).

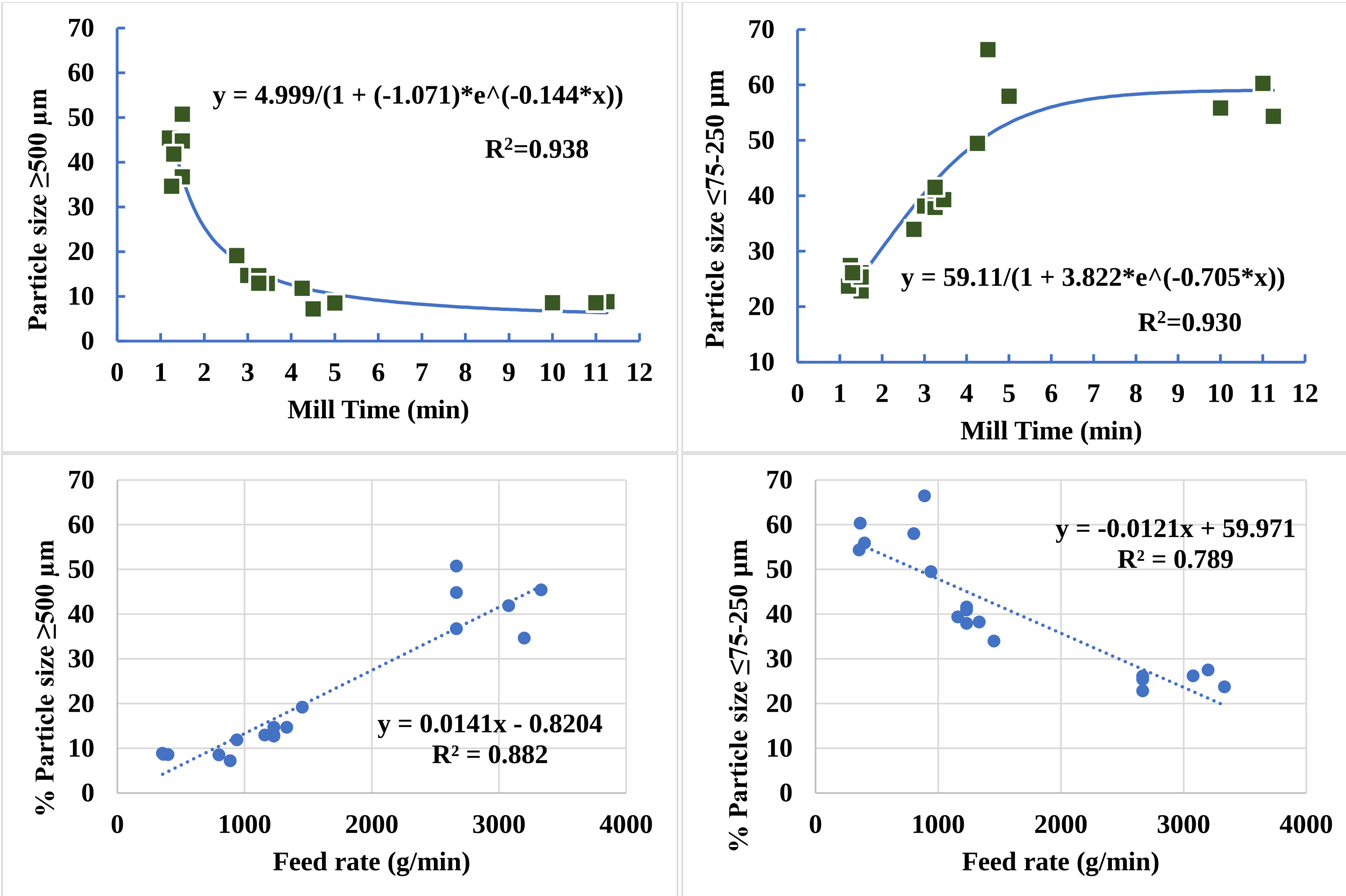

Figure 10. Non-linear relationship between the mill time and the particle size fraction of the flours ≥500 µm and ≤250-75 µm and linear correlation between feed rate (g/min) and the particle size fractions ≥500 µm and ≤250-75 µm.
*The coefficient of determination (R^2) of the analysis was calculated using the mean values.

ANOVA indicate a highly significant effect ($p \leq 0.01$) of the stone rotational speed and gap setting interaction with the starch damage. The feed rate (r: -0.892; $p \leq 0.001$) and stone rotational speed (r: -0.842; $p \leq 0.001$) had a negative linear correlation with the starch damage, meaning that an increase of those settings reduced the amount of starch damage. The positive correlation with the feed time (r: 0.686; $p \leq 0.01$) can explain the increase in starch damage, where the more time the grains were inside the milling chamber, they were exposed to a more extended grinding, increasing the damaged starch. Figure 11 shows the non-linear relationship between mill time's and flour starch damage increasing in time until around the 4th or 5th minute were started to plateau (R^2 =0.881). The milling caused damaged starch or mechanically activated starch due to the various forces inflected on the starch granules causing them to be broken into smaller particles (Wang et al. 2020). The starch damage is mainly influenced by three factors: the quality of the raw material, flour coarseness, and milling conditions (Wang et al. 2020). There was a significantly negative correlation between the starch damage and the ≥500 µm particle size fraction and a positive one with the particle size fraction <250 µm in the flour (Table 3). There is usually an increase in starch damage when smaller particle sizes in the flour, as shown in control and the 200 rpm flours (Wang et al. 2020).

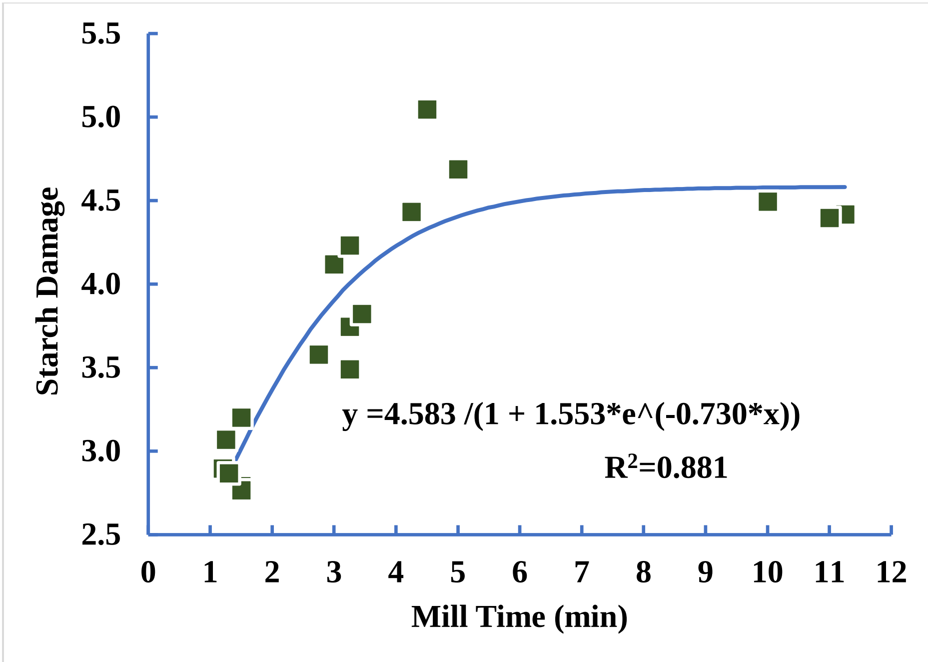

Figure 11. Non-linear relationship between the feed (mill) time and the starch damage.
*The coefficient of determination (R^2) of the analysis was calculated using the mean values

A high increase in damaged starch affects the water retention capacity, leading to a sticky dough, lower extensibility and elasticity in the dough, strong proofing, and undesirable red crust color (Arya et al. 2015; Mulla et al. 2010). Damaged starch has a higher water absorption capacity than undamaged starch granules (Arya et al. 2015). The increase in damage starch correlates with more available reducing sugars, affecting dough formation (Lever et al. 2005; Mulla et al. 2010; Wang et al. 2020). The amylosis of damaged starch produce fermentable sugars like maltose and provide further substrate so the gas cells can continue to expand and increase loaf volume (Arya et al. 2015). In this analysis, the starch damage had a significant linear correlation with the loaf volume (r: 0.658; $p \leq 0.01$). Studies have shown that high percentages of damaged starch (7.2%) compared to lower ones (4.7%) can decrease the flour functionality, delaying the yeast gas production in the dough and lowering the total gas volume (Wang et al. 2020). Starch damage can improve the baking properties at the right level, where several studies show to be in a range between 4.5% and 8.0% were in this study did not exceed

4.7% (Arya et al. 2015). Also, the control sample starch damage was 4.3%, and the other samples did not exceed 4.7%, which is considered an optimum starch damage level.

The stone rotational speed and the gap settings interaction show a significant effect ($p \leq 0.001$) on the angle of repose. The material's particle size directly influences the angle of repose and shows a positive correlation with particle size fractions <250 µm and negative with ≥250 µm (Table 3). The correlation shows the significant effect of those two fractions in the angle of repose and starch damage value, reducing or increasing its measurement. The angle of repose correlates with the particle size distribution and shows the effect of the agglomeration of finer particles. Angle of repose is mostly used in the industry for product storage and transportation to have the right inclination angle so the grains can have a continuous flow without slipping and less damage (Jan et al. 2015). The angle of repose forms a cone pike like formation in the flour and increases cohesion between its particles. The finer particles have more area of exposure between smaller fractions and have more interactions and bonding points (Jan et al. 2015; Kuakpetoon et al. 2001).

The flowing of the particles can be estimated by its angle of repose with excellent flow (25-30) or low (>60), therefore affecting its handling (Jan et al. 2015). In flour, this measurement can be used for characterization but not as a flowability characteristic because flour undergoes compaction and aeration within storage and processing equipment (Bian, Sittipod, Garg & Kingsly Ambrose 2015). The finest particles in the flour agglomerates with the other due to the cohesion with the other particles. As shown in Table 2, the higher measurements for repose angle were the flour with the smaller particle size fractions (Jan et al, 2015; Lumay 2012). The control flour was not part of the statistical analysis and had the highest value of angle of repose combined with the highest <250 µm particle size fraction. The 200 rpm setting medium flour had the following higher angle of repose, which can be explained by its higher content of smaller particle size fractions (<250 µm), and the 400 rpm narrow gap setting had the lowest angle of repose been the flour with the highest amount of coarser particle size fraction (≥500 µm).

3.3. Pasting properties

Starch granules have an essential role in dough viscoelasticity properties and the water binding capacity (Sahlstrom et al. 2003; Sarker et al. 2008). The six different flours were analyzed with the rapid visco analyzer (RVA), and the mean values are presented in Table 4. The RVA analysis data showed a significant difference (P=0.05) among samples produced by the stone rotational speed (200 and 400 rpm), gap settings (wide, medium, and narrow), and their interaction. The gap settings and the speed interaction were significant at $p \leq 0.0001$ on the parameters peak viscosity, breakdown, setback, and at $p \leq 0.001$ with hot paste viscosity and peak time. The final viscosity was affected ($p \leq 0.001$) by the stone rotational speed and pasting temperature by the stone speed ($p \leq 0.0001$) and gap settings ($p \leq 0.01$).

The 200 rpm gap setting wide and medium produced flours that had the highest mean values and significantly different from the other flour samples (P=0.05) for the RVA parameters, such as peak viscosity, hot paste viscosity, breakdown, final viscosity, setback, and peak time. Each measurement gives different information about the starch viscosity in the flour. The 200 rpm setting wide and medium showed the highest mean value peak time and viscosity, resulting in a higher time for cooking and energy cost and more significant granule swelling and water-holding capacity (Table 4). Figure 12 shows the difference in the highest mean value's flour viscosity and the lowest mean value.

Table 4. Mean values of the RVA measurements on the control, 200 rpm, and 400 rpm in settings wide, medium, and narrow in HRSW stone mill flour.

Setting	Speed (rpm)	Peak Viscosity (cP)	Hot Paste Viscosity (cP)	Breakdown (cP)	Final Viscosity (cP)	Setback (cP)	Peak Time (Minutes)	Pasting Temperature (°C)
Setting wide	200	2817.5	1720.8	1096.7	2791.7	1070.8	6.0	75.3
Setting medium	200	2749.3	1680.3	1069.0	2768.3	1088.0	6.0	77.7
Setting narrow	200	2498.5	1589.3	909.2	2751.5	1162.2	5.8	86.1
Setting wide	400	2472.3	1550.5	921.8	2698.7	1148.2	5.8	85.5
Setting medium	400	1495.7	1205.8	289.8	2597.5	1391.7	5.6	88.3
Setting narrow	400	1609.7	1254.8	354.8	2628.8	1374.0	5.6	87.9
Control[a]		2237.5	1101.8	1135.7	2379.3	1277.5	5.9	87.3
LSD (P=0.05)		171.2	89.6	94.5	105.0	53.6	0.1	5.6

[a] Control sample was not part of the LSD analysis (P=0.05).

In this study, the flours with the finer particle size distribution (<250 µm) showed a significantly positive correlation ($p \leq 0.001$) with peak viscosity, hot paste viscosity, breakdown, final viscosity, and peak time (Table 5). Smaller flour particles have shown a higher damage starch, and in other studies, <38 µm flour fractions have shown a higher content of free starch granules. The flour particles also affect the bond between particles where finer particles can create stronger bonds between them. The particles' intermolecular force will depend on the contact area (increased in smaller particles), and the higher it is, the more potent the force between them. Even though this process is not stable, it can affect the pasting properties due to the bonding properties, and it tends to break and bond again (Kuakpetoon et al. 2001). The control sample had a higher percentage of fine particle size fraction but responded differently to the pasting measurements. The starch granules' physicochemical characteristics also affect it's swelling, pasting, gelling, and retrogradation properties (Majzoobi et al. 2013).

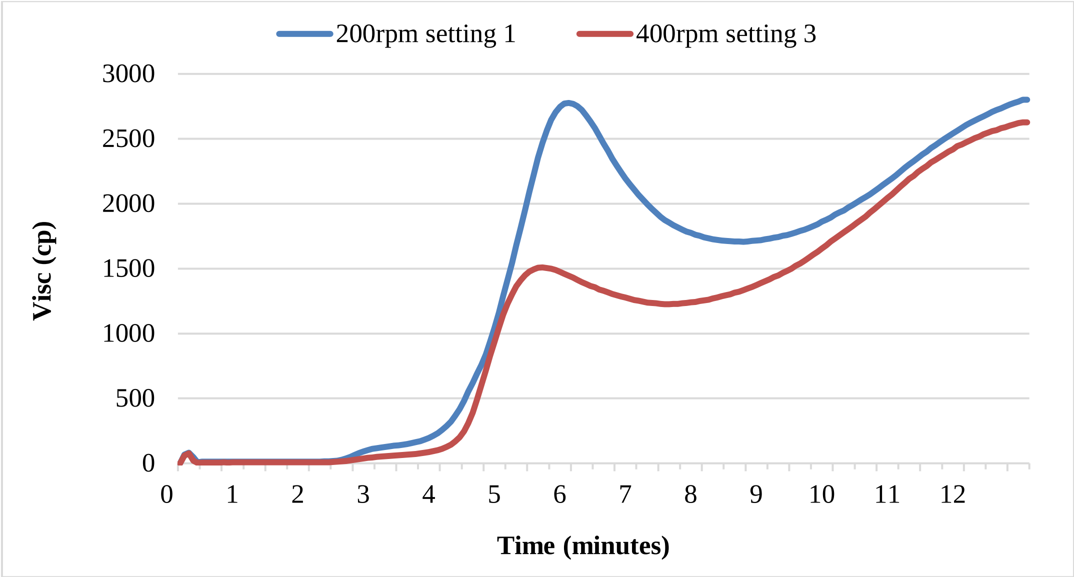

Figure 12. Mean values of the RVA viscosity(cp) measurements on a 13 minutes time frame on 200 rpm setting wide and 400 rpm 0setting narrow flour.

Whole wheat flour with finer particles is easier to integrate into the dough matrix, and this can promote interactions between starch and wheat fiber particles been a possible reason for the increase in viscosity (Rosell et al. 2010; Sun et al. 2015). The peak viscosity could have increased due to the bran particles' higher water-absorbing capacity in the 200 rpm setting wide and medium and reducing the starch capacity of absorbing water, increasing the starches concentration (Sun et al. 2015). The breakdown viscosity expresses the paste's stability during cooking, which considers the maximum and minimum viscosity value. Smaller bran particle size has shown to be less disruptive on the gluten matrix than coarser bran particles (Li et al. 2012). As shown with the control sample, having a higher amount of smaller particle size flour showed higher stability with the highest measurement for the breakdown viscosity.

The final viscosity indicates the cooked paste's stability at 50°C, and the setback value correlates with the retrogradation starch, which shows the viscosity increase on cooling to 50°C (Liang and King 2003). Wheat fiber with a >250 µm particle size can have a stronger effect than finer particle size (≤250µm) on the setback measurement due to the swollen starch leached amylose interaction with the fiber (Sun et al. 2015). In this analysis, the ≥500 µm particle size fraction showed a positive correlation ($p \leq 0.001$) and <250 µm a negative correlation ($p \leq 0.001$) with the setback measurement (Table 5).

The hot paste viscosity or trough is essential because it depends on the material's ability to withstand the heating and shear process, which shows its holding strength (RVA 2015). In the parameters already mentioned, 400 rpm gap settings medium and narrow produced flour that had the lowest mean value. It can be explained because the fiber-enriched dough is also affected by the fiber's particle size, in which the coarser bran particles are more water-insoluble, lowering its viscosity (Rosell et al. 2010).

The high viscosity helps the dough's gas bubbles form the starch gel/coagulated protein matrix into a porous structure, which is vital for bread structure and crumb structure. The starch availability can be reduced due to the dietary fibers retaining water from the starch granules, which can lower the viscosity during heating (Rosell et al. 2010). The fibers interfere with the intermolecular associations between amylopectin molecules affecting the starch pasting and gelatinization properties. Also, in Table 5, the particle size fraction ≥500 µm negatively and 75-250 µm positively correlates ($p \leq 0.001$) with the flour viscosity measurements. The coarser fibers and water-insoluble can lead to lower mixing and overmixing parameters, as shown in the hot paste viscosity measurement (Rosell et al. 2010). The pasting temperature was significantly different (P=0.05) between 200 rpm gap settings wide and medium with 200 rpm setting narrow and 400 rpm regardless the gap setting. The mean values of 200 rpm setting wide and medium had lower pasting temperature, meaning that the temperature at which starch viscosity started to rise, which means faster swelling (Liang and King 2003).

Table 5. Correlation of the particle size distribution of flour on 200 rpm and 400 rpm at settings wide, medium, and narrow with the RVA measurements.

	% Particle size ≥500 µm		% Particle size 250-500 µm		% Particle size 75-250 µm		% Particle size ≤75 µm	
Breakdown	-0.987	***	0.277	NS	0.886	***	0.4109	*
Final Viscosity	-0.606	***	0.155	NS	0.541	***	0.3362	*
Setback	0.942	***	-0.219	NS	-0.888	***	-0.2579	NS
Peak Time	-0.891	***	-0.002	NS	0.948	***	0.2867	NS
Pasting Temperature	0.587	***	0.308	NS	-0.774	***	-0.2912	NS

NS, nonsignificant (p >0.05); **, $p \leq 0.01$; and ***, $p \leq 0.001$. n=36;

3.4. Viscoelastic properties

The farinograph results are shown in Table 6 and showed a significant difference (P=0.05) between samples and a significant effect of the gap settings ($p \leq 0.001$) and stone rotational speed ($p \leq 0.0001$) with Farinogram water absorption (14% basis). ANOVA showed a significant effect of the stone speed and gap setting interaction with the stability ($p \leq 0.001$) and peak time ($p \leq 0.0001$) of the dough. These measurements indicate the dough's development by the action of mixer blades and estimate its rheological properties. The 200 rpm setting wide and medium had the highest water absorption, and the 400 rpm setting medium and narrow had the lowest one. The control showed a water absorption closer to the 400 rpm flours.

Table 6. Farinograph measurements of control, 200 rpm, and 400 rpm at setting wide, medium and narrow HRSW stone mill flours.

Stone gap	Speed (rpm)	Absorption (%, 14% MB [a])	Peak Time (Minutes)	Stability (Minutes)	MTI [b] (BU [c])	Quality Number
Setting wide	200	68.8	7.0	8.5	26.3	143.0
Setting medium	200	68.7	7.0	8.6	24.0	149.0
Setting narrow	200	68.3	7.6	9.2	22.3	160.3
Setting wide	400	67.6	6.7	8.4	25.7	151.3
Setting medium	400	66.8	10.3	12.9	17.3	212.0
Setting narrow	400	66.9	9.6	11.9	17.0	201.7
Control [d]		67.2	5.7	9.2	26.0	135.0
LSD (P=0.05)		0.4	0.8	1.3	-	-

[a] MB = Moisture basis
[b] MTI = Mixing tolerance index
[c] BU = Brabender units
[d] Control sample was not part of the LSD analysis (P=0.05).

Higher water absorption negatively correlates with dough stability and a positive correlation with starch damage (Ghodke et al. 2008; Kang et al. 2019; Prabhasankar and Haridas 2001; Rosell et al. 2010). The farinograph water absorption (r:0.923; $p \leq 0.001$) and baking absorption (r:0.918 ; $p \leq 0.001$) had a high positive correlation with starch damage. As mentioned before, damaged starch granules can increase water absorption in flour (Wang et al. 2020). In bread making, higher water absorption is positive economically, and it is determinant in bread quality resulting in greater loaf volume potential (Baasandorj et al. 2015).

The particle size of the flour (endosperm) also affects water absorption, where finer fractions have a positive correlation and coarser fractions a negative effect (Table 7) (Posner and Hibbs 2005; Wang et al. 2017). Whole wheat flour bread has shown higher water absorption in bread. The bran particles compete for the water in the dough, and its higher water absorption can be explained by the great number of hydroxyl groups in the fiber structure (Rosell et al. 2010). Bran particles have a higher water retention capacity in coarser particles (mean vales ≥500 µm), but the finer the bran particles, the faster they can absorb water too (Doblado-Maldonado et al. 2012; Wang et al. 2017). Coarser bran particles (≥500 µm) need more time to hydrate and showed a negative correlation with farinograph water absorption (r: -0.877; $p \leq 0.001$) and baking absorption (r:-0.826; $p \leq 0.001$).

Table 7. Correlation of the particle size distribution of flour on 200 rpm and 400 rpm at settings wide, medium, and narrow with the Farinograph measurements.

	% Particle size ≥500 µm		% Particle size >250µm		% Particle size >75µm		% Particle size ≤75 µm	
Farinograph absorption (14% basis)	-0.877	***	0.0831	NS	0.864	***	0.476	**
Farinograph stability (min)	0.867	***	-0.371	*	-0.728	***	-0.270	NS
Farinograph peak time (min)	0.917	***	-0.359	*	-0.779	***	-0.301	NS

NS, nonsignificant (p >0.05); **, $p \leq 0.01$; and ***, $p \leq 0.001$. n=36;

Farinograph stability and peak time, the flours with the highest value were 400 rpm gap settings medium and narrow. The other flours have the lowest values for stability and peak time, 200 rpm gap regardless of the gap setting 400 rpm gap setting wide (P=0.05). The control also showed a lower peak time and lower stability than 400 rpm setting medium and narrow. Figure 13 shows the graph of the measurements of the highest and lower value in the farinograph measurements. The 400 rpm setting medium and narrow also had the lowest starch damage; the dough development time (r:-0.785; $p \leq 0.001$) and stability (r: -0.765; $p \leq 0.001$) have shown a negative correlation with starch damage content (Haridas Rao et al. 1989).

The farinograph measurements are essential for bakers to know the amount of water required to reach a standard consistency and dough profile. The stability shows the strength and tolerance of mixing of the flour and the number of minutes it can stay with this same strength during mixing; longer stability times is a usual trait for hearth and bread production (Farinograph-TS 2018). The values of quality number in Table 6 showed that the higher the value it represents stronger flours, as shown with the 400 rpm gap setting medium and narrow. The peak time or mixing time is the time needed for the dough to develop its maximum consistency after adding water, and usually, stronger flours have longer development times. The 400 rpm setting medium and narrow had higher values for the dough development showing that it needed more time until the flour particles were wholly hydrated and reaching its maximum consistency (Sarker et al. 2008). These measurements help evaluate the mechanical behavior of the flour in bread making. It also helps to know the optimum kneading time to reach the optimum dough formation, which balances the structuring and shearing effect on the protein network (Cuq et al. 2003).

The flour with coarser fraction, been 400 rpm setting medium, and narrow had higher stability that correlates with flour stability and, most of the time has longer mixing times. Figure 13 shows the first addition of water to the dough development the 200 rpm gap setting wide peaked its dough consistency faster than the 400 rpm setting narrow. In the stability and peak time measurements, there is a positive correlation between the particle size fraction ≥500 μm ($p \leq 0.001$) and a negative with 250-500 μm ($p \leq 0.05$), 75-250 μm ($p \leq 0.001$), and ≤75 μm (Table 7). The stability is affected by the type of mill, the variety, and their interaction. Ross and

Kongraksawech (2017) show that depending on the variety and the milling, it changed its particle size and responded differently for the stability and development time. The coarser median particle size (333.0µm) showed higher stability and development time, but these measurements increased or decreased depending on the variety and the mill (Ross and Kongraksawech 2017). The dietary fiber particle size affects its stability, where a mixture of fine and coarse particles shows a positive correlation; fine particle size shows a negative effect (Rosell et al. 2010). Small particle size in wheat bran can decrease the dough mixing tolerance, reduce its mixing time, and increase the MTI values, as shown in Table 6 (Zhang and Moore 1997). The mixing tolerance index (MTI) increased when the bran particle size decreased, meaning that it is less tolerant of mixing (Zhang and Moore 1997). By adding fiber, depending on the material, stability can increase. However, if it exceeds a certain percentage (>5%) in the formulation, it can also shorten its stability and development time (Mis et al. 2012).

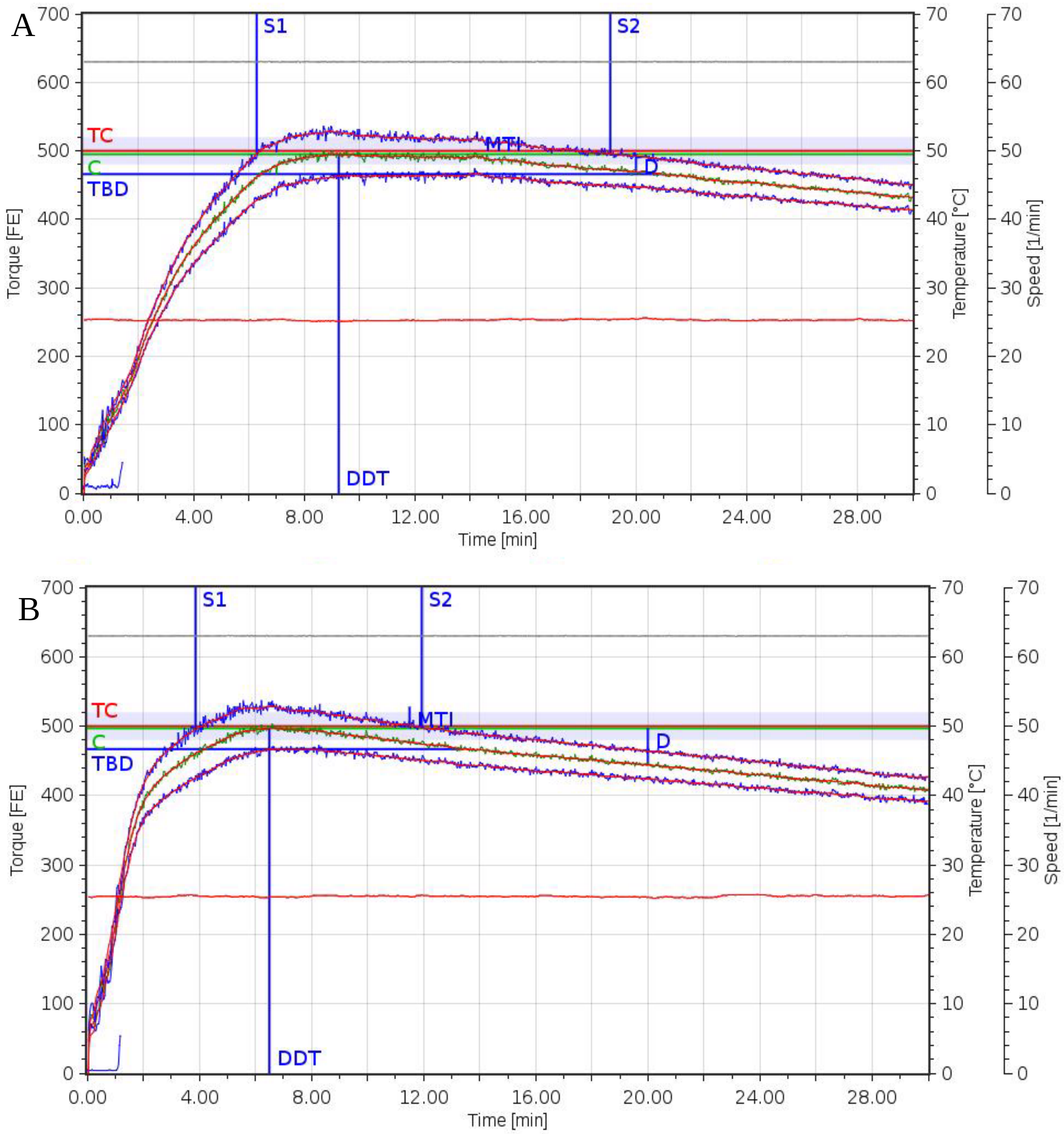

Figure 13. Farinograph graphic results of 400 rpm setting narrow (A) and 200 rpm setting wide (B).

3.5. Effect of particle size distribution on bread features

Milling settings directly influence the particle size of the flour and the baking product (Ross and Kongraksawech 2017). The particle size distribution is a functional characteristic of the flour and influence water absorption, rheological properties of the dough, loaf volume, crumb color, and firmness (Ross and Kongraksawech 2017). The stone mill's speed and gap setting interaction significantly affected the baking absorption ($p \leq 0.05$) and loaf volume ($p \leq 0.01$). The loaf weight was significantly affected ($p \leq 0.05$) by the gap setting, while the stone rotational speed affected the bread crumb firmness ($p \leq 0.001$). The water absorption of the 200 rpm flours was higher than the 400 rpm, as shown in the farinograph results. In the baking industry, water absorption is an important feature, and sometimes flour with low water absorption is associated with not the best quality bread (Synder 2007). The control sample also showed similar water absorption to the 400 rpm gap setting medium and narrow.

Table 8. Baking measurements of control, 200 rpm, and 400 rpm at setting wide, medium and narrow HRSW stone mill flours.

Setting	Speed (rpm)	Baking Absorption (%, 14% MB[a])	Loaf Weight (g)	Loaf Volume (cm^3)	Crumb Firmness (mN)
Setting wide	200	73.1	465.2	1895	781.0
Setting medium	200	73.2	461.2	1949	827.2
Setting narrow	200	72.5	466.4	1863	823.5
Setting wide	400	71.4	465.8	1817	905.7
Setting medium	400	70.7	459.8	1734	884.0
Setting narrow	400	70.8	463.5	1746	960.3
Control[b]		70.7	460.8	1811	1677.0
LSD (P=0.05)		0.5	5.8	59.8	113

[a] MB = Moisture basis

[b] Control sample was not part of the LSD analysis (P=0.05).

The loaf weight values were not significantly different between 200 rpm flours and 400 rpm gap setting wide and fine. The 400 rpm gap setting medium had the highest value for the loaf weight and significantly different to the other flours except 200 rpm gap setting medium and 400 rpm gap setting fine. The parameter loaf weight did not show a significant linear correlation with the stone rotational speed, feed rate, and the different particle size fractions.

The flours 200 rpm setting wide and medium, which are also the ones with lower coarse particles (≥500 µm), showed the highest and significantly different (p=0.05) loaf volumes from the other flours and the 200 rpm flours with the softest crumb texture (Table 8). There is no exact information of the right particle size for fibers to integrate the gluten structure easily, but according to Rosell et al. (2010), fine particles are easier integrated. The bran physically and chemically disrupts the gluten network development in whole wheat bread, but smaller bran particles can be less disruptive resulting in a continuous and compact gluten network (Li et al. 2012). The percentage of bran and particle size also influences the loaf volume. Low concentration and small to median particle size can increase loaf volume, RVA peak, and final viscosities, and reduce crumb texture (Doblado-Maldonado et al. 2012; Hemdane et al. 2016; Li et al. 2012; Ross and Kongraksawech 2017). Smaller bran particles also can increase the dough extensibility, allowing the expansion of gas bubbles during proofing and cooking, producing a larger loaf volume (Wang et al. 2017). However, if the medium particle size is too fine (97 µm), loaf volumes can decrease, and a 235 µm median in the particle size have shown larger loaf volumes (Li et al. 2012). Even the control sample having the finer particle size distribution did not have the highest loaf volume (Table 8).

Starch impacts the bread structure and crumb texture (Sahlstrom et al. 2003). The bran negatively affects the loaf volume, starch retrogradation, and bread staling (Cai et al. 2014). In this study, the damaged starch content did not exceed 4.7% and affected water absorption, loaf volume, starch viscosity, and dough extensibility positively (Table A8). Flour with starch damage also increases the addition of water to the formulation. It decreases starch degradation, resulting in better shelf life and a more excellent digestibility of the starch in the bread (Wang et al. 2020).

Table 9. Flour and bread color (L*, a*, b*) mean values of samples Control, 200 rpm, and 400 rpm at setting wide, medium, and narrow HRSW stone mill flours.

		Flour Color [a]			Bread Color [a]		
Stone gap	Speed (rpm)	L*	a*	b*	L*	a*	b*
Setting wide	200	77.9	1.7	10.6	57.4	6.9	19.3
Setting medium	200	78.9	1.7	10.5	57.5	6.9	19.3
Setting narrow	200	76.7	2.0	11.0	56.2	6.9	19.0
Setting wide	400	76.3	2.1	11.4	56.6	6.9	19.2
Setting medium	400	74.2	2.5	11.8	55.4	6.9	19.1
Setting narrow	400	74.5	2.5	11.8	55.4	6.9	19.0
Control [b]		78.8	1.4	11.2	57.1	6.8	20.2
LSD (P=0.05)		0.6	0.1	0.1	1.2	0.2	0.4

[a] Flour and bread color were measured using the CIE LAB color space
[b] Control sample was not part of the LSD analysis (P=0.05).

The bread texture increases with larger bran particle size in flat-bread, becoming less cohesive and harder crumb (Majzoobi et al. 2013). Larger bran particles can form a more discontinuous and fracture gluten network, not retaining the CO^2 gas during baking and releasing it in the early stages leading to inferior baking results like increase crumb texture (firmness) and lower loaf volume (Li et al. 2012). Also, coarser bran particles can have a higher water holding capacity than starch granules, which leads to an increase in starch retrogradation and bread staling (Sun et al. 2015). The increase in the flour’s water absorption can also enhance initial softness and decrease bread firmness due to the water’s plasticization effect in the bread network (Hug-Iten et al. 2003). The Farinograph water absorption has a positive correlation with loaf volume (r: 0.576; $p \leq 0.001$) and a negative correlation with crumb firmness (r: -0.367; $p \leq 0.05$). The bread firmness had a negative correlation with the baking water absorption ($p \leq 0.05$) and a positive correlation with the starch setback ($p \leq 0.01$) and pasting temperature ($p \leq 0.05$). The setback measurement showed a positive correlation with ≥500 μm particle size, inferring that the formation of this intra and intergranular amylose networks induces firming in the bread and positively correlate with coarser particle size flours (Hug-Iten et al. 2003) (Table5).

Table 10. Correlation of the particle size distribution of flour on 200 rpm and 400 rpm at settings wide, medium, and narrow with the flour and bread color (L*, a*, b*).

		Particle Size ≥500 µm		Particle Size >250µm		Particle Size >75µm		Particle Size ≤75 µm	
Flour Color	L*	-0.893	***	0.004	NS	0.937	***	0.369	*
	a*	0.919	***	-0.029	NS	-0.947	***	-0.407	*
	b*	0.867	***	0.081	NS	-0.934	***	-0.533	***
Bread Color	L*	-0.590	***	-0.011	NS	0.653	***	-0.005	NS
	a*	0.219	NS	-0.101	NS	-0.210	NS	0.255	NS
	b*	-0.256	NS	-0.112	NS	0.324	NS	0.131	NS

Flour and bread color were measured using the CIE LAB color space; NS, nonsignificant (*p* >0.05); **, $p \leq 0.01$; and ***, $p \leq 0.001$; n=36.

Also, bran affects bread and flour color (Hemdane et al. 2016). Table 9 shows the mean values of the measurements of the flour and bread color. The color measurement was done with the CIE LAB color values were 'L' stands for the lightness (0-100), 'a' for red (+a) and green (-a) value, and 'b' for the yellow (+b) and blue (-b) value (Posner and Hibbs 2005). Besides the control sample, the 200 rpm setting medium had the highest and significantly different (p=0.05) from the rest of the flour in lightness value and the lowest yellow and red values. This flour also had the lowest values for ≥500 µm while the flour 400 rpm gap settings medium and narrow that had higher values of the coarser fractions had the lowest values for lightness and higher for yellow and red values. The color in the bread was not significantly different between samples for the yellow and red values; just for lightness were 200 rpm setting medium had the highest value and significantly different from the other samples except for the 200 rpm and 400 rpm setting wide. Table 10, shows the values of the correlation between the different fractions of particle size with the color. The fractions ≥500 µm showed negative correlation for the flour ($p \leq 0.001$;

r: -0.893) and bread ($p \leq 0.001$; r:-0.590) lightness. The incorporation of wheat bran and larger bran particle size gives a darker color to the crumb than smaller bran particles (Hemdane et al. 2016; Majzoobi et al. 2013).

4. CONCLUSIONS

Whole wheat flour was successfully produced with the stone mill and made six flours with different particle size distributions. After milling, the flour temperature was below 40°C and resulted in low starch damage flour (below 5%). The stone gap, stone rotational speed, and feed rate significantly affected the flour's particle size distribution. The whole wheat flour with the configuration at 200 rpm had a larger fine particle size fraction (≤250 µm) than at the 400 rpm stone speed. Feed rate showed a significant effect on the particle size, where the lower feed rate resulted in higher fine particles (≤250 µm) and the higher feed rate in coarser particle size fraction (≥500 µm).

The six flour were mainly separated between 200 rpm settings wide and medium, with the finer particle size fraction, 200 rpm setting narrow, and 400 rpm setting wide, with the medium particle size fraction and 400 rpm setting medium and narrow with the coarser particle size fraction. The whole wheat flours with the fine particle size fraction (200 rpm setting medium) showed the highest values in starch damage, angle of repose, peak viscosity (RVA), final viscosity, breakdown, hot paste viscosity, water absorption, loaf volume, lighter bread and flour color. The flours with the fine particle size distribution, which in this study were the ones with the highest percentage <250µm, showed better dough and bread characteristics. The flour from 400 rpm settings medium and narrow showed a higher crumb firmness, darker flour and bread color, dough stability, dough development time. The flour particle size significantly affected the flour, and bread quality, where flour with a higher particle size ≤250 µm showed better traits such as higher loaf volume and less crumb firmness than the one with a higher percentage >250 µm.

5. FUTURE RESEARCH

To complement the study of the effect of stone mill settings on flour, dough, and bread quality will be interesting to have a controlled feeder and evaluate how it affects the particle size distribution. A controlled feed rate combined with different mill settings can result in finer particle size fractions and compare these results with higher percentages of fine particle size flours. For the whole wheat milling, it will also be helpful to measure the gap between the stones to have a base number of how close they could still impact and create smaller particles in the flour. Also, different wheat conditioning could be different seed moisture and assess their performance in the mill. The grain moisture affects the breakage of the grain in the mill and could help to have a finer particle size extraction.

The effect of the particle size flour distribution on the dough and bread quality would be interesting to evaluate the impact of the non-starch polysaccharides. An example of this will be if the different particle size distribution also affected the arabinoxylans in wheat flour. Another exciting investigation can be the change of the whole wheat flour properties in time to see the flours' effect with different particle size distribution in the dough rheology and bread quality. Whole wheat flour usually has a shorter shelf life due to the lipids and lipid degrading enzyme that reduces functionality, palatability and nutritional properties. Also, evaluate the crumb firmness of the bread and have a panel to assess the particle size distribution of the flour in the taste and texture of the bread.

In the bread-making process, it would be interesting to evaluate different fermentation times and bread-making methods. Coarser bran particles showed a better performance with extended fermentation times because the coarser particles need a longer time to hydrate. It would be interesting to see which bread-making process can be better suited depending on the whole wheat flour particle size distribution and evaluate if they all can reach a similar quality with the right procedures. The sourdough method can also be used for whole wheat bread and see which particle size distribution had the best performance and bread quality.

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APPENDIX

Table A1. F-value for the particle size fractions obtained by the stone mill on whole-wheat flour milling.

Parameters	Sources of variation	DF	Sum of Squares	Mean Square	F Value	Pr > F
Particle Size ≥500 µm	Speed (SPD)	1	4205.584	4205.584	459.520	****
	Settings (SIV)	2	2114.194	1057.097	115.500	****
	SPD*SIV	2	1528.898	764.449	83.530	****
	Rep	2	28.850	14.425	1.580	
	Error	28	256.258	9.152		
Particle Size ≤250-500µm	Speed (SPD)	1	0.931	0.931	0.130	
	Settings (SIV)	2	773.015	386.508	52.440	****
	SPD*SIV	2	906.024	453.012	61.460	****
	Rep	2	37.488	18.744	2.540	
	Error	28	206.377	7.371		
Particle Size ≤75-250 µm	Speed (SPD)	1	3883.780	3883.780	353.920	****
	Settings (SIV)	2	1646.930	823.465	75.040	****
	SPD*SIV	2	732.683	366.341	33.380	****
	Rep	2	108.505	54.252	4.940	*
	Error	28	307.263	10.974		
Particle Size ≤75 µm	Speed (SPD)	1	13.396	13.396	67.480	****
	Settings (SIV)	2	7.370	3.685	18.560	****
	SPD*SIV	2	1.019	0.509	2.570	
	Rep	2	73.818	36.909	185.920	****
	Error	28	5.559	0.199		
Angle of Repose	Speed (SPD)	1	97.799	97.799	76.840	****
	Settings (SIV)	2	11.969	5.985	4.700	*
	SPD*SIV	2	22.087	11.043	8.680	***
	Rep	2	7.584	3.792	2.980	
	Error	28	35.635	1.273		
Starch Damage	Speed (SPD)	1	6.422	6.422	119.490	****
	Settings (SIV)	2	0.893	0.446	8.300	**
	SPD*SIV	2	1.184	0.592	11.010	**
	Rep	2	0.014	0.007	0.130	
	Error	10	0.537	0.054		

*Significant at P≤0.05, **Significant at P≤0.01; *** Significant at P≤0.001; **** Significant at P≤0.0001; DF= Degrees of freedom.

Table A2. Mean values of the particle size fractions between 75-250 µm of control, 200 rpm and 400 rpm in gap settings wide, medium, and narrow in hard red spring wheat stone mill flour.

Speed (rpm)	Settings	Particle Size 250-212 µm (%)	Particle Size 212-150 µm (%)	Particle Size 150-105 µm (%)	Particle Size 105-75 µm (%)
200	Setting wide	12.7	17.5	11.5	15.2
200	Setting medium	11.9	17.1	12.8	16.1
200	Setting narrow	9.1	9.7	7.5	11.5
400	Setting wide	9.9	10.5	7.9	11.3
400	Setting medium	5.1	6.6	5.3	7.8
400	Setting narrow	5.5	6.6	5.4	8.3
Control[a]		11.6	27.2	21.8	20.7
LSD (P=0.05)		0.8	1.2	1.4	1.5

[a] Control sample was not part of the LSD analysis (P=0.05).

Table A3. F-value for RVA parameters obtained by the stone mill on whole-wheat flour milling.

Parameters	Sources of variation	DF	Sum of Squares	Mean Square	F Value	Pr > F
Peak Viscosity	Speed (SPD)	1	6188485.000	6188485.000	295.190	****
	Settings (SIV)	2	2506736.000	1253368.000	59.790	****
	SPD*SIV	2	1254049.000	627025.000	29.910	****
	Rep	2	15787.000	7893.583	0.380	
	Error	28	586997.000	20964.000		
Hot Paste Viscosity	Speed (SPD)	1	959094.000	959094.000	167.220	****
	Settings (SIV)	2	332589.000	166294.000	28.990	****
	SPD*SIV	2	139068.000	69534.000	12.120	***
	Rep	2	7016.222	3508.111	0.610	
	Error	28	160594.000	5735.516		
Breakdown	Speed (SPD)	1	2275069.000	2275069.000	356.640	****
	Settings (SIV)	2	1013424.000	506712.000	79.430	****
	SPD*SIV	2	559789.000	279895.000	43.880	****
	Rep	2	7740.056	3870.028	0.610	
	Error	28	178619.000	6379.236		
Final Viscosity	Speed (SPD)	1	149382.000	149382.000	18.960	***
	Settings (SIV)	2	27811.000	13905.000	1.760	
	SPD*SIV	2	9258.167	4629.083	0.590	
	Rep	2	40767.000	20384.000	2.590	
	Error	28	220627.000	7879.524		
Setback	Speed (SPD)	1	351451.000	351451.000	171.400	****
	Settings (SIV)	2	171734.000	85867.000	41.880	****
	SPD*SIV	2	77750.000	38875.000	18.960	****
	Rep	2	51978.000	25989.000	12.670	***
	Error	28	57414.000	2050.504		
Peak Time	Speed (SPD)	1	0.810	0.810	177.320	****
	Settings (SIV)	2	0.214	0.107	23.460	****
	SPD*SIV	2	0.083	0.041	9.080	***
	Rep	2	0.025	0.013	2.780	
	Error	28	0.128	0.005		
Pasting Temperature	Speed (SPD)	1	507.751	507.751	22.520	****
	Settings (SIV)	2	267.098	133.549	5.920	**
	SPD*SIV	2	144.003	72.002	3.190	
	Rep	2	45.962	22.981	1.020	
	Error	28	631.219	22.544		

*Significant at $P \leq 0.05$, **Significant at $P \leq 0.01$; *** Significant at $P \leq 0.001$; **** Significant at $P \leq 0.0001$; DF= Degrees of freedom.

Table A4. F-value for Farinograph parameters obtained by the stone mill on whole-wheat flour milling.

Parameters	Sources of variation	DF	Sum of Squares	Mean Square	F Value	Pr > F
Farinograph absorption (%, 14% Mba)	Speed (SPD)	1	20.703	20.703	156.530	****
	Settings (SIV)	2	2.625	1.313	9.920	***
	SPD*SIV	2	0.852	0.426	3.220	
	Rep	2	0.065	0.033	0.250	
	Error	28	3.703	0.132		
Farinograph stability	Speed (SPD)	1	47.243	47.243	38.170	****
	Settings (SIV)	2	38.257	19.128	15.460	****
	SPD*SIV	2	29.864	14.932	12.070	***
	Rep	2	3.235	1.618	1.310	
	Error	28	34.653	1.238		
Farinograph peak time	Speed (SPD)	1	26.832	26.832	56.320	****
	Settings (SIV)	2	25.173	12.586	26.420	****
	SPD*SIV	2	19.588	9.794	20.560	****
	Rep	2	2.461	1.231	2.580	
	Error	28	13.341	0.476		

*Significant at P≤0.05, **Significant at P≤0.01; *** Significant at P≤0.0001; DF= Degrees of freedom.

Table A5. F-value for baking measurements obtained by the stone mill on whole-wheat flour milling.

Parameters	Sources of variation	DF	Sum of Squares	Mean Square	F Value	Pr > F
Baking Absorption (%, 14% Mba)	Speed (SPD)	1	34.928	34.928	166.890	****
	Settings (SIV)	2	2.238	1.119	5.350	**
	SPD*SIV	2	1.359	0.680	3.250	*
	Rep	2	0.281	0.141	0.670	
	Error	28	5.860	0.209		
Loaf Weight	Speed (SPD)	1	13.814	13.814	0.570	
	Settings (SIV)	2	177.284	88.642	3.630	*
	SPD*SIV	2	17.144	8.572	0.350	
	Rep	2	298.524	149.262	6.120	**
	Error	28	682.884	24.389		
Loaf Volume	Speed (SPD)	1	168100.000	168100.000	65.650	****
	Settings (SIV)	2	17106.000	8552.778	3.340	*
	SPD*SIV	2	29817.000	14908.000	5.820	**
	Rep	2	255343.000	127672.000	49.860	****
	Error	28	71690.000	2560.367		
Crumb Firmness	Speed (SPD)	1	101336.000	101336.000	11.100	***
	Settings (SIV)	2	15322.000	7661.028	0.840	
	SPD*SIV	2	11149.000	5574.694	0.610	
	Rep	2	63654.000	31827.000	3.490	*
	Error	28	255659.000	9130.671		

*Significant at P≤0.05, **Significant at P≤0.01; *** Significant at P≤0.001; **** Significant at P≤0.0001; DF= Degrees of freedom.

Table A6. Correlation between Baking measurements and particle size fractions for 200 and 400 rpm at gap settings wide, medium, and narrow stone mill HRSW samples.

	% Particle size ≥500 µm		% Particle size >250µm		% Particle size >75µm		% Particle size ≤75 µm	
Baking absorption	-0.826	***	-0.005	NS	0.853	***	0.497	**
Loaf weight	-0.210	NS	0.242	NS	0.047	NS	0.447	**
Loaf volume	-0.623	***	0.061	NS	0.685	***	-0.268	NS
Loaf firmness	0.357	*	0.173	NS	-0.491	**	0.006	NS

*Significant at P≤0.05, **Significant at P≤0.01; *** Significant at P≤0.001; **** Significant at P≤0.0001.

Table A7. F-value for flour and bread color CIE LAB color space obtained on 200 rpm and 400 rpm at gap settings wide, medium, and narrow.

Parameters	Sources of variation	DF	Sum of Squares	Mean Square	F Value	Pr > F
Flour Color L	Speed (SPD)	1	73.359	73.359	269.540	****
	Settings (SIV)	2	14.175	7.088	26.040	****
	SPD*SIV	2	17.020	8.510	31.270	****
	Rep	2	0.643	0.322	1.180	
	Error	28	7.620	0.272		
Flour Color A	Speed (SPD)	1	2.496	2.496	328.290	****
	Settings (SIV)	2	0.644	0.322	42.320	****
	SPD*SIV	2	0.334	0.167	21.940	****
	Rep	2	0.006	0.003	0.370	
	Error	28	0.213	0.008		
Flour Color B	Speed (SPD)	1	7.849	7.849	584.300	****
	Settings (SIV)	2	1.047	0.524	38.970	****
	SPD*SIV	2	0.599	0.299	22.280	****
	Rep	2	0.365	0.183	13.600	****
	Error	28	0.376	0.013		
Bread Color L	Speed (SPD)	1	13.153	13.153	12.430	**
	Settings (SIV)	2	8.239	4.119	3.890	*
	SPD*SIV	2	3.376	1.688	1.600	
	Rep	2	20.415	10.207	9.640	***
	Error	28	29.634	1.058		
Bread Color A	Speed (SPD)	1	0.025	0.025	1.040	
	Settings (SIV)	2	0.016	0.008	0.330	
	SPD*SIV	2	0.020	0.010	0.410	
	Rep	2	0.346	0.173	7.190	**
	Error	28	0.673	0.024		
Bread Color B	Speed (SPD)	1	0.070	0.070	0.780	
	Settings (SIV)	2	0.267	0.134	1.490	
	SPD*SIV	2	0.155	0.077	0.860	
	Rep	2	1.758	0.879	9.810	***
	Error	28	2.511	0.090		

*Significant at $P \leq 0.05$, **Significant at $P \leq 0.01$; *** Significant at $P \leq 0.001$; **** Significant at $P \leq 0.0001$; DF= Degrees of freedom.

Table A8. Correlation between starch damage and RVA measurements with angle of repose, baking and farinograph measurements for 200 and 400 rpm at gap settings wide, medium, and narrow stone mill HRSW samples.

	Starch damage		Peak Viscosity		Hot Paste Viscosity		Breakdown		Final Viscosity		Setback		Peak Time		Pasting Temperature	
Angle of repose	0.745	***	0.671	***	0.663	***	0.668	***	0.472	**	-0.620	***	0.683	***	-0.507	**
Baking Absorption	0.918	***	0.843	***	0.837	***	0.836	***	0.593	***	-0.785	***	0.844	***	-0.657	***
Loaf Weight	-0.017	NS	0.232	NS	0.240	NS	0.224	NS	0.431	**	-0.018	NS	0.083	NS	-0.197	NS
Loaf Volume	0.658	**	0.605	***	0.593	***	0.605	***	0.169	NS	-0.756	***	0.699	***	-0.460	**
Crumb Firmness	-0.375	NS	-0.368	*	-0.352	*	-0.374	*	-0.050	NS	0.488	**	-0.479	**	0.365	*
Farinograph absorption (14% basis)	0.923	***	0.875	***	0.856	***	0.876	***	0.546	***	-0.851	***	0.869	***	-0.620	***
Farinograph stability (min)	-0.765	***	-0.818	***	-0.784	***	-0.830	***	-0.439	**	0.827	***	-0.705	***	0.442	**
Farinograph peak time (min)	-0.785	***	-0.869	***	-0.830	***	-0.883	***	-0.441	**	0.895	***	-0.776	***	0.450	**
Starch damage	1.000		0.908	***	0.892	***	0.903	***	0.575	*	-0.903	***	0.940	***	-0.655	**

*Significant at P≤0.05, **Significant at P≤0.01; *** Significant at P≤0.001; **** Significant at P≤0.0001.

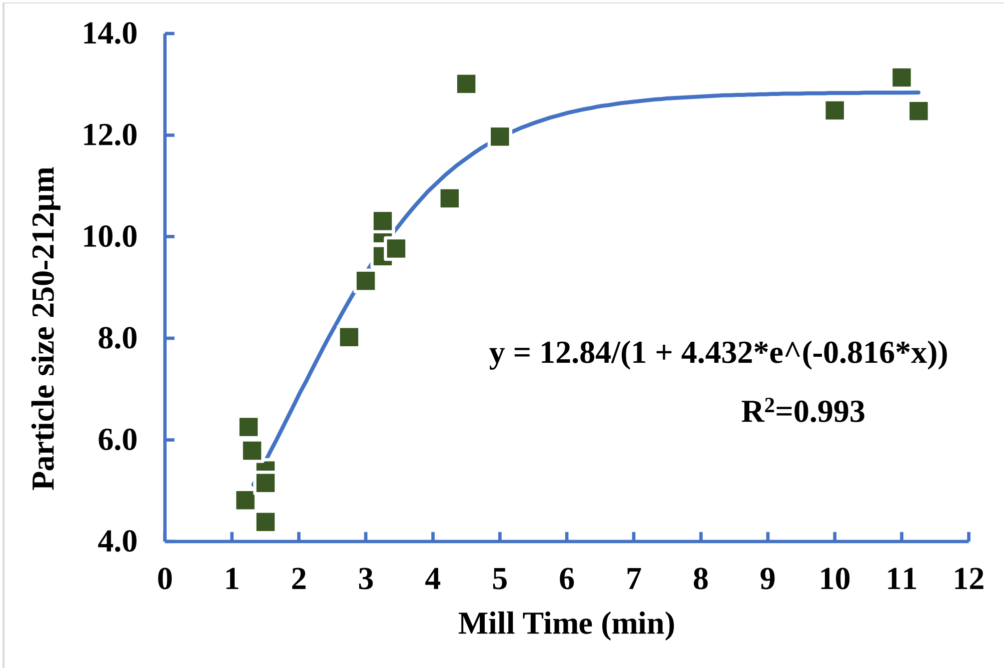

Figure A1. Non-linear relationship between the mill time and the particle size fraction of the flours between 212-250µm.
*The coefficient of determination (R^2) of the analysis was calculated using the mean values

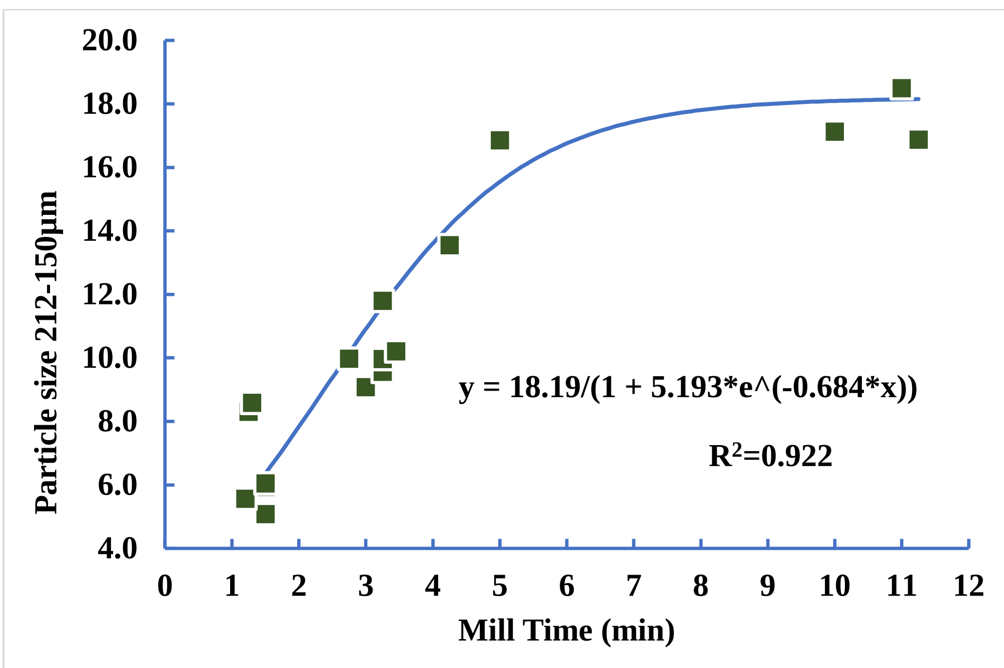

Figure A2. Non-linear relationship between the mill time and the particle size fraction of the flours between 150-212µm.
*The coefficient of determination (R^2) of the analysis was calculated using the mean values

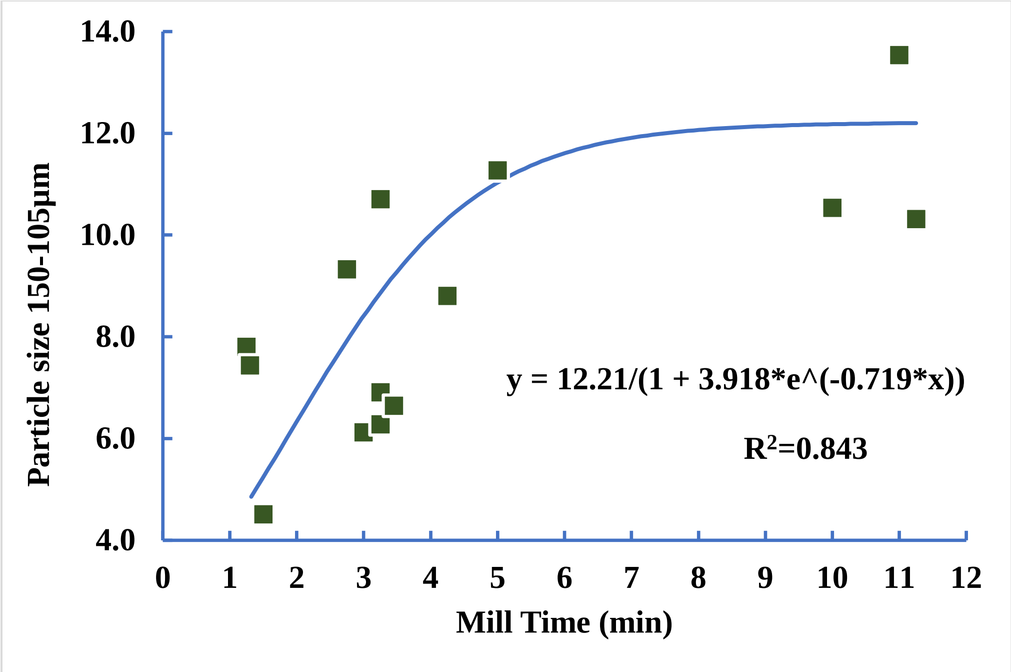

Figure A3. Non-linear relationship between the mill time and the particle size fraction of the flours between 105-150µm.
*The coefficient of determination (R^2) of the analysis was calculated using the mean values

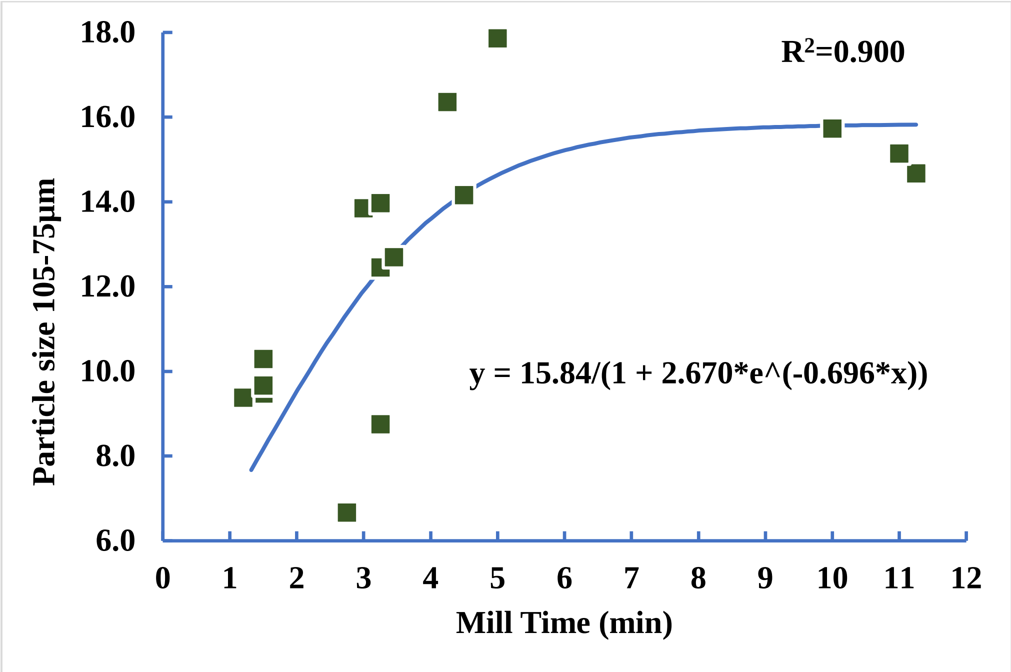

Figure A4. Non-linear relationship between the mill time and the particle size fraction of the flours between 75-105µm.
*The coefficient of determination (R^2) of the analysis was calculated using the mean values

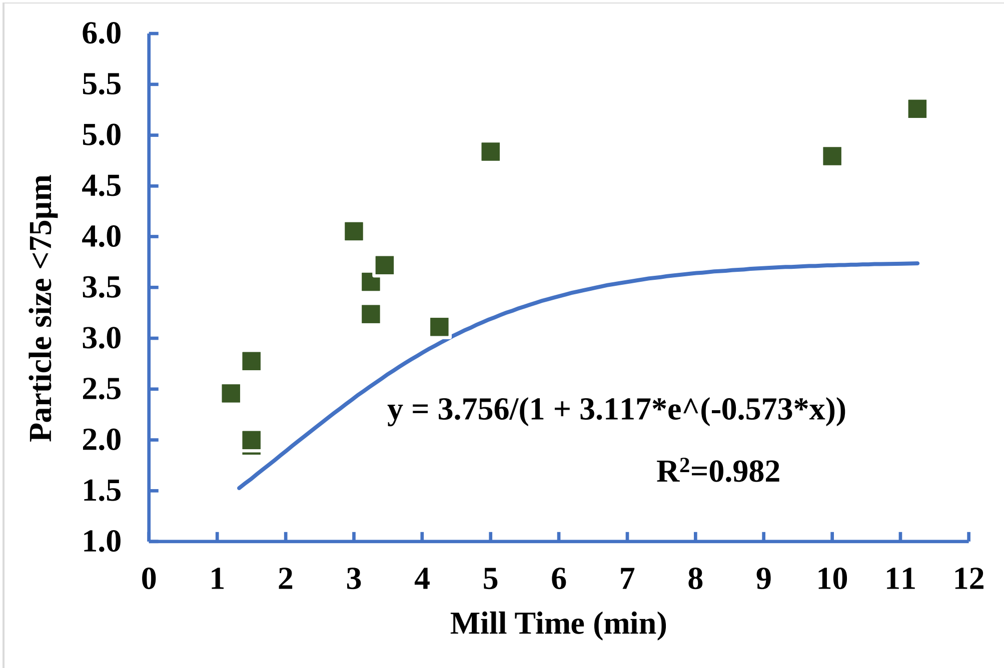

Figure A5. Non-linear relationship between the mill time and the particle size fraction of the flours between ≤75 µm.
*The coefficient of determination (R^2) of the analysis was calculated using the mean values

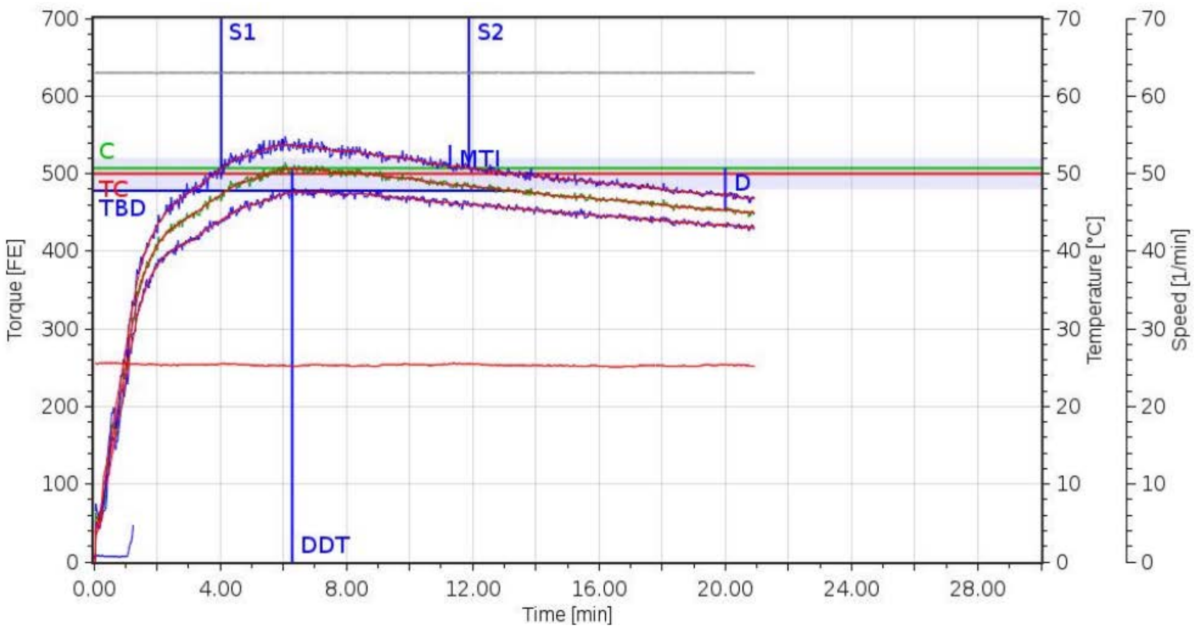

Figure A6. Farinograph graphic results of 200 rpm setting medium, repetition 2.

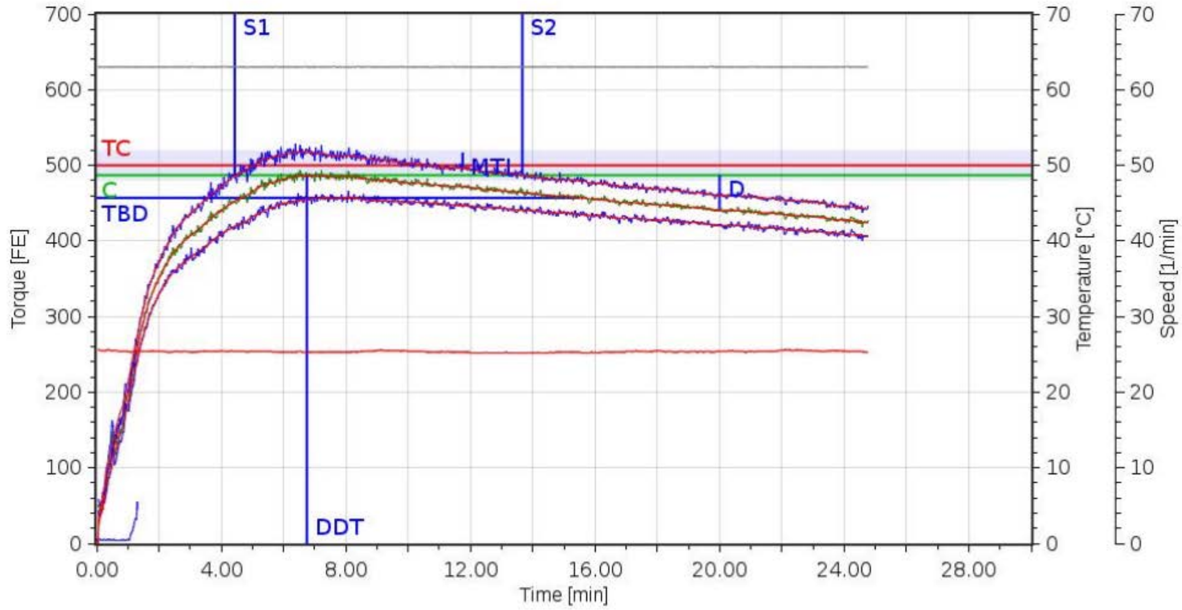

Figure A7. Farinograph graphic results of 200 rpm setting narrow, repetition 2.

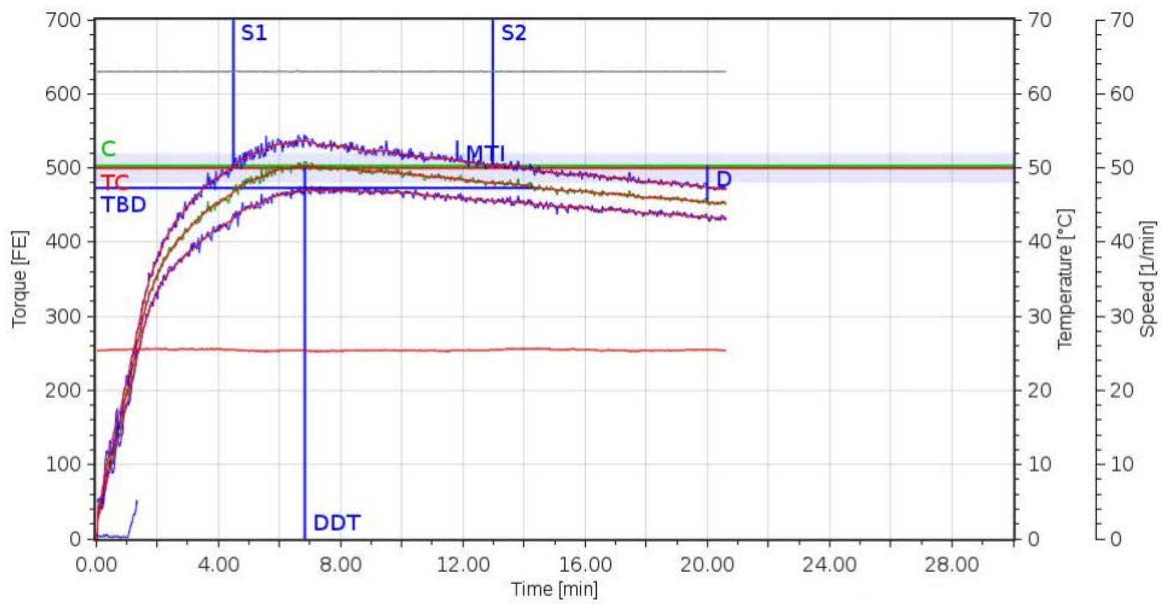

Figure A8. Farinograph graphic results of 400 rpm setting wide, repetition 2.

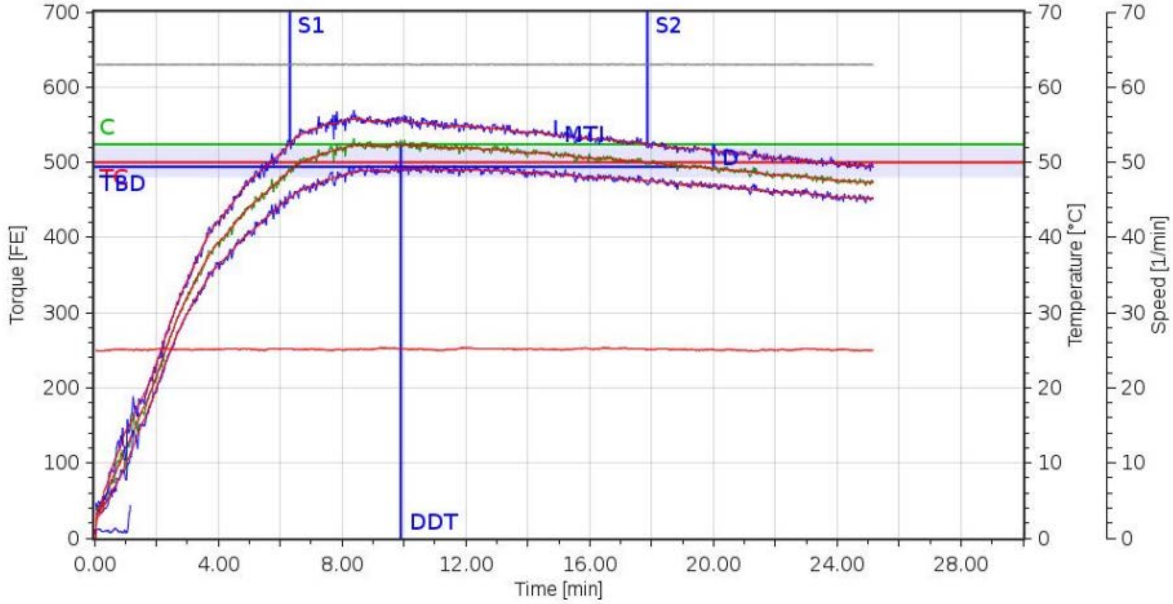

Figure A9. Farinograph graphic results of 400 rpm setting medium, repetition 3.