KERNEL AND MILLING CHARACTERISTICS OF DURUM GENOTYPES GROWN IN NORTH DAKOTA

A Thesis
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agriculture and Applied Science

By

Yu Liu

In Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE

Major Program:
Cereal Science

August 2019

Fargo, North Dakota

North Dakota State University
Graduate School

Title

KERNEL AND MILLING CHARACTERISTICS OF DURUM GENOTYPES GROWN IN NORTH DAKOTA

By

Yu Liu

The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

SUPERVISORY COMMITTEE:

Dr. Frank A. Manthey
Chair

Dr. Senay Simsek

Dr. Elias Elias

Approved:

08/13/2019
Date

Dr. Richard D. Horsley
Department Chair

ABSTRACT

Two sets of durum samples were used to determine kernel characteristics and milling properties of durum genotypes grown in North Dakota, USA. Kernels were characterized for kernel size (length, width, and thickness), germ size (length and width), and shape (kernel width/kernel length, volume, sphericity, germ width/germ length, germ length/kernel length, and germ width/kernel width). Kernels were also characterized for their test weight, kernel weight, vitreousness and hardness. Milling properties evaluated were break release, milling rate, total extraction, semolina extraction, and semolina quality. All kernel characteristics and milling properties varied with genotype and growing location. First break release and milling rate were influenced by kernel shape and size. Larger, wider, and rounder kernels tended to result in better milling performance in the first break. Kernel hardness and vitreousness were strongly correlated and both were positively correlated to semolina extraction but not total extraction.

ACKNOWLEDGMENTS

Greatest appreciation expresses to my dear advisor Dr. Frank Manthey, who gave me continuous assistance, advice, guidance, and encouragement during my master and career. His valuable support helped me get through those difficult times in my life. Also he helped me develop the skills and abilities required for my professional career.

My gratitude goes to other research committee members, Dr. Senay Simsek and Dr. Elias Elias for their professional assistance for my thesis; to Dr. Jae-Bom Ohm for his laboratory assistance and technical support for part of my research. My gratitude extends to Cereal Science graduate students for their friendship and kindly help.

My special appreciation expresses to myself, who have been working so hard to achieve the goal. My special acknowledge extends to my families and friends for endless love and support.

TABLE OF CONTENTS

ABSTRACT iii

ACKNOWLEDGMENTS iv

LIST OF TABLES vii

LIST OF FIGURES viii

INTRODUCTION 1

LITERATURE REVIEW 4

Grain Description 4

Milling 6

Factors That Affect Milling 8

Grain Physical and Mechanical Characteristics 9

Sample Preparation 12

Mill Operation 14

Evaluation of Milling Performance 15

MATERIALS AND METHODS 18

Samples 18

Grain Quality 18

Kernel Dimensional Characteristics 19

Milling Procedures 21

Semolina Quality 22

Statistical Analysis 23

RESULTS AND DISCUSSION 24

Kernel Characteristics 24

Kernel Dimensional Characteristics 30

Milling Properties 38

Break Roll Release 38
Bühler Milling 42
Semolina Quality 48
CONCLUSIONS 53
FUTURE RESEARCH AND INDUSTRIAL APPLICATION 54
LITERATURE CITED 55

LIST OF TABLES

Table		Page
1.	Genotype averages and standard deviations for grain protein content, ash content and Falling Number of nine genotypes grown in Casselton in 2017 (Experiment 1) and eight genotypes grown in five locations in ND in 2018 (Experiment 2).	25
2.	Genotype averages and standard deviations for physical grain quality characteristics, of nine genotypes grown in Casselton in 2017 (Experiment 1) and eight genotypes grown in five locations in ND in 2018 (Experiment 2).	26
3.	Genotype averages for kernel dimensional properties[a] of nine genotypes grown in Casselton in 2017 (Experiment 1) and eight genotypes grown at five locations in ND in 2018 (Experiment 2)[b].	31
4.	Variance components and intraclass correlation coefficients from analysis of eight genotypes grown in five locations for grain related parameters in 2018.	35
5.	Pearson correlation coefficients between important grain quality properties and kernel characteristics[a].	37
6.	Genotype averages[a] for break release from first and second break rolls on a Bühler mill 202 MLU, expressed as a % of material in each break, for nine genotypes grown in Casselton in 2017 (Experiment 1) and eight genotypes grown in three locations in ND in 2018 (Experiment 2)[b].	39
7.	Milling rate and mill fractions (P1 to P4), total extraction (TEXT) and semolina extraction (SEXT) calculated based on total product for nine genotypes grown in Casselton in 2017 (Experiment 1) and eight genotypes grown in five locations in ND in 2018 (Experiment 2)[*].	43
8.	Estimates of variance components and intraclass correlation coefficients from analysis of eight genotypes grown in three locations for break roll release and Bühler milling in 2018[a].	48
9.	Effect of durum genotype on semolina particle size distribution expressed in % for nine genotypes grown in Casselton in 2017 (Experiment 1) and eight genotypes grown in five locations in ND in 2018 (Experiment 2).	49
10.	Semolina quality properties[a] related to milling of nine genotypes grown in Casselton in 2017 (Experiment 1) and eight genotypes grown in three locations in ND in 2018 (Experiment 2)[b].	51

LIST OF FIGURES

Figure Page

1. A: small kernel example image (side view); B: large kernel example image (side view); C: small kernel example image (top view); D: large kernel example image (top view); all images were taken under same distance between camera and base. 20

2. Demonstration of kernel measurements on the image: A: 1) kernel length, 2) kernel width, 3) germ length, and 4)germ width; B: 5) kernel thickness. 20

INTRODUCTION

Wheat grain is milled into whole wheat flour (meal) or to refined flour. Refined flour or semolina refers to finely ground and coarsely ground endosperm, respectively. Stone mill, hammer mill, and disc mill are commonly used in single-pass milling system to produce whole wheat flour (Miller Jones et al., 2015). Roller mill is a multi-pass system designed to remove bran and germ from wheat endosperm and to reduce the endosperm to flour or semolina.

Bran, aleurone layer, and endosperm are the primary layers of the durum kernel. Botanically, the aleurone layer is the outermost layer of the endosperm. However, during the roller milling process, the bran and aleurone layer are removed together from the endosperm. This occurs because the aleurone layer is more strongly adhered to the bran layer than to the endosperm (Marshall et al., 1986). Thus, in the milling discipline, bran refers to both bran and aleurone layers.

Roller mill has two major sections or systems, break system and reduction system (Posner and Hibbs, 2005). The function of the break system is to break the kernel into large pieces and to remove the bran and germ from the endosperm. The function of the reduction system is to reduce the endosperm pieces to desired particle size, fine for flour or coarse for semolina, and to further remove any bran or germ particles from the ground stock. Both systems are comprised of a series of paired rolls and a series of sieves and purifiers.

In durum milling, semolina extraction and total extraction are important quality parameters. Total extraction includes semolina and flour produced while semolina extraction indicates the percentage of semolina produced from a given weight of grain. Milling performance is evaluated by comparing the break release, flour/semolina extraction, and semolina quality of different grain samples (Matsuo and Dexter, 1980; Manthey and Hareland,

2001; Fowler, 2014). First break release measures the size of stock after the grain has passed through the first paired break rolls. The amount of material sent to the adjacent break rolls, the amount of material sent to the purifiers, and the amount of flour produced are determined. Desired break release from the first break rolls is lower for semolina milling than for flour milling (Abercrombie, 1980; Hsieh, et al., 1980; Li and Posner, 1989; Posner and Hibbs, 2005). Low release from the first break rolls reflects the desire to produce large particle characteristic of semolina.

Factors affecting milling yield among cultivars generally fall into two classes: 1) the proportion of endosperm in the wheat kernel and 2) the ease that the endosperm can be separated from germ and bran (Marshall et al., 1986). The first class includes factors like grain size distribution, kernel shape, kernel crease width and depth, and germ size. And the second class includes factors such as kernel hardness, bulk density, and fiber content.

Germ, crease, and main body are three prominent physical parts of a durum kernel. Germ occurs on the dorsal side at the base of the kernel and extends about one-third of the kernel length, while the crease occurs on the ventral side and extends the length of the kernel. The size (length, width, and thickness) of the germ, crease and main body have been reported to vary with genotype and growing environment (Troccoli and di Fonzo, 1999; Novaro et al., 2001). Size and shape of germ, crease and main body help to determine grain test weight, 1000-kernel weight, and kernel size.

The internal structure of the kernel determines kernel vitreousness and hardness. Kernel vitreousness is associated with the continuity of protein matrix or lack of air space in the endosperm. Vitreous condition results in the kernel endosperm fracture but not be crushed during milling. Kernel hardness is associated with the occurrence of proteins called puroindolines A and

B that are associated with starch and with continuity of protein matrix in the endosperm (Hrušková and Švec, 2009; Oury et al., 2017). Thus, kernels can be hard and not vitreous (Matsuo and Dexter 1980).

Grain test weight, 1000-kernel weight, and kernel size, shape, hardness and vitreousness are often associated with semolina extraction from durum wheat in roller milling (Simmons and Meredith, 1979; Posner and Hibbs, 2005; Hrušková and Švec, 2009). Simmons and Meredith (1979) proposed that milling yield was determined by endosperm weight, endosperm structure, adhesion between bran and endosperm and by bran coherence which is the ability to hold together and not fracture into small pieces. Studies aiming at the relationship between physical properties and milling properties of wheat kernel have been carried out by numerous researchers (Sissons et al., 2000; Troccoli et al., 2000; Dziki and Laskowski, 2005; Kong and Baik, 2016; Ştefan et al., 2018). In general, grains with high test weight and high 1000-kernel weight potentially result in high milling yield (Dziki and Laskowski, 2005). Ştefan et al. (2018) proposed that high extraction from large seeds was due to having a greater percentage of endosperm relative to bran. In durum wheat, kernel hardness and vitreousness have been shown to be important for high semolina extraction (Sissons et al., 2000).

Much research has been carried out on the milling properties of grains; however, limited information is available concerning the milling properties of commercially available genotypes grown in North Dakota area and the effect of physical and mechanical characteristics of these different genotypes on the milling of durum wheat into semolina. The overall objective of this work was to characterize the kernel properties and determine their relationship with milling quality of durum genotypes grown in ND.

LITERATURE REVIEW

Grain Description

Wheat is one of the most important staple crops grown all around the world. Approximately 75-78% of wheat production is used for human consumption; 16-17% is used as feed or for industrial purpose; and 9-10% is used to sow a future crop (Psaroudaki, 2007). Durum consumption reached 38.9 million tons in 2017-2018. Durum wheat is used primarily for pasta products in European and North American countries and for bread products in other areas (Troccoli et al., 2000). Wheat production in United States was reported 1.884 billion bushels in 2018, of which 77 million bushels was durum wheat (USDA, 2019). Although durum wheat constitutes only 5 to 8% of the world wheat production, it is still an important crop because of its unique characteristics and its use of making pasta. USDA (2019) reported that durum growers planted 2,065 million acres; harvested 1,967 million acres; and had average yields of 39.3 bushels/acre.

Endosperm, bran, and germ are three distinct parts of a wheat kernel comprising of 83, 14.5, and 2.5% of the kernel weight, respectively, that are separated during wheat milling process (MacMasters et al., 1964). Botanically, endosperm contains aleurone layer (6-9%) and starchy endosperm (80-85%) (Saulnier et al., 2007). Durum endosperm contains 75-80%, db, starch and 10.5-14.5%, db, protein (Marti et al., 2013; de la Peña et al., 2015). Starch is a source of glucose used for formation of macromolecules and for energy. Storage proteins are a source of amino acids for protein formation by the germ and for developing seedling. Bran consists of outer and inner pericarp and seed coat all of which protects the seed. Bran is the major source of dietary fiber and contains small amount of B-vitamins and trace minerals (Kunerth and Youngs, 1984). Germ, also known as the embryo, is a cluster of cells from which a new organism

develops. Germ contains the embryonic axis which consists of the cotyledon, epicotyl and hypocotyl. The epicotyl is above, and the hypocotyl is below the point of attachment of the cotyledon. The tip of the epicotyl is the plumule and the tip of the hypocotyl is the radicle. The plumule develops into stem and leaves while the radicle develops into roots. Wheat kernel is monocotyledonous, meaning that it has only one cotyledon. The cotyledon is called scutellum which acts in absorbing nutrients from the endosperm. The germ contains high level of fat (10%) (Mahmoud et al., 2015), which limits the shelf-life of flour, particularly whole wheat flour, because of rancidity.

Grain quality is defined and determined by various physical and compositional properties according to end-use requirements (El-Khayat et al., 2006; Khan et al., 2010). Grain quality depends on its use and so differs with different groups of people. For durum growers, grain quality is determined by factors that affect yield (test weight, kernel weight, and kernel size) and price grain grade (test weight, kernel vitreousness, and kernel protein content); for end-users of durum wheat, grain quality is determined by milling yield, protein content and functionality, and yellow pigment content (Troccoli et al., 2000). The physical characteristics (test weight, 1000-kernel weight, kernel size distribution, kernel vitreousness, and hardness), milling properties (total and semolina extraction, speck count, and starch damage) (Gaines et al., 1996; Haddad et al., 1999; Dobraszczyk et al., 2002; Pasha et al., 2010), functional/ chemical properties (kernel protein content and quality, ash content, starch content and quality, and falling number), and the relationship among these factors have been studied for years (Matsuo and Dexter, 1980; Marshall et al., 1986; Troccoli and di Fonzo, 1999; Dziki and Laskowski, 2005; El-Khayat et al., 2006; Dziki et al., 2014; Fu et al., 2018).

In previous research, genotype, environment, and interaction of genotype and environment have been shown to affect quality traits differently (Troccoli et al., 2000; El-Khayat et al., 2006). Chaurand et al. (1999) tested nine durum wheat cultivars grown under four conditions and concluded that genetic variation was considerable for semolina extraction. Taghouti et al. (2010) tested twelve cultivars grown under nine environments and showed that majority of quality traits they tested (vitreousness, protein content, and test weight) were determined primarily by environment while yellow pigment index and SDS sedimentation were controlled mostly by genotype. Nuttall et al. (2017) reported the strong genetic control over kernel characteristics such as shape, kernel crease, and bran thickness. Pinheiro et al. (2013) concluded that even though environmental factors were important, durum wheat quality was genetically controlled, and this conclusion was drawn after investigation of twenty-seven lines and three varieties from two field trials. They reported that 1000-kernel weight, test weight, kernel vitreousness, and protein content were significantly different for genotype and environmental sources of variation.

Milling

There are two types of milling: 1) reduction of entire seed into whole wheat flour (meal) and 2) fractionation of seed into refined flour and bran/germ. There are several types of mills that are used to make whole wheat flour including hammer mill, disc mill, centrifugal mill, stone mill, and pin mill (Miller Jones et al., 2015). These mills generally involve a single-pass of grain through the mill, ending with whole wheat flour. Roller mill is a multiple-pass system designed to remove bran and germ from endosperm and to reduce endosperm into fine particles (flour) or coarse particles (farina/semolina). Farina is coarsely ground endosperm of common wheat and semolina is coarsely ground endosperm of durum wheat.

The objective of milling durum wheat on a roller mill is to produce semolina, minimize flour production and specks, and maintain functional properties of semolina. Milling is achieved in three steps: breaking the kernel, scraping bran and germ from broken pieces of endosperm, and reducing endosperm into coarse granular (Haque, 1991; Dziki et al., 2014). To achieve these steps, the grain and ground stock are passed through two major sections or systems, break system and reduction system (Posner and Hibbs, 2005). The function of the break system is to remove the bran and germ from the endosperm and to break the endosperm into large pieces. The function of the reduction system is to reduce the endosperm pieces to desired particle size, fine for flour or coarse for semolina, and to further remove any bran or germ particles from the ground stock. Both systems are comprised of a series of paired rolls and a series of sieves and purifiers. Usually, there are five to seven paired rolls in the break system and in the reduction system (Fowler, 2014; Dal-Pastro et al., 2016). The long break system makes it possible for the release of coarse particles with minimum flour being produced.

Rolls in a roller mill are paired with counter rotation. Manthey and Hareland (2001) stated that break roll speed differential can vary from 2:1 to 2.5:1 in commercial mills and the roll speed varies from 250-600 rpm. This speed differential promotes shearing action that is required to remove or scrape off large pieces of bran and germ from the endosperm as the kernels pass through the paired rolls. Higher roll speed differential means that speed ratio of fast to slow rolls is greater, also more corrugations pass each other in a certain time. This will increase shearing and increase production of endosperm and bran particles. Conversely, lower roll speed differential will decrease shearing action but increase crushing action resulting in smaller particle size from existing endosperm. Roll speed differential is of critical importance on semolina extraction and semolina quality because of the considerable effect on the shear and

compression forces applied on milled stocks. It was shown that there were positive correlations between roll speed differential and semolina extraction, speck count, protein content, and ash content of semolina; and negative correlations between roll speed differential and bran extraction, flour extraction, and starch damage (Manthey and Hareland, 2001).

A corrugation has a sharp and a dull edge. Rolls can be oriented to produce sharp-to-sharp, sharp-to-dull, dull-to-dull, and dull-to-sharp configurations. Minimizing the production of flour can be achieved by setting rolls at a sharp-to-sharp configuration (Manthey and Hareland, 2001). Break rolls have deep grooves or corrugations that ensure the endosperm being coarsely ground. In a durum mill, the reduction rolls have shallow corrugations. In contrast, the rolls associated with reduction system of a flour mill often are smooth and lacking corrugation. The smooth surface of reduction rolls promotes crushing action resulting in production of small flour particles. Each pair differs in the space or gap between rolls. As the ground stock moves through the mill, the gap between paired rolls generally decreases resulting in particle size reduction. The roll gap and roll speed differential are relatively easy to adjust.

Factors That Affect Milling

Factors affecting roller mill performance basically falls into three aspects: 1) grain physical and mechanical characteristics (kernel moisture, size and shape, volume, density, hardness, and resistance to crushing) (Ştefan et al., 2018); 2) sample preparation (cleaning and tempering); and 3) mill design and operation (roll size, roll corrugation, roll gap, and roll speed differential). The mill design and operation monitors mill behavior during milling. Those grain physical and mechanical characteristics affect grain behavior during milling; and sample preparation modifies the physical and mechanical characteristics before milling.

Grain Physical and Mechanical Characteristics

Grain quality, especially physical and mechanical characteristics, affects the milling process. Physical properties, such as test weight, 1000-kernel weight, kernel size distribution, kernel dimensions, kernel vitreousness, and kernel hardness are of importance in durum wheat milling and can affect semolina extraction (Matsuo and Dexter, 1980; Dziki and Laskowski, 2005; El-Khayat, 2006).

Test weight (kg/hL) is one of the oldest and traditional quality parameters being used to measure the density and soundness of wheat kernels and to predict milling quality. Test weight is determined by kernel density and kernel packing efficiency (Hlynka and Bushuk, 1959; Doehlert and McMullen, 2008). A high test weight is recommended. Test weight can be affected by kernel shape, weight, insect damage, foreign material content, broken and shriveled kernel content, and kernel weathering (Gaines, 1997). High test weight usually indicates a greater ratio of endosperm to bran and this can be correlated with high flour/semolina extraction. However, test weight is not consistently correlated to milling quality. Matsuo and Dexter (1980) speculated that the effect of test weight on milling yield was more pronounced with low test weights and they proposed that there was a limit of test weight below which milling yield declines. They did not define or identify where the low limit occurred for test weight.

1000-Kernel weight is another quality parameter commonly used as an indicator of milling quality. 1000-Kernel weight is determined by average kernel size and density (Hlynka and Bushuk, 1959). Previous research has been done to study the relation between 1000-kernel weight and milling properties (Dziki et al., 2005). 1000-Kernel weight has been associated with semolina extraction. Matsuo and Dexter (1980) concluded that high test weight and high 1000-kernel weight were strongly associated with maximum milling yield.

Kernel size distribution significantly affects wheat milling as different size of kernels mill differently. Large kernels have a higher proportion of endosperm-to-bran which favors to increase semolina extraction while small kernels have a higher proportion of bran section which generally results in low milling yield and high ash content (Marshall et al., 1986). This property is important in the commercial milling process because the roll gap of paired rolls are adjusted to the mean size of kernels. Small variation of size distribution is preferred because uniform kernels are milled similarly and evenly. Wide size distribution results that small and large kernels are not milled optimally (Posner and Hibbs, 2005).

Several researchers have related kernel size to shape and milling yield (Marshall et al., 1986; Troccoli and di Fonzo, 1999; Novaro et al., 2001; Dziki and Laskowski, 2004). These researchers measured kernel dimensional characteristics, including kernel length, width, and thickness, and germ length and width from computerized image analysis (Marshall et al., 1986; Troccoli and di Fonzo, 1999; Novaro et al, 2001). They used these dimensional measurements to calculate kernel volume, equivalent diameter, sphericity, and length-to-width ratios of germs, kernels, and germ-to-kernel. The fact that kernel dimensions were related to test weight was reported by Troccoli and di Fonzo (1999). This matched the conclusion drawn by Marshall et al. (1986) that seed size and test weight had influence in milling yield when variation from other factors were controlled. Furthermore, Novaro et al. (2001) came up with two equations to predict semolina extraction using kernel volume from image analysis along with test weight or 1000-kernel weight.

Vitreous durum kernels have an amber, translucent, glassy appearance, and generally have a high density, compared to mealy kernels which are opaque with a lower density (Hlynka and Bushuk, 1959; Samson et al., 2005). Vitreous kernels tend to be high in protein content and

harder than mealy appearing kernels. Vitreous appearance is due to the lack of air space between starch granules within endosperm (Dexter et al., 1989). Non-vitreous regions within endosperm are generally low in protein content. Importance of vitreousness of durum wheat is underscored by the US Grading system having three subclasses for durum wheat that are based on vitreous kernel content (USDA, 2014). The three subclasses are: Hard Amber Durum (above 75%), Amber Durum (between 60 and 75%), and Durum (below 60%).

Vitreousness is very important for durum wheat quality evaluation, particularly milling properties. Vitreousness is associated with kernels' tendency to fracture but not to crush during milling. When starchy kernels being milled, fine particles (flour) is produced, which reduces semolina extraction (Dexter and Matsuo, 1981). Kernel vitreousness does not always relate to milling yield since other factors. For example, green immature kernels, kernels affected by scab, sprouted kernels, foreign material, and all other classes of wheat are not considered vitreous (USDA, 2014).

Kernel hardness is measured by single-kernel characterization system (SKCS) which determines the force required to crush individual seed. It is well developed for evaluation of individual kernel quality by providing fast, convenient, and accurate measurement of kernel hardness (Ohm et al., 1998; Pasha et al., 2010; Dziki et al., 2014). Kernel hardness has been proved to be an important grain quality factor by numerous researchers, and it has been correlated to milling properties (Ohm et al., 1998; Haddad et al., 1999; Sissons et al., 2000; Dobraszczyk et al., 2002; Osborne et al., 2007; Pasha et al., 2010; Haraszi et al., 2016; Fu et al., 2018).

Kernel vitreousness and hardness are not the same. Dexter et al. (1988) reported that vitreous and non-vitreous hard red spring wheat had comparable hardness. Kernel hardness is

associated with the occurrence of proteins called puroindolines A and B that is associated with starch and with the continuity of protein matrix in the endosperm (Hrušková and Švec, 2009; Oury et al., 2017), whereas kernel vitreousness is associated with the continuity of protein matrix or lack of air space in the endosperm. The presence of puroindolines A and B proteins confers soft texture of soft wheat. Hard wheats such as hard spring, hard winter, and durum wheat do not have the puroindoline proteins. Haraszi et al. (2016) reported hardness index values of 72.1-97.1 for durum; 25.1-96.6 for hard wheat; and 12.2-33.4 for soft wheat. Thus, hard wheat can still have hard kernels even though they are not vitreous.

In durum wheat, kernel hardness is often associated with kernel vitreousness, protein content, and kernel size. The results obtained by Dziki et al. (2014) showed that kernel hardness index and kernel vitreousness were the most useful factors for predicting wheat milling yield and were related to flour particle size and starch damage.

Sample Preparation

Cleaning and tempering grain are essential to the milling process. Management of these stages can improve milling performance and avoid milling problems. Before the grain reaches the mill, it is subjected to various contaminants. In the cleaning step, impurities such as sand, soil, stones, straw, dust, foreign seed, diseased grain and broken or shriveled kernels are removed. There are five principles used during grain cleaning (Miller Magazine): 1) sorting by size which is a sieving method that removes substances smaller or larger than wheat by shaking; 2) sorting by specific weight which uses vibration and air stream to remove non-wheat material that is the same size as wheat kernel but differs in weight; 3) sorting by air resistance which majorly removes dust, particulates, and shriveled kernel that is much lighter than wheat; 4) sorting by shape which deals with substances with similar size and weight as wheat that can be

sorted by shape using disc, spiral, and cylinder separators; and 5) sorting by color using color sorters. Grain cleanliness can affect the color and ash content of milled material. Scouring is typically the last step in grain cleaning that occurs just before the tempering step. Scouring is achieved by friction from grain against screen, grain against rotor segments, and grain against grain inside the scourer. Scouring removes dirt, dust and broken kernels with substantial insect damage, and reduces microbial load (yeast and mold) prior to tempering.

After scouring, the grain is tempered. Tempering is a standard procedure that brings grain moisture content to the desired level. Regarding different types of wheat, different lengths of tempering time is required: short tempering time (6-12 hours) for soft wheat, medium tempering time (12-24 hours) for hard wheat, and long tempering time (24-48 hours) for durum wheat (Posner and Hibbs, 2005; Pauly et al., 2013). Water penetrates at a faster rate with soft wheat than with hard wheat. Thus tempering time is shorter for soft wheat than hard wheat. Tempering has some significant purposes to milling. Tempering mellows or softens the endosperm of hard wheat which can result in increased flour extraction, reduced ash content, and reduced energy consumption (Hourston et al., 2017). Moisture added during tempering acts as a plasticizer in the bran layer which toughens the bran and prevents the bran from breaking into small pieces. Large bran pieces allow bran flakes to be removed easily and reduce bran accumulation (speck count) in semolina or flour (Fang and Campbell, 2003). In the research conducted by Hsieh et al. (1980), the effect of tempering moisture on the first break rolls was investigated and they found that with increasing tempering moisture, first break release increased, ash content and protein content decreased, and starch damage was not affected. According to Bizzarri and Morelli (1988), durum wheat, which was not sufficiently friable during first break, tended to produce angular semolina particles with adhered bran with high ash content.

Mill Operation

Tempered grain is fed into the first break rolls of the break system. Break roll configuration setting is complex according to roll orientation, number of corrugations, roll speed differential, and roll gap. Paired rolls are counter-rotating at different speeds and separated by a small and fixed gap (adjusted based on mean kernel size) which together result in a shearing action that removes bran and germ from endosperm. Break rolls can be adjusted to optimize milling performance such as roll gap, roll speed, and roll speed differential. For example, Fang and Campbell (2002) concluded that as roll gap increased, less kernel breakage occurred which resulted in more large particles and low break release. In the break system of durum mill, paired rolls have wider gap and deeper and wider corrugations compared to flour mill because minimizing flour production is desired (Posner and Hibbs, 2005). Roll corrugations break the kernel into large pieces. As milled stock passes through the mill, these gaps and corrugations become smaller. It was reported by Dexter and Matsuo (1978) that widening roll gap increased semolina extraction.

After each break roll, the milled stock is sorted by size through a series of sifters with various screen aperture sizes (Campbell et al., 2001; Posner and Hibbs, 2005). Inside the sifter, each frame is covered with a nylon screen with square openings and the opening becomes smaller as the ground stock progresses through the various sieves to the bottom of the sifter. From the sifter, large sized stock material is sent to the next set of break rolls; medium sized stock material (mids) is sent to purifiers; and small sized stock material (flour) is collected as flour or might undergo further bran removal. Stock sent to purifiers is passed over a series of sieves and exposed to aspiration designed to remove bran and dust particles. Particles of appropriate size are collected as semolina and large particles that are too large for desired

particle size of semolina are sent to reduction rolls that are adjusted for particle size. Separation (sifters to purifiers) and size reduction (reduction rolls) are repeated to achieve an effective separation of endosperm from bran and germ and a desired particle size.

The reduction system of a durum mill utilizes paired rolls with narrow, shallow corrugations selected to produce coarse semolina particles of desired size. In a durum mill, all paired rolls have corrugations; whereas in a flour mill, the paired rolls in the reduction section are smooth and are designed to maximize compression resulting in flour production.

Evaluation of Milling Performance

Milling performance is evaluated by first break release, semolina and total extraction, semolina granulation, speck count, ash content, and color according to NDWC (2018). The first break rolls initiate the milling process by breaking the kernels, removing bran and germ, and releasing the endosperm that makes it a critical control point in the whole milling performance. Break release is a good indicator of milling efficiency (Fowler, 2012) and it represents the amount of stock removed from the break system. This is the amount of material being sent to the purifier or collected as flour. First break release is less when milling coarse products such as semolina or farina compared to flour. Typically, first break release in a durum mill is about 10-15% compared to 30-40% in a flour mill (Li and Posner, 1989; Posner and Hibbs, 2005; Sebastian, 2018). Low release from the first break reflects the desire to produce coarse granulation with producing little or no flour.

To keep the mill in balance, a proper break release is needed. Too high or too low break release will cause too much stock being sent to purifiers, sifter or adjacent break rolls (Fowler, 2014). Each purifier, sifter and paired rolls is designed for a specific capacity. Too much or too

little ground stock will affect their ability to function efficiently, which will affect final product quality.

Historically, the extraction of commercial U. S. semolina was 60-65%, with flour percentage less than 3% (Dick and Youngs, 1988). To improve profits in industry with narrow profit margins, durum millers have trended towards higher semolina extraction over 70% and total extraction near 80% (Dexter et al., 2004). The total extraction and semolina extraction are very important indicators in milling evaluation because these two directly reflect how well and efficient the milling is done and they are the typical concerns of millers.

Speck count shows the amount of bran particles in the final semolina product. Low speck count indicates good milling operation and milling efficiency. Semolina with a speck count less than 77 per dm^2 is considered desirable (Dick and Youngs, 1988). Manthey and Twombly (2005) evaluated five commercial semolinas and reported that their speck counts ranged from 26 to 46 dm^2. High speck count can occur with improper tempering which affects the separation of endosperm from bran and germ; presence of poor quality grain; poorly cleaned grain; and imbalance of the mill resulting in too much or too little stock for optimum sieve efficiency.

Protein content is associated with milling and semolina extraction because bran and aleurone layer have higher protein content than endosperm. Results from Dexter and Matsuo (1978) and Dexter et al. (2004) indicated that protein content increased with increased semolina extraction. Flour or semolina purity can also be evaluated by ash content to show milling efficiency. The reason is that mineral content in endosperm is not distributed evenly and it decreases from outer to inner part. According to Cubadda (1988) and Matsuo (1988), ash content in semolina increased with increased semolina extraction producing a dull color of semolina. Starch damage is affected by milling and it affects pasta processing because of the effect on

hydration during the mixing procedure. Manthey and Hareland (2001) studied the effect of break roll differentials and found that the degree of starch damage differed with roll variables and purifier efficiency. They concluded that increasing roll differential decreased the degree of starch damage of semolina. And grain hardness affects starch damage that harder wheat kernels encounter more shear force thus more damaged starch obtained (Dziki and Laskowski, 2005).

MATERIALS AND METHODS

Samples

Two sets of grain samples were used to evaluate kernel characteristics and milling properties of durum genotypes grown in ND. These genotypes represent cultivars currently grown in North Dakota or have potential to be released to growers as new cultivars. The first set consisted of Carpio (Elias et al., 2014), Divide (Elias and Manthey, 2007), Joppa (Elias and Manthey, 2016), Maier (Elias and Miller, 2000a), Mountrail (Elias and Miller, 2000b), ND Riveland (Elias and Manthey, 2019), D13541, D13899, and D131090 grown at the North Dakota Agricultural Experiment Station (NDAES) near Casselton, ND in 2017. Second set was similar to the first set except that it lacked D131090 and that these genotypes were grown at NDAES located near Casselton, Carrington, Langdon, Dickinson, and Minot, ND in 2018. Each sample contained approximately 2 kg of wheat and was stored at 7 to 15°C in securely closed, moisture proof plastic bags. All grain samples were cleaned (Carter-Day dockage tester, Simon Carter Co., Minneapolis, MN) and scoured (Forster Manufacturing Company, Wichita, KS).

Grain Quality

Moisture content of cleaned grain was determined using a moisture meter (Motomco, Dickey-John, Auburn, IL) by AACC International Approved Method 44-11.01. Grain protein content was determined using FOSS Infratec^{TM} 1241 Grain Analyzer (FOSS Tecator, Hogonas, Sweden). Grain was ground into meal using a small laboratory hammermill (Laboratory mill 3100, Perten Instruments, Hägersten, Sweden). Meal was used to determine ash content and Falling Number according to AACC International Approved Methods 08-01.01 and 56-81.03, respectively.

Test weight was determined as described by AACC International Approved Method 55-10.01). 1000-Kernel weight was determined based on the number of kernels in 10 g of cleaned grain (free of foreign material and broken kernels). Kernels were counted by electronic seed counter (Seedburo Equipment Co., Chicago, IL). Kernel size distribution was determined according to the procedure described by Shuey (1960). Kernels remaining over a Tyler No. 7 (2.92 mm opening) were classified as "large". Vitreous kernel content was determined by cutting two sets of 50 kernels in half using a farinator and kernels with white opaque regions in their endosperms were counted as non-vitreous. SKCS (model 4100, Perten Instruments, Hagersten, Sweden) was used to determine mean values of single kernel hardness index, single kernel moisture content, single kernel weight, and single kernel diameter of grain tempered to 12.5% moisture content based on the procedure described by Martin et al. (1993).

Kernel Dimensional Characteristics

Kernels (50) were selected randomly to measure individual kernel dimensional characteristics. A microscope camera with adjustable focal lens (model OT-M, Opti-TekScope, Chandler, AZ) was used to obtain images of individual kernels. Ten kernels were placed on cellulose tape 19 x 35 mm with crease side to the left for the side view and crease side down for the top view (Figure 1). The images were printed on paper and the kernel length, width, and thickness, and germ length and width were measured with a digital caliper (model 147, General Tools & Instruments, New York, NY) that had an accuracy of 0.01 mm (Figure 2).

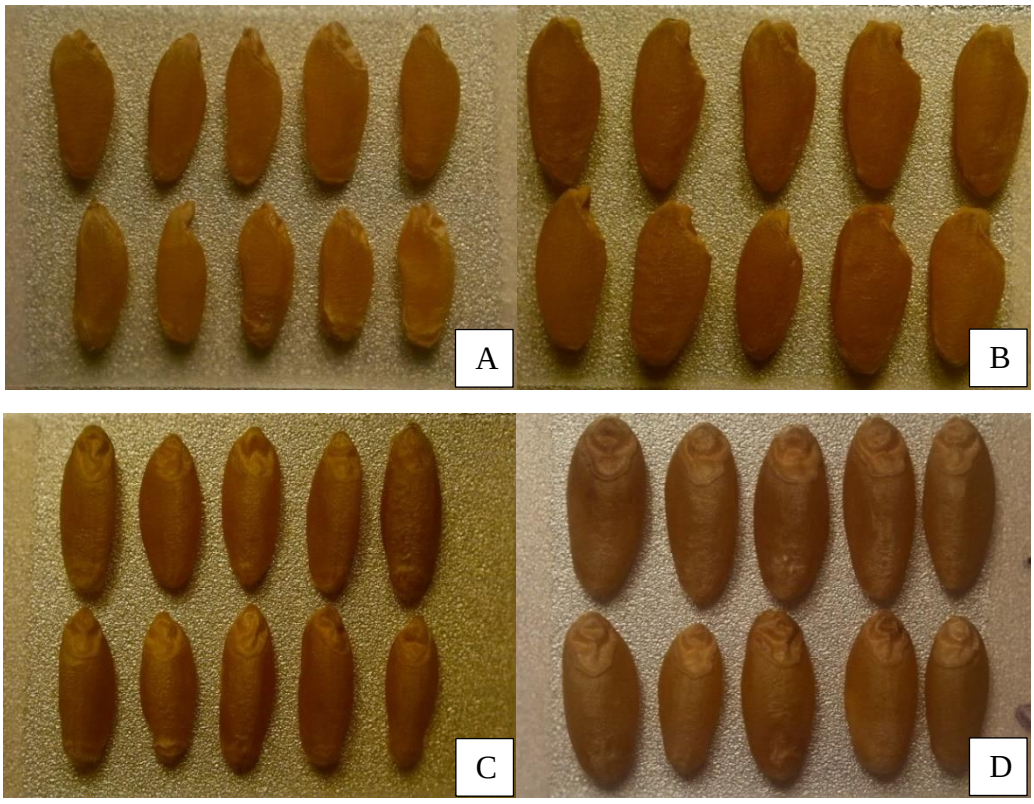

Figure 1. A: small kernel example image (side view); B: large kernel example image (side view); C: small kernel example image (top view); D: large kernel example image (top view); all images were taken under same distance between camera and base.

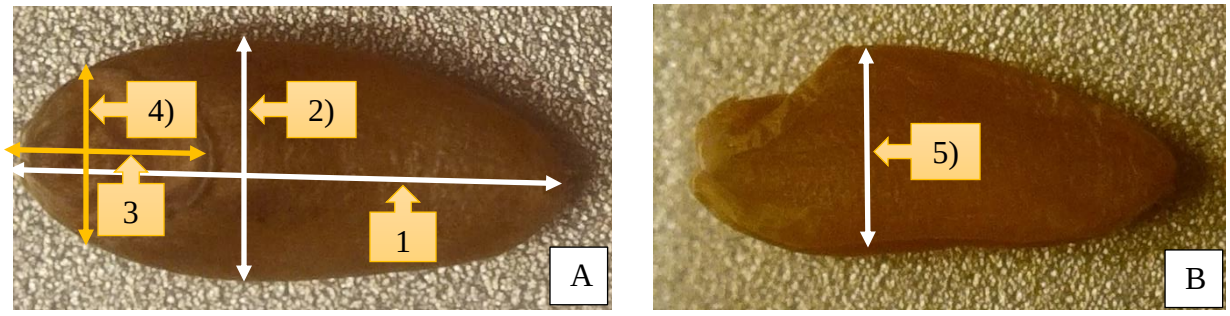

Figure 2. Demonstration of kernel measurements on the image: A: 1) kernel length, 2) kernel width, 3) germ length, and 4) germ width; B: 5) kernel thickness.

The sphericity (Ø) defined as the ratio of the surface area of the sphere and that of the grain having same volume was calculated through the equation (Mohsenin, 1986; Dursun and Dursun, 2005):

$$Ø = \frac{(LWT)^{1/3}}{L}$$

Kernel volume was calculated through the equation (Al-Mahasneh and Rababah, 2007):

$$V = \frac{\pi B^2 L^2}{6(2L - B)}$$

where $B = \sqrt{WT}$.

Milling Procedures

Cleaned, scoured grain was tempered by three-step process to increase moisture content. First, water was added to increase kernel moisture content to 12.5% and allowed to equilibrate 48 hours before second tempering; second, kernel moisture was increased to 14.5%, about 24 hours before milling; and third, kernel was conditioned to 17.5%, 45 minutes before milling. The tempered kernels were then milling into semolina on a Bühler MLU 202 pneumatic laboratory mill (Bühler AG, Uzwil, Switzerland) with two Miag purifiers according to AACC International Approved Methods 26-10.02 and 26-42.01. Milling rate was determined as the time the grain entered the first break roll to all stock material moved through and out of the mill and was expressed in gram per minute. Flour (break and reduction), purifier fractions (P1, P2, P3, and P4), bran, shorts and dust were collected and weighed, then expressed as percentage on a total product basis. Semolina extraction (SEXT) and total extraction (TEXT) were calculated as

SEXT = semolina weight / total product weight x 100

TEXT = (flour weight + semolina weight) / total product weight x 100

Large bran percentage was determined by sizing the entire bran fraction through a No. 8 sieve (2.36 mm screen aperture) using a rotary sifter at 102 RPM for 2 minutes. This milling procedure was done in three replicates for each genotype in first set of samples. Each replicate was prepared (tempered) and milled on a different day.

Break release was determined in duplicate by milling tempered grain samples through the first, second, and third break rolls. Ground stock was sifted after each break. Data was recorded

as percentage of weight in each break. Stock remaining over a sieve was recorded as: Over 16 (1180 µm sieve, U.S. standard sieve #16) in first break and Over 18 (1000 µm sieve, U.S. standard sieve #18) in second break. After sieving with these sieves in each break, flour was separated by another sifting with 180 µm sieve (U.S. standard sieve #80), recorded as over 80 and thru. All sieving was conducted by a rotary sifter at 102 RPM for 2 minutes.

Semolina Quality

Semolina was characterized for ash content, moisture content, and protein content according to AACC International Approved Methods 08-01.01, 44-15.02, and 46-30.01, respectively, and expressed on a 14% moisture basis. The starch damage of semolina was determined using a commercial assay kit from Megazyme according to AACC International Approved Method 76-31.01.

Visible specks in semolina were counted on a flat surface under a constant light source with three readings on different 6.5 cm^2 areas then converting the average to the number of specks/dm^2. Semolina granulation was measured by Retsch Vibratory Sieve Shaker AS 200 (Verder Scientific, Inc., Newtown, PA) which separating semolina samples by sieves with aperture sizes of 500, 425, 250, 150, 100, and 50 µm, recorded in weight percentage retained on sieves. Values reported in triplicate. The geometric mean diameter (d_{gw}) and geometric standard deviation (s_{gw}) of semolina particle were determined as described by ASABS Method S319.4 and Deng and Manthey (2017). The equations are listed below:

$$d_{gw} = \log^{-1}\left[\frac{\sum_{i=1}^{n}(Wi\log\overline{di})}{\sum_{i=1}^{n}Wi}\right]$$

$$s_{log} = \left[\frac{\sum_{i=1}^{n}Wi\,(\log\overline{di}-\log dgw)^2}{\sum_{i=1}^{n}Wi}\right]^{1/2}$$

$$s_{gw} = \frac{1}{2}\,d_{gw}[(\log^{-1}slog) - (\log^{-1}slog)^{-1}]$$

where d_{gw} is the geometric mean diameter of particles (µm), s_{log} is the geometric standard deviation of the log-normal distribution, s_{gw} is the geometric standard deviation of the particle diameter (µm). W_i is the weight retained on the *i*th sieve (g), n is the number of sieve, and d_i is the nominal sieve aperture size of the *i*th sieve (µm).

Statistical Analysis

The experimental design was a randomized complete block for the first experiment. All tests were conducted in three replicates and each replicate was separated in time. The design of the second experiment was a randomized complete block, analyzed once where locations were considered replications and once where genotypes were considered replications. For each variable in grain quality tests and semolina quality tests, an analysis of variance (ANOVA) was performed by SAS 9.4 (SAS Institute Inc., Cary, NC). For kernel dimensional measurements, an analysis of variance (ANOVA) on the individual 50 measurements of each genotype was performed. Fisher's protected least significant differences (LSD) test was used to differentiate treatment means at the 5% significance level. Variance components were reported as relative proportion of total variance. Intraclass correlation coefficients were computed as the ratio of the genotypic variance to the genotypic plus residual variances as described by Caffe-Treml et al. (2011). Pearson's correlation was used to evaluate the relationship among all the mean values for parameters in grain quality, milling, and semolina quality in experiment 1 (n=9) and experiment 2 (n=40).

RESULTS AND DISCUSSION

Kernel Characteristics

Grain protein content, ash content and Falling Number of genotype in experiment 1 and genotype and location in experiment 2 are presented in Table 1. Range of protein content was greater for genotype in experiment 1 (10.4 to 14.1%) than experiment 2 (13.4 to 14.7%). In both experiments, Maier had the highest protein content (14.1 and 14.7%, respectively) and D13541 had the lowest protein content (10.4 and 13.4%, respectively). Range of ash content was greater for genotype in experiment 2 (1.65 to 1.87%) than experiment 1 (1.49 to 1.61%). In both experiments, Maier had the greatest ash content (1.61 and 1.87%, respectively) and Carpio had the least ash content (1.49 and 1.65%, respectively). In experiment 2, ranges for both protein content and ash content were greater with location (11.8 to 15.2% and 1.56 to 1.94%) than those with genotype (13.4 to 14.7% and 1.65 to 1.87%). The highest average protein content and the lowest average ash content occurred at Minot. Conversely, lowest protein content and highest ash content occurred at Casselton. Data from experiment 2 suggested that growing location affects kernel protein and ash content more than genotype. In experiment 1, Falling Number was high (above 400 sec) for Carpio and D13899; intermediate (between 330 and 400 sec) for D13541 and Mountrail; and low (below 330 sec) for D131090, Divide, Joppa, Maier, and ND Riveland (Table 1). Commercially, price discount begins at 330 sec (Beach Cooperative Grain Company, 2016). All Falling Numbers in experiment 2 were above 400 sec. Falling Numbers above 400 sec indicate little or no effect of moisture/damp conditions on grain quality. Low Falling Number indicates exposure to damp conditions after grain maturity. Overall, the protein content, ash content and Falling Number were greater in experiment 2 than in experiment 1.

Table 1. Genotype averages and standard deviations for grain protein content, ash content and Falling Number of nine genotypes grown in Casselton in 2017 (Experiment 1) and eight genotypes grown in five locations in ND in 2018 (Experiment 2).

Experiment 1	Protein[a]	Ash[a]	Falling Number[a]
Genotype	%	%	sec
Carpio	14.0±0.1	1.49±0.02	500±34
D131090	12.2±0.1	1.55±0.02	243±3
D13541	10.4±0.1	1.57±0.03	354±10
D13899	10.9±0.1	1.58±0.02	426±13
Divide	14.0±0.1	1.49±0.02	319±5
Joppa	12.2±0.1	1.52±0.02	305±14
Maier	14.1±0.1	1.61±0.02	218±4
Mountrail	13.1±0.0	1.52±0.02	382±10
ND Riveland	13.6±0.1	1.53±0.00	256±4
Experiment 2			
Genotype			
Carpio	13.8±1.4	1.65±0.24	541±53
D13541	13.4±1.1	1.72±0.18	620±64
D13899	14.2±1.9	1.72±0.17	531±45
Divide	14.0±1.7	1.69±0.22	522±55
Joppa	13.4±1.5	1.74±0.20	508±64
Maier	14.7±1.0	1.87±0.19	502±37
Mountrail	14.0±1.5	1.74±0.15	490±36
ND Riveland	13.6±1.8	1.72±0.18	490±44
Location			
Carrington	13.2±0.9	1.91±0.04	576±44
Casselton	11.8±0.6	1.94±0.11	474±41
Dickinson	15.0±0.8	1.67±0.06	511±53
Langdon	14.2±0.2	1.58±0.11	550±32
Minot	15.2±0.6	1.56±0.11	518±81
5-yr Avg[b]	13.6	1.57	374

[a] Protein, ash and falling number on 12% moisture basis.
[b] 2013-2017 Average for durum grown in the Northern Plains, USA (NDWC, 2018).

Grain physical characteristics in the two experiments are presented in Table 2. Test weight, 1000-kernel weight, large kernel content, vitreous kernel content and kernel hardness are common grain quality factors that have been associated with semolina extraction (Matsuo and Dexter, 1980; Marshall et al., 1986; Peyron et al., 2003; Hrušková and Švec, 2009; Haraszi et al., 2016). Except for 1000-kernel weight of Divide in experiment 1 (39.0g), the test weight, 1000-

kernel weight and large kernel content in experiment 1 and genotypes in experiment 2 were greater than their respective 5-year averages. Test weight ranged from 79.4 to 81.0 kg/hL in experiment 1 and from 80.0 to 81.7 kg/hL for genotypes in experiment 2. Test weights for all samples exceeded the 78.2 kg/hL (60.0 lb/bu) needed for US No. 1 grade (USDA, 2014). For both experiments, Maier and Mountrail had the lowest test weights.

Table 2. Genotype averages and standard deviations for physical grain quality characteristics, of nine genotypes grown in Casselton in 2017 (Experiment 1) and eight genotypes grown in five locations in ND in 2018 (Experiment 2).

Experiment 1	Test WT[a]	1000-KWT[a]	Large[b]	VitK[a]	Single WT[a]	Kernel Diameter	Hardness Index
Genotype	kg/hl	g	%	%	mg	mm	
Carpio	81.0±0.1	47.1±0.5	83±1	85±3	50.3±0.7	3.10±0.02	83.6±1.4
D131090	80.9±0.2	48.2±0.6	85±1	60±1	51.7±1.4	3.13±0.02	73.4±0.2
D13541	80.3±0.1	48.0±0.4	89±1	40±3	51.8±1.7	3.23±0.04	62.8±0.1
D13899	79.7±0.0	41.3±0.2	79±1	25±2	44.8±1.0	3.03±0.03	60.2±0.9
Divide	79.4±0.1	39.0±0.4	57±3	76±2	43.2±0.5	2.90±0.02	78.3±0.1
Joppa	80.4±0.1	44.8±0.7	71±2	68±3	46.6±0.8	2.97±0.03	76.6±1.0
Maier	79.6±0.1	40.7±0.1	67±2	70±4	44.5±0.7	2.98±0.03	80.5±0.1
Mountrail	79.6±0.1	43.4±0.3	65±1	70±4	44.8±0.9	2.94±0.02	78.8±2.3
ND Riveland	80.1±0.0	44.3±0.1	74±2	63±1	49.0±0.5	3.03±0.01	72.9±1.8
Experiment 2							
Genotype							
Carpio	81.6±1.7	46.3±5.9	74±13	84±18	47.8±5.3	3.06±0.16	70.7±5.5
D13541	81.6±1.1	47.5±6.0	77±8	89±8	48.3±4.9	3.05±0.17	74.1±3.1
D13899	81.7±1.7	41.5±5.5	60±19	89±14	43.1±4.5	2.91±0.17	71.2±5.3
Divide	81.0±1.4	45.1±5.3	66±15	89±13	45.4±4.7	2.97±0.13	73.1±4.7
Joppa	81.5±1.4	44.5±4.6	60±14	90±10	45.8±4.1	2.95±0.12	74.5±4.1
Maier	80.1±1.6	40.9±5.3	56±19	94±3	43.9±4.7	2.94±0.18	75.2±2.0
Mountrail	80.4±1.2	43.7±6.0	58±20	89±15	45.8±5.4	2.95±0.17	72.0±3.1
ND Riveland	81.3±1.3	46.1±3.7	70±9	93±5	47.5±3.6	3.01±0.19	71.6±1.5
Location							
Carrington	80.8±1.2	37.0±2.9	43±14	92±4	39.9±2.3	2.76±0.08	76.5±1.9
Casselton	80.1±1.3	43.2±2.5	66±11	71±12	44.3±1.8	2.97±0.07	68.3±5.1
Dickinson	80.1±0.6	46.5±2.1	69±6	94±2	47.4±2.4	3.03±0.07	71.7±0.9
Langdon	82.7±0.8	51.0±3.2	81±6	96±2	52.0±2.7	3.15±0.06	72.7±2.3
Minot	82.1±0.8	44.5±2.9	67±10	95±2	46.2±2.7	2.99±0.09	75.0±1.7
5-yr Avg[c]	78.6	39.9	50	86	na[a]	na[a]	na[a]

[a] WT = weight; KWT = kernel weight; VitK = vitreous kernels; na = not available.
[b] Percentage large kernel content.
[c] 2013-2017 Average for durum grown in the Northern Plains, USA (NDWC, 2018).

1000-Kernel weight (KWT) ranged from 39.0 (Divide) to 48.0 g (D131090 and D13541) in experiment 1 and from 40.9 (Maier) to 47.5 g (D13541) for genotypes in experiment 2. Except for Divide, D13899, and Maier with mean KWT of 39, 41.3 and 40.7 g, respectively, the remaining six genotypes had mean KWT much greater than the five-year average of 39.9 g in experiment 1. In experiment 2 location had higher mean KWT (43.2 to 51.0 g) than five-year average (39.9 g), except for Carrington with mean KWT of 37.0 g. In experiment 1, large kernel content varied from 57% (Divide) to 89% (D13541) and all genotypes had much more large kernels than the 5-year average (50%). In experiment 2, large kernel content differed with genotypes and ranged from 56% (Maier) to 77% (D13541) and varied with locations which ranged from 43% (Carrington) to 81% (Langdon). Carrington was the only location that had a lower mean large kernel content than the five-year average (50%).

SKCS provided averages for single kernel weight and for kernel diameter based on 300 kernels (Table 2). Single kernel weight in experiment 1 ranged from 43.2 to 51.8 mg, with the highest single kernel weight for D13541 (48.0 mg), D131090 (48.2 mg), and Carpio (47.1 mg); intermediate for Mountrail (43.4 mg), ND Riveland (44.3 mg) and Joppa (44.8 mg); and lowest for D13899 (41.3 mg), Divide (39.0 mg), and Maier (40.7 mg). Compared to experiment 1, the range for genotype single kernel weight was much less in experiment 2 and varied from 43.1 to 48.3 mg, with the highest single kernel weights for D13541 (48.3 mg), Carpio (47.8 mg), and ND Riveland (47.5 mg) and lowest single kernel weights for D13899 (43.1 mg) and Maier (43.9 mg). Genotype ranking was similar for experiment 1 and 2. In experiment 2, single kernel weight varied more with location than with genotype. Single kernel weight was least at Carrington (39.9 mg) and was greatest at Langdon (52.0 mg).

Genotype rankings in experiment 1 and experiment 2 for SKCS single kernel weight and 1000-KWT were similar (Table 2). SKCS single kernel weight had a strong positive correlation with 1000-KWT in experiment 1 (r=0.949, $P<0.0001$) and in experiment 2 (r=0.972, $P<0.0001$). Although there were small differences in genotype rankings for SKCS kernel diameter and large kernel content between experiment 1 and experiment 2, SKCS kernel diameter had a strong positive correlation with large kernel content in experiment 1 (r=0.952, $P<0.0001$) and in experiment 2 (r=0.941, $P<0.0001$). Thus the methods were equally effective in determining kernel weight and kernel size.

In US durum grain grading, durum is sub-classified as Hard Amber Durum (HAD), Amber Durum (AD), and Durum (D) based on vitreous kernel content. To meet HAD, AD, and D subclassification, the vitreous kernel content must be $\geq$ 75%, between 60 and 74%, and <60%, respectively (USDA, 2014). Commercially, there is a fourth classification referred to as Choice Milling Durum which requires $\geq$ 90% vitreous kernel content. Based on these criteria, in experiment 1, Carpio and Divide would be classified as HAD; D131090, Joppa, Maier, Mountrail, and ND Riveland would be classified as AD; and D13541 and D13899 would be classified as D. None of these genotype samples would be classified as Choice Milling Durum. All genotypes in experiment 2 would be classified as HAD but only Joppa, Maier, and ND Riveland would be classified as Choice Milling Durum (Table 2). Considering location in experiment 2, grain from Casselton had low average vitreousness (71%) while grain from the other four locations had high average vitreous kernel content (92-96%) and would be classified as Choice Milling Durum. Vitreousness is important to durum milling as it is associated with fracturing of the endosperm into large pieces as opposed to crushing associated with flour production (Peyron et al., 2003). Starchy non-vitreous kernels tend to be lower in protein content

compared to vitreous kernels and starchy durum kernels tend to be softer than vitreous durum (Dexter et al., 1989).

Kernel hardness has been associated with milling properties of different classes of wheat; soft wheat, hard wheat, and durum wheat of which durum is known to have the hardest kernels (Hrušková and Švec, 2009; Haraszi et al., 2016; Oury et al., 2017). Hardness index (HI) determined by SKCS is widely used to characterize kernel hardness and was initially introduced by Martin et al. (1993). This machine calculates a kernel hardness index based on algorithmic treatment of data obtained during the crushing of individual kernels (Gaines et al., 1996; Osborne and Anderssen, 2003).

In experiment 1, kernel hardness index was greatest with Carpio (83.6) and Maier (80.5) and least with D13899 (60.2) and D13541 (62.8) (Table 2). Variation in hardness index for genotype (70.7 to 75.2) and location (68.3 to 76.5) in experiment 2 was much less than that for genotype in experiment 1 (60.2 to 83.6). Hardness index was greatest with Maier (75.2) and lowest with Carpio (70.7) in experiment 2. Thus, genotype rankings for kernel hardness were not consistent between the two experiments. The hardness index values in both experiments were somewhat lower than what was expected but are within the range that has been reported for durum. Katyal et al. (2018) evaluated 40 durum lines and reported hardness index values of 33-111, with most values >90. Similarly, Haraszi et al. (2016) reported the hardness index values (72.1-97.1) for durum wheat cultivars.

Kernel Dimensional Characteristics

Data for kernel and germ dimensions and shape are presented in Table 3. All kernel dimensional parameters showed significant genotype differences in experiment 1 and genotype and location differences in experiment 2. Experiment 1 genotypes varied in their average length from 6.92 mm (D13899) to 7.51 mm (ND Riveland), width from 2.92 mm (Maier) to 3.30 mm (D13541) and thickness from 2.68 mm (Mountrail) to 3.15 mm (D13541). In experiment 2, genotypes varied in average length from 7.24 mm (Carpio) and 7.25 mm (D13899) to 7.54 mm (ND Riveland) and 7.56 mm (Mountrail), width from 2.89 mm (Maier) to 2.99 mm (Mountrail), and thickness from 2.99 mm (Maier) to 3.31 mm (D13541). Rankings of genotypes were similar for both experiments. Except for Carpio, all genotypes were wider than thicker in experiment 1. Conversely in experiment 2, kernels from genotypes and locations were all thicker than wider. These results are similar to those reported by Troccoli and di Fonzo (1999) who reported that 16 durum wheat cultivars grown in Southern Italy in 1994 had kernel length (6.79-7.23 mm), width (2.36-3.09 mm), and thickness (2.82-2.88 mm) and also reported that in one year kernels were thicker than wider while in another year the kernels were wider than thicker. Among five locations, grain grown near Langdon had the greatest averages for all three basic dimensions of length (7.54 mm), width (3.11 mm), and thickness (3.28 mm), while grain grown near Carrington had the lowest average values for width (2.72 mm) and thickness (2.95 mm), and relative low value of length (7.35 mm). On average, kernel length was 2.4 to 2.5 times longer than kernel width in experiment 1 and experiment 2, respectively.

Table 3. Genotype averages for kernel dimensional properties[a] of nine genotypes grown in Casselton in 2017 (Experiment 1) and eight genotypes grown at five locations in ND in 2018 (Experiment 2)[b].

Experiment 1	Ker L	Ker W	Ker T	Ker D	Ker W/L	Ker V	Sphericity	Germ L	Germ W	Germ W/L	GermL /KerL	GermW /KerW
Genotype	mm	mm	mm	mm		mm^3	%	mm	mm			
Carpio	7.19bcd	2.99def	3.11a	4.06b	0.42c	22.3b	56.5bc	2.55ab	1.94a	0.76ef	0.354a	0.652a
D131090	7.25bc	3.15b	2.93b	4.06b	0.43b	22.3b	56.0cd	2.50bcd	1.92abc	0.77def	0.345bc	0.610cd
D13541	7.20bcd	3.30a	3.15a	4.21a	0.46a	25.3a	58.5a	2.32f	1.93ab	0.84a	0.323d	0.587ef
D13899	6.92e	3.12bc	2.86bc	3.95cd	0.45a	20.7cd	57.1b	2.17g	1.79e	0.82ab	0.315e	0.574f
Divide	7.12cd	2.94ef	2.87bc	3.91de	0.41c	20.0cde	55.1de	2.51bc	1.87cd	0.75f	0.353ab	0.637b
Joppa	7.28bc	3.02de	2.75de	3.93de	0.42c	19.8de	53.9fg	2.35ef	1.88bcd	0.80bc	0.323d	0.620c
Maier	7.06de	2.92f	2.81cd	3.87e	0.41c	19.1e	54.9ef	2.42de	1.90abc	0.78cde	0.344c	0.651a
Mountrail	7.32b	3.03cd	2.68e	3.91de	0.41c	19.5de	53.3g	2.61a	1.82de	0.70g	0.357a	0.600de
ND Riveland	7.51a	3.00def	2.89bc	4.02bc	0.40d	21.3bc	53.5g	2.45cd	1.94ab	0.79cd	0.326d	0.646ab
Experiment 2												
Genotype												
Carpio	7.24e	2.98ab	3.22b	4.11b	0.411a	23.2b	56.7a	2.48b	2.04a	0.83b	0.343a	0.689a
D13541	7.32d	2.95bc	3.31a	4.15a	0.403b	24.0a	56.6a	2.33e	1.97c	0.85a	0.318d	0.672cd
D13899	7.25de	2.91de	3.07d	4.01c	0.402b	21.6e	55.4b	2.34e	1.89f	0.81c	0.323c	0.652e
Divide	7.48bc	2.95bc	3.16c	4.11b	0.395cd	23.0bc	55.0b	2.49b	2.00b	0.81c	0.333b	0.679b
Joppa	7.53ab	2.94cd	3.07d	4.08b	0.391de	22.4d	54.2cd	2.39d	1.96cd	0.82b	0.318d	0.667cd
Maier	7.44c	2.89e	2.99e	4.00c	0.389e	21.2e	53.8d	2.43c	1.94de	0.80c	0.327c	0.673bc
Mountrail	7.56a	2.99a	3.03e	4.09b	0.397c	22.6cd	54.1cd	2.60a	1.93e	0.74d	0.344a	0.645f
ND Riveland	7.54ab	2.95bc	3.08d	4.09b	0.392cde	22.6cd	54.3c	2.44c	1.97cd	0.81c	0.324c	0.666d
Location												
Carrington	7.35bc	2.72d	2.95d	3.89e	0.371d	19.2e	52.9d	2.38c	1.84d	0.78d	0.324c	0.678b
Casselton	7.28c	2.93c	3.00c	4.00d	0.404b	21.1d	55.0c	2.32d	1.90c	0.83a	0.318d	0.648c
Dickinson	7.54a	3.02b	3.17b	4.16b	0.401bc	23.9b	55.2bc	2.59a	2.08a	0.81c	0.343a	0.691a
Langdon	7.54a	3.11a	3.28a	4.25a	0.413a	25.7a	56.5a	2.45b	2.00b	0.82ab	0.325c	0.645c
Minot	7.39b	2.94c	3.18b	4.10c	0.398c	23.0c	55.5b	2.46b	1.99b	0.81bc	0.332b	0.678b

[a] Ker = kernel; L = length; W = width; T = thickness; D = diameter = (width + thickness)/2; V = volume.

[b] Mean values followed by different letters in the columns of each experiment are significantly different at $P \leq 0.05$.

Kernel shape was evaluated by estimating kernel volume and sphericity (Table 3). In both experiment 1 and experiment 2, average kernel volume was greatest for D13541 (25.3 mm^3 and 24.0 mm^3, respectively) and was lowest for Maier (19.1 mm^3 and 21.2 mm^3, respectively). Variation in kernel volume for genotypes was much less in experiment 2 (21.2 to 24.0 mm^3 with a difference of 2.8 mm^3) than in experiment 1 (19.1 to 25.3 mm^3 with a difference of 6.2 mm^3). Range in kernel volume was greater for location than for genotype in experiment 2, where average kernel volume was lowest at Carrington (19.2 mm^3) and greatest at Langdon (25.7 mm^3). Logically, kernel volume was positively correlated with kernel width and thickness (r=0.804, *P*=0.0091 and r=0.885, *P*=0.0015, respectively) in experiment 1 and (r=0.904, *P*<0.0001 and r=0.895, *P*<0.0001, respectively) in experiment 2. Interestingly, kernel length was not correlated with kernel volume in experiment 1. Best correlations occurred between kernel volume and diameter [(width + thickness)/2] which were r=0.981, *P*<0.0001 in experiment 1 and r=0.987, *P*<0.0001 in experiment 2.

Sphericity values estimate circularity of the kernel, where low values indicate long thin rectangular shape; intermediate values indicate oval/oblong shape; and high values indicate circular shape. Sphericity values differed with genotype. The sphericity in experiment 1 was observed in the range of 53.3 to 58.5% and for eight genotypes in experiment 2 the range was 53.8 to 56.7%. The narrow range in values indicates that the overall shape of kernels was similar and oval. Markowski et al. (2013) reported sphericity value for winter wheat of 60.6%, which agrees with a general observation that bread wheat is rounder than durum wheat.

Results of germ length, width, and width/length ratio are presented in Table 3. In experiment 1, Mountrail had longest germ (2.61 mm) and D13899 had the shortest germ (2.17 mm) and Carpio and ND Riveland had widest germ (1.94 mm) and D13899 had narrowest germ

(1.79 mm). So, D13899 had the lowest values for both germ length and width which could be considered having smallest germ section. Similarly in experiment 2, Mountrail had the longest germ (2.60 mm) and D13541 and D13899 had the shortest germ, 2.33 and 2.34 mm, respectively. Carpio had the widest germ (2.04 mm) and D13899 had the narrowest germ (1.89 mm). These results indicate that genotype rankings for germ length and germ width were similar for both experiments. Germ length and width varied with location. Dickinson had largest average germ section with greatest length (2.59 mm) and width (2.08 mm) while Casselton had shortest germ length (2.32 mm) and one of the shortest germ widths (1.90 mm). Range of germ length and width for both genotype and location in experiment 2 were similar (2.33 to 2.60 mm and 1.89 to 2.04 mm; 2.32 to 2.59 mm and 1.84 to 2.08 mm, respectively). Germ length was greater than germ width for all genotypes in both experiment 1 and experiment 2. Germ width/length ratio gives an estimate of roundness of the germ. The closer the ratio is to 1.0, the rounder is the germ. In both experiment 1 and experiment 2, D13541 had the highest ratio (most circular) 0.84 and 0.85, respectively, and Mountrail had the lowest ratio (least circular) 0.70 and 0.74, respectively.

Ratios of length and width of germ to kernel are presented in Table 3. Carpio and Mountrail had highest ratios of germ length-to-kernel length (0.354 and 0.357 in experiment 1, and 0.343 and 0.344 in experiment 2, respectively). Thus germ length was about 35% of the kernel length. Carpio, Maier, and ND Riveland had highest ratios of germ width-to-kernel width (0.652, 0.651, and 0.646, respectively) in experiment 1 and Carpio had highest value of 0.689 in experiment 2. Thus, germ width makes up two thirds of kernel width. D13899 in experiment 1 had the lowest average values for these two ratios indicating that germ section of this genotype was relatively smaller than the others. Germ length-to-kernel length and germ width-to-kernel

width ratios varied with location. Germ length-to-kernel length ranged from 0.318 for grain grown in Casselton to 0.343 for grain grown in Dickinson. Similarly, germ width-to-kernel width ratio ranged from 0.645 and 0.648 for grain grown in Langdon and Casselton, respectively, to 0.691 for grain grown in Dickinson. These data indicated that the kernel shape and size can vary with genotype and with growing location and that genotype ranking is similar.

Relative proportion of variance due to genotype, location, and residual (genotype x location) based on experiment 2 is shown in Table 4. For all parameters in grain quality and kernel dimensional characteristics, location represented the largest source of variation, except for germ width/length ratio (35.9%). For Falling Number, kernel length, and ratio of germ length-to-kernel length, location had relatively same effect as genotype (54.2, 45.0, and 55.4%, respectively). Location was the main source of variation for all the other parameters with relative proportion above 60%. Relative proportion of variance was >90% for location effect on protein content, ash content and vitreous kernel content in grain quality, SKCS kernel diameter, and kernel width in kernel dimensions. Haraszi et al. (2016) reported that location had greater effect than genotype for all parameters tested including kernel weight and kernel diameter.

Intraclass correlation coefficient (ICC) provides an estimate of broad sense heritability (Koo and Li, 2016). Intraclass correlation coefficient was determined by the proportion of variance attributed to genotype relative to that of genotype x location interaction and error variance, so traits with higher intraclass correlation coefficient would have more response to genotype (Caffe-Treml et al., 2011). It was suggested by Koo and Li (2016) that ICC values less than 0.5 had poor reliability, values between 0.5 and 0.75 had moderate reliability, values between 0.75 and 0.9 had good reliability, and values greater than 0.90 had excellent reliability. Based on these criteria, intraclass correlation coefficients were excellent for 1000-KWT, ratio of

germ length-to-kernel length (>0.90); good for protein content, ash content, large kernel content, Falling Number, single kernel weight, SKCS diameter, sphericity, germ length, germ width/length ratio, and ratio of germ width-to-kernel width (between 0.75 and 0.90) (Table 4).

Table 4. Variance components and intraclass correlation coefficients from analysis of eight genotypes grown in five locations for grain related parameters in 2018.

Parameters	Relative Proportion (%) of Variance Components			Intraclass Correlation[a]
	Genotype	**Location**	**Residuals**	
Grain Quality				
Test weight	13.4	81.3	5.3	0.72
1000-kernel weight	11.3	87.5	1.1	0.91**
Protein content	6.1	92.0	1.9	0.76*
Ash content	6.7	91.4	1.9	0.78*
Large kernel	15.8	81.5	2.7	0.86*
Falling number	40.3	54.2	5.5	0.88*
Vitreous kernel content	4.8	92.2	3.0	0.62
Hardness index	14.1	79.7	6.2	0.69
Single kernel weight	9.7	88.7	1.6	0.86*
Single kernel diameter	7.7	90.5	1.8	0.81*
Kernel Dimension				
Kernel length	36.1	45.0	18.9	0.66
Kernel width	3.1	90.9	6.0	0.34
Kernel thickness	24.1	65.4	10.4	0.70
Kernel diameter	10.2	83.0	6.8	0.60
Kernel volume	6.9	85.2	8.0	0.46
Sphericity	30.7	64.1	5.2	0.85*
Kernel W/L	11.2	81.9	6.9	0.62
Germ length	30.7	64.8	4.5	0.87*
Germ width	12.2	82.1	5.7	0.68
Germ W/L	56.3	35.9	7.8	0.88*
Germ L/Kernel L	41.0	55.4	3.6	0.92**
Germ W/Kernel W	22.2	71.2	6.6	0.77*

[a] Parameter with * is good (0.75-0.90); parameter with ** is excellent (>0.90).

Test weight, 1000-kernel weight, kernel vitreousness, kernel hardness, and kernel size are often associated with milling quality (Matsuo and Dexter, 1980; Sissons et al., 2000; Novaro et al., 2001; Sissons and Hare, 2002; Hrušková and Švec, 2009). Relationships between these five

important grain quality variables and kernel characteristics are presented in Table 5. Test weight represents the combination of kernel density and kernel packing efficiency (Hlynka and Bushuk, 1959; Troccoli and di Fonzo, 1999; Doehlert and McMullen, 2008). Packing efficiency is determined by kernel shape. Troccoli and di Fonzo (1999) reported that packing efficiency was independent of kernel weight or kernel volume but was more a matter of kernel shape, particularly rectangular aspect ratio (kernel width/kernel length) and circularity. Kernel density is affected by kernel size. Results of this research indicated that test weight was positively correlated to kernel size and shape factors. For example, test weight was positively correlated with 1000-KWT and large kernel content in experiment 1 (r=0.905, P=0.0008 and r=0.761, P=0.0171, respectively) and experiment 2 (r=0.496, P=0.0011 and r=0.516, P=0.0007, respectively). In experiment 2, test weight was also correlated to kernel width, thickness, diameter, volume, and sphericity. 1000-Kernel weight reflects average kernel size and density and was positively correlated with large kernel content, kernel diameter and kernel volume in both experiments (r=0.840, P=0.0046; r=0.691, P=0.0391; r=0.757, P=0.0182 and r=0.927, P<0.0001; r=0.915, P<0.0001; r=0.913, P<0.0001, respectively).

Table 5. Pearson correlation coefficients between important grain quality properties and kernel characteristics[a].

	Test Weight		1000-KWT		Large Kernel		Vitreousness		Hardness Index	
Parameter	Exp1	Exp2	Exp1	Exp2	Exp1	Exp2	Exp1	Exp2	Exp1	Exp2
Grain Quality										
Test weight			0.91***	0.50***	0.76*	0.52***				
1000-kernel weight	0.91***	0.50***			0.84**	0.93***				-0.34*
Protein content							0.86**	0.73***	0.89**	0.39*
Ash content		-0.66***		-0.67***		-0.61***		-0.48**		
Large kernel content	0.76*	0.52***	0.84**	0.93***						-0.42**
Falling number		0.31*								0.39*
Vitreous kernel content									0.97***	0.71***
Hardness index				-0.34*		-0.42**	0.97***	0.71***		
Kernel Dimension										
Kernel length				0.36*				0.49**		
Kernel width		0.35*		0.87***	0.77*	0.81***	-0.70*		-0.77*	-0.40**
Kernel thickness		0.53***		0.80***	0.71*	0.80***				
Kernel diameter		0.49**	0.69**	0.92***	0.86**	0.88***				
Kernel volume		0.45**	0.76*	0.91***	0.84**	0.84***				
Sphericity		0.56***		0.78***	0.71*	0.87***				-0.39*
Kernel W/L		0.42**		0.76***		0.82***	-0.80**		-0.80**	-0.58***
Germ length							0.83**	0.42**	0.80**	
Germ width				0.72***		0.69***				
Germ W/L		0.33*		0.51***		0.65***	-0.67*		-0.70*	

[a] Exp1=Experiment 1; Exp2=Experiment 2. *, **, and *** indicate *F* value is significant at $P< 0.05$, 0.01, and 0.001, respectively.

As would be expected, large kernel content was related to kernel physical size parameters which were confirmed with positive correlations between large kernel content and kernel dimensional characteristics including width, thickness, diameter, volume and sphericity in both experiments (Table 5). Kernel vitreousness is related to protein content and continuity. Starchy and non-vitreous kernels are the result of air space within endosperm when protein is not continuous. Kernel vitreousness was positively correlated to protein content in both experiments. Hardness is mainly affected by the lack of protein and starch interaction with the specific protein called puroindolines A and B and to continuity of protein matrix in the endosperm (Oury et al., 2017). This also differentiates soft wheat from hard wheat (Haraszi et al., 2016). For both experiments, hardness index was positively correlated to protein content and vitreousness (r=0.886, P=0.0015 and r=0.863, P=0.0028, respectively, in experiment 1; r=0.388, P=0.0135 and r=0.730, P<0.0001, respectively in experiment 2). Because test used to determine kernel hardness by crushing kernels is always done on the width or thickness side, kernel width is also related to kernel hardness which was shown from the result that kernel width was negatively correlated to the hardness.

Milling Properties

Break Roll Release

Break release is the stock that passes through the top sieve associated with a break roll. Once through the top sieve, the stock is passed over a fine sieve that removes the flour, and the remaining stock is sent to the purifier. Break release was determined for the first and second paired break rolls (Table 6). Break release was determined for samples in experiment 1 and for samples harvested near Carrington, Casselton, and Dickinson in 2018 in experiment 2. Break release was not determined for samples from Minot and Langdon due to lack of sufficient grain.

Table 6. Genotype averages[a] for break release from first and second break rolls on a Bühler mill 202 MLU, expressed as a % of material in each break, for nine genotypes grown in Casselton in 2017 (Experiment 1) and eight genotypes grown in three locations in ND in 2018 (Experiment 2)[b].

Experiment 1	First Break		Second Break	
Genotype	B1 release	B1 flour	B2 release	B2 flour
Carpio	13.7d	1.0c	64.5de	3.2g
D131090	14.6c	1.1c	67.2a	4.9c
D13541	16.4a	1.5b	64.9cd	7.3b
D13899	15.2b	1.9a	63.0f	8.5a
Divide	10.7f	0.6de	63.3ef	3.7f
Joppa	13.2d	0.9cd	65.2bcd	4.6d
Maier	11.9e	0.6de	66.5ab	3.8f
Mountrail	13.2d	0.6de	66.1abc	3.7f
ND Riveland	10.7f	0.6e	64.9cd	4.3e
Experiment 2				
Genotype				
Carpio	13.3a	1.0a	61.2a	4.4b
D13541	12.8b	0.7cd	60.5b	3.8d
D13899	12.1d	0.9b	59.0d	4.7a
Divide	12.3c	0.8bc	59.7c	3.9cd
Joppa	12.7b	0.8bc	60.7ab	4.3b
Maier	10.9f	0.5e	59.6c	3.3e
Mountrail	11.1f	0.6de	59.6c	3.8d
ND Riveland	11.6e	0.7cd	58.7d	4.0c
Location				
Carrington	10.4c	0.4b	58.7b	3.1b
Casselton	14.7a	1.4a	61.6a	5.8a
Dickinson	11.2b	0.5b	59.3b	3.2b

[a] B1 release = first break release; B1 flour = first break flour; B2 release = second break release; B2 flour = second break flour.
[b] Mean values followed by different letters in the columns of each experiment are significantly different at $P \leq 0.05$.

In experiment 1, first break release ranged from 10.7 to 16.4% where the greatest release occurred with D13541 (16.4%) and least release was with Divide (10.7%) and ND Riveland (10.7%) (Table 6). In experiment 2, first break release ranged from 10.9 to 13.3% which Carpio had the greatest release of 13.3% and Maier had the least release of 10.9%. Thus, genotype ranking differed between experiment 1 and experiment 2. Break release varied with location.

Grain from Carrington had the lowest average release (10.4%) while grain from Casselton had the highest average release (14.7%). The range of break release was greater among locations than among genotypes in experiment 2. Different from the first break, release from the second break was much higher and varied from 63.0 to 67.2% in experiment 1 and from 58.7 to 61.2% in experiment 2. The variation in experiment 2 was less than that in experiment 1 for genotype. Dexter et al. (1990) milling on an Allis Chamber roller mill reported break releases of 4, 55, and 45% for the first, second, and third break rolls, respectively. Break release for the first break rolls was much lower than that for the second break rolls (Table 6). Low first break release reflects the desire to produce coarse granulation with little or no flour as compared to flour mill that desires to produce small granulation in the first break (Abercrombie, 1980; Hsieh, et al., 1980; Li and Posner, 1989; Posner and Hibbs, 2005).

The goals for the break section, when milling durum wheat into semolina, is to produce coarse particles and to minimize flour production. Only very small amount of flour was produced from the first break rolls in experiment 1 and experiment 2 (0.6 to 1.9% and 0.5 to 1.0%, respectively). Much more flour was produced from second break rolls for both experiments (3.2 for Carpio to 8.5% for D13899 and 3.3 for Maier to 4.7% for D13899, respectively). In experiment 1, D13899 had the greatest amount of flour produced in first and second breaks, while Carpio, Divide, Maier, and Mountrail all had small amounts of flour produced in first and second breaks. In experiment 2, D13899 produced the most flour from first and second breaks and Maier produced the least (0.5 and 3.3%, respectively).

First break release was negatively correlated with protein content (r=-0.847, P=0.0040 for experiment 1 and r=-0.640, P=0.0007 for experiment 2), and positively correlated with large kernel content (r=0.797, P=0.0101 for experiment 1 and r=0.583, P=0.0028 for experiment 2);

SKCS kernel diameter (r=0.737, *P*=0.0234 for experiment 1 and r=0.505, *P*=0.0118 for experiment 2); sphericity (r=0.761, *P*=0.0172 for experiment 1 and r=0.583, *P*=0.0028 for experiment 2); and kernel width/length ratio (r=0.902, *P*=0.0009 for experiment 1 and r=0.673, *P*=0.0003). These results indicate that first break release was strongly correlated with kernel shape and size, where larger and rounder kernels tended to have more chance to break into more pieces in the first grinding section and result in a higher percentage of release from first break. This matched previous research that kernel size had large influence on grinding process because small kernel fraction (2.0-2.5 mm) was more difficult to grind than large kernel fraction (3.1-3.5 mm) (Dziki and Laskowski, 2004). Additionally in experiment 2, kernel vitreousness and hardness were negatively correlated with first break release (r=-0.812, *P*<0.0001 and r=-0.689, *P*=0.0002, respectively). This could be the reason that more vitreousness and harder kernels were more difficult to be broken by first break rolls.

Flour production during wheat milling has been related to kernel hardness and vitreousness. Tsuge (1985) reported that less flour was produced when milling harder kernels compared to softer ones. Dziki and Laskowski (2005) reported that non-vitreousness kernels produced more flour. There were negative correlations between flour produced in first and second break and grain hardness index (r=-0.830, *P*=0.0056 and r=-0.970, *P*<0.0001, respectively) and between flour produced in first and second break and vitreousness (r=-0.835, *P*=0.0051 and r=-0.978, *P*<0.0001, respectively) in experiment 1. Similarly in experiment 2, there were negative correlations between flour produced in first and second break and grain hardness index (r=-0.766, *P*<0.0001 and r=-0.771, *P*<0.0001, respectively) and between flour produced in first and second break and kernel vitreousness (r=-0.920, *P*<0.0001 and r=-0.903, *P*<0.0001, respectively). Kernel vitreousness and kernel hardness have been reported to favor the

production of large particles (Dziki and Laskowski, 2005). These results support those of Ohm et al. (1998) and Baasandorj et al. (2016) who also reported a negative relationship between kernel vitreousness and flour produced in first break.

Bühler Milling

Feed rate and milling rate were not the same. The target feed rate for all samples was 150 g/min. Milling rate was based on the time for ground grain to pass through and out of the mill. Milling rate averaged 109 g/min in experiment 1and 101 g/min for experiment 2 (Table 7). The range of these values was similar to that reported by Shinezorigt (2019). Milling rate in experiment 1 tended to be greatest for D13899 (118 g/min) and D13541 (114 g/min); intermediate for Carpio (111 g/min), D131090 (110 g/min), and Divide (111 g/min); and least for Joppa (101 g/min), Maier (106 g/min), Mountrail (104 g/min) and ND Riveland (106 g/min). In experiment 2, milling rate averaged 101 g/min and except for Carpio (107 g/min) and D13899 (97 g/min), all other genotypes had similar milling rates. The ranking of genotypes differed between the two experiments. For example, D13899 had the highest milling rate (118 g/min) in experiment 1 but the lowest milling rate (97 g/min) in experiment 2. The reason for the variation in milling rate is not apparent.

Miag purifiers were used to remove semolina by sieving and bran was removed through aspiration; particles too big to be semolina were transferred via pneumatic lines to the appropriate break roll or reduction roll. As stock moved through the mill from different break rolls and reduction rolls, the semolina removed became coarser so that the coarsest semolina was collected in purifier 4 (P4). In experiment 1, purifier 1 collected the most semolina with D131090 (41.2%) and Maier (40.6%) and collected the least with Mountrail (36.2%) (Table 7). Rankings were different in experiment 2 where the least semolina in purifier 1 occurred with

Table 7. Milling rate and mill fractions (P1 to P4), total extraction (TEXT) and semolina extraction (SEXT) calculated based on total product for nine genotypes grown in Casselton in 2017 (Experiment 1) and eight genotypes grown in five locations in ND in 2018 (Experiment 2)*.

	Mill Rate	Mill Fraction, %									TEXT	SEXT
Experiment 1 Genotype	g/min	P1	P2	P3	P4	Total flour	Flour break	Flour reduction	Bran	Large bran	%	%
Carpio	111abc	39.3ab	8.1ab	13.2bc	8.2d	7.1c	4.4cd	2.7abc	20.1ab	10.1b	75.8bcd	60.6abc
D131090	110bc	41.2a	7.6ab	13.2abc	8.8abc	7.6c	4.7c	2.9ab	18.4c	8.3c	78.5a	62.0ab
D13541	114ab	39.5ab	7.1b	12.9bc	8.5abcd	9.3b	6.6b	2.7bc	18.9bc	8.6c	77.3ab	59.5c
D13899	118a	37.5ab	6.6b	12.6c	8.4bcd	11.5a	8.6a	2.9ab	20.3ab	11.4a	76.6abc	56.7d
Divide	111abc	40.0ab	7.4ab	13.7ab	9.0ab	6.2d	3.5e	2.6c	19.8abc	6.5de	76.3bcd	61.1abc
Joppa	101d	40.1ab	7.2b	13.7ab	9.0a	7.4c	4.6c	2.8abc	18.9bc	8.2c	77.4ab	61.0abc
Maier	106cd	40.6a	8.2ab	13.4abc	8.6abcd	6.1d	3.5e	2.6c	19.3bc	6.0e	76.9abc	62.2a
Mountrail	104cd	36.2b	8.9a	14.0a	8.8abc	6.4d	3.6e	2.8abc	21.2a	7.0d	74.4d	59.1c
ND Riveland	106cd	39.0ab	7.5ab	13.2abc	8.3cd	7.1c	4.2d	3.0a	21.1a	4.9f	75.2cd	59.8bc
Experiment 2 Genotype												
Carpio	107a	40.2ab	8.9a	16.0b	6.6a	6.0ab	na	na	21.0cd	10.5a	77.6abc	65.0a
D13541	101ab	40.3a	8.5ab	16.2b	6.7a	6.0ab	na	na	20.9cd	9.7ab	77.7ab	65.0a
D13899	97b	39.3b	8.3ab	16.0b	6.8a	6.8a	na	na	22.1ab	11.2a	77.2bc	63.5b
Divide	103ab	40.9a	8.6ab	15.8b	6.6a	5.7b	na	na	21.3bc	9.4ab	77.6abc	65.3a
Joppa	102ab	40.8a	8.5ab	16.2b	6.7a	6.4ab	na	na	20.5d	10.6a	78.6a	65.5a
Maier	100ab	40.9a	8.5ab	15.8b	6.7a	5.5b	na	na	21.0cd	7.9bc	77.5bc	65.2a
Mountrail	102ab	40.5a	8.0b	16.1b	6.9a	5.6b	na	na	21.6abc	9.9a	77.0bc	64.5ab
ND Riveland	99ab	37.7c	8.3ab	17.4a	7.0a	6.3ab	na	na	22.1a	7.4c	76.6c	63.3b
Location												
Carrington	112a	41.9b	9.0ab	15.8c	6.4c	4.7c	na	na	21.1bc	9.5b	77.8b	66.7a
Casselton	96b	40.6c	7.5c	14.5d	6.6bc	8.0a	na	na	21.8a	14.7a	77.3bc	62.6c
Dickinson	92b	37.7d	9.4a	16.5b	7.3a	5.7b	na	na	21.8a	6.9c	76.6c	63.6bc
Langdon	94b	42.7a	7.8c	16.1bc	6.6bc	5.7b	na	na	20.6c	8.6b	78.9a	66.6a
Minot	113a	37.4d	8.5b	17.9a	6.9b	6.2b	na	na	21.3ab	8.1bc	76.9c	63.9b

* Mean values followed by different letters in the columns of each experiment are significantly different at P≤0.05. na = not available.

D13899 (39.3%) and ND Riveland (37.7%). The remaining genotypes all had higher and similar amounts of semolina (40.2-40.9%). Semolina accumulation in purifiers 1-4 varied with location, with greatest differentiation occurring with purifier 1 where semolina accumulation was greatest with Langdon (42.7%), intermediate with Carrington (41.9%) and Casselton (40.6%), and least with Dickinson (37.7%) and Minot (37.4%). In both experiments, differences among genotypes in the semolina collected in purifiers 2, 3, and 4 were relatively small.

Total flour percentage ranged from 6.1 to 11.5% in experiment 1 with the lowest amount produced with Maier (6.1%), Divide (6.2%), and Mountrail (6.4%) and the highest amount with D13899 (11.5%) and D13541 (9.3%) (Table 7). About two-thirds of total flour was produced by the first three break rolls. Genotype ranking was similar for total flour and break flour. The variation of total flour percentage in experiment 2 was much smaller (5.5 to 6.8%) than the variation in experiment 1. Similar to experiment 1, D13899 produced most flour (6.8%) and Maier, Divide, and Mountrail produced the least (2.5, 5.6, and 5.7%, respectively).Variation was greater for location with a range of 4.7 to 8.0%. Grain grown near Casselton produced the most flour (8%) and grown near Carrington (4.7%) the least, similar to flour produced in break release experiment (Table 6).

In experiment 1, D131090, Joppa, and D13541 produced least amount of bran (18.4, 18.9, and 18.9%) and Mountrail and ND Riveland produced the most bran (21.2 and 21.1%) (Table 7). In experiment 2, variation in the amount of bran removed was small ranging from 20.5 to 22.1% and 20.6 to 21.8%, for genotype and location, respectively. It should be noted that similar to experiment 1, ND Riveland produced the most bran (22.1%) and Joppa and D13541 produced the least bran (20.5 and 20.9%, respectively).

Within the bran fraction, the percentage of large bran particles was also determined; and this parameter varied greatly in experiment 1 and experiment 2 (Table 7). In experiment 1, large bran percentage was highest with D13899 (11.4%) and Carpio (10.1%); intermediate with D131090, D13541, and Joppa (8.3, 8.6, and 8.2%, respectively); lowest with Divide, Maier, Mountrail, and ND Riveland (6.5, 6.0. 7.0, and 4.9, respectively). Genotype ranking was similar in experiment 1 and experiment 2 for the amount of large bran produced. Location had more impact on large bran percentage with a greater variation from 6.9 to 14.7%. Casselton had more than twice the amount of large bran pieces than Dickinson (14.7 and 6.9%, respectively). Differences in bran size suggest differences in mechanical and probably chemical properties of bran (Mabille et al., 2001).

Further research is needed to determine what factors promote production of large bran particles during milling. In experiment1, large bran content was affected by kernel shape and had positive correlations with sphericity (r=0.674, P=0.0465), width/length ratio (r=0.684, P=0.0422), first break release (r=0.758, P=0.0181), mill rate (0.657, P=0.0546), break flour (0.754, P=0.0190) and total flour (r=0.741, P=0.0224), and negative correlations with semolina protein (r=-0.721, P=0.0283) and starch damage (r=-0.808, P=0.0084). In experiment 2, large bran content was negatively correlated with kernel protein content (r=-0.742, P<0.0001), vitreousness (r=-0.838, P<0.0001), and hardness (r=-0.462, P=0.0027) and positive correlation with ash content (r=0.473, P=0.0020). Kernel physical characteristics seemed to affect large bran content with large bran content having negative correlations with kernel length (r=-0.467, P=0.0024), germ length (r=-0.825, P=0.0005), and germ width (r=-0.375, P=0.0172). Kernels that were less vitreous, hard, and short with large germ section, tended to produce more large bran particles. Hard and glassy vitreous grain would require high shear force and probably

caused the bran to be broken into small particles, resulting in fewer large bran pieces. Kernels with a high ratio of germ-to-kernel tended to have less kernel surface covered by bran and resulted in smaller bran pieces during milling. Large bran content had positive correlations with total flour (r=0.605, $P<0.0001$) and negative correlation with semolina protein (r=-0.727, $P<0.0001$) in experiment 2.

Total extraction includes semolina and flour. In experiment 1, total extraction ranged from 74.4% with Mountrail to 78.5% with D131090 (Table 7) and all genotypes were higher than the 5-year average (71.5%). In experiment 2, total extraction for genotype ranged from 76.6% with ND Riveland to 78.6% with Joppa and for location ranged from 76.6% for durum grown near Dickinson to 78.9% for durum grown near Langdon and all were higher than the 5-year average (71.5%). There were no correlations between grain characteristics and total extraction except for experiment 2 except for test weight (r=0.443, $P=0.0042$).

Semolina extraction in experiment 1 and experiment 2 were lower than the 5-year average (66.3%) except for Carrington (66.7%) and Langdon (66.6%) in experiment 2. This could be the result of different sets of milling fractions being combined to obtain semolina. In this experiment, P4, which contained a high level of specks, was not blended into the final semolina and this made the semolina extraction lower than the average. Semolina extraction in experiment 1 was lower (56.7 to 62.2%) than in experiment 2 genotype (63.3 to 65.5%) and location (62.6 to 66.7%) (Table 7). In experiment 1, D13899 had an intermediate total extraction of 76.6% but the lowest semolina extraction of 56.7% because of the high flour percentage of 11.5%. On the other hand, D131090 had the highest total extraction (78.5%) and second highest semolina extraction (62.0%). These results proved that high total extraction does not guarantee a high semolina extraction; a similar conclusion was reported by Matsuo and Dexter (1980). In

experiment 2, Joppa had the highest total (78.6) and semolina (65%) extractions and ND Riveland had the lowest total (76.6%) and semolina (63.3%) extractions. In experiment 2, grain from Langdon had the highest total (78.9%) and second highest semolina (66.6%) extractions while grain from Dickinson had the lowest total (76.6%) and second lowest semolina (63.6%) extractions. There were few correlations between kernel characteristics and semolina extraction except for positive correlation with hardness (r=0.681, P=0.0436 and r=0.651, P<0.0001) and vitreousness (r=0.701, P=0.0353 and r=0.513, P=0.0007) in both experiments. These correlations showed that more vitreous kernels or harder kernels tended to produce higher semolina extraction. It was in agreement with the theory discussed by Dziki and Laskowski (2005).

Relative proportion of variance due to genotype, location, and residual in milling is presented in Table 8. Location had a large impact on the variation in all parameters except for bran content where the impact of genotype and location were similar. The intraclass coefficients were good for semolina accumulation in purifier 3, bran content, large bran content, total extraction, and semolina extraction and excellent for semolina accumulation in purifier 1.

Table 8. Estimates of variance components and intraclass correlation coefficients from analysis of eight genotypes grown in three locations for break roll release and Bühler milling in 2018[a].

Parameters	Relative Proportion (%) of Variance Components			Intraclass Correlation[b]
	Genotype	Location	Residuals	
Break Roll Release				
BRK 1 release	4.7	92.3	3.0	0.61
BRK 2 release	8.7	76.3	15.0	0.37
Bühler Milling				
Milling rate	5.1	90.2	4.7	0.52
P1	11.5	87.4	1.1	0.91**
P2	5.6	88.0	6.4	0.47
P3	9.4	88.2	2.4	0.79*
Total P4	8.2	82.7	9.1	0.48
Total flour	7.4	89.1	3.5	0.68
Shorts	28.3	56.0	15.7	0.64
Bran	42.4	48.0	9.6	0.81*
Large bran	10.5	87.2	2.3	0.82*
Total extraction	19.4	73.7	6.9	0.74
Semolina extraction	10.6	86.3	3.1	0.77*

[a] BRK 1 = first break; BRK 2 = second break.
[b] Parameter with * is good (0.75-0.90); parameter with ** is excellent (>0.90).

Semolina Quality

Semolina granulation is an important quality factor that has been reported to vary with environment and genotype (Haraszi et al., 2016; Dziki et al., 2017). Genotypes did not differ greatly in their particle size distributions (Table 9), with 75-85% of semolina particles were between 150 and 425µm. Experiment 1 had higher percentage (9.4 to 11.0%) of large semolina particles (425-500 µm) than experiment 2 (4.2 to 5.0%). Geometric mean diameter (d_{gw}) is an indicator of semolina particle size. The d_{gw} was significantly different but only ranged from 256 for D13899 to 268 µm for Divide in experiment 1 and was similar for all genotypes in experiment 2, having a narrow range of 250 to 253 µm. The d_{gw} for location in experiment 2 was significantly different and ranged from 246 for grain from Dickinson to 260µm for grain from Carrington.

Table 9. Effect of durum genotype on semolina particle size distribution expressed in % for nine genotypes grown in Casselton in 2017 (Experiment 1) and eight genotypes grown in five locations in ND in 2018 (Experiment 2).

Experiment 1 Genotype	>500 µm	425-500 µm	250-425 µm	150-250 µm	100-150 µm	50-100 µm	<50 µm	d_{gw}[a] (µm)	s_{gw}[a]
Carpio	0.06ab	9.5bc	54.6ab	25.5bc	6.7bcd	3.4c	0.14a	261.9bc	113.8cd
D131090	0.08ab	10.3ab	52.9de	26.4a	6.9abc	3.4c	0.06a	261.1c	114.5bc
D13541	0.04b	9.4c	52.7de	26.5a	7.3ab	3.9b	0.06a	257.2de	115.1b
D13899	0.04ab	9.5bc	52.3e	26.4a	7.5a	4.2a	0.08a	255.9e	116.4a
Divide	0.06ab	10.7a	55.0a	25.2c	6.1d	2.7e	0.20a	268.2a	111.7e
Joppa	0.07ab	11.0a	53.2d	26.1ab	6.5cd	3.0d	0.14a	264.9ab	113.4d
Maier	0.08a	10.8a	54.5ab	25.5bc	6.2d	2.7e	0.18a	267.3a	111.9e
Mountrail	0.07ab	10.6a	54.2bc	25.5bc	6.5cd	3.0d	0.15a	265.6a	113.1d
ND Riveland	0.05ab	9.7bc	53.5cd	26.0ab	6.9abc	3.7b	0.07a	259.8cd	115.0b
Experiment 2 Genotype									
Carpio	0.05a	4.2b	56.3ab	27.7a	7.5a	4.0ab	0.09a	250.1a	107.8bcd
D13541	0.01a	4.6ab	56.4ab	27.9a	7.5a	3.6c	0.05a	252.1a	106.6d
D13899	0.03a	5.0a	55.8b	27.2a	7.7a	4.3a	0.02a	250.0a	110.1a
Divide	0.01a	4.6ab	56.5ab	27.6a	7.5a	3.8bc	0.07a	251.8a	107.5bcd
Joppa	0.02a	4.6ab	55.9ab	27.8a	7.6a	4.0ab	0.02a	250.2a	108.5bc
Maier	0.04a	5.0a	56.2ab	27.9a	7.4a	3.5c	0.09a	252.9a	107.1cd
Mountrail	0.03a	4.9a	55.7b	27.8a	7.5a	3.9abc	0.06a	251.1a	108.5b
ND Riveland	0.03a	4.3b	57.1a	27.3a	7.4a	3.9abc	0.08a	251.7a	107.7bcd
Location									
Carrington	0.02a	7.3a	56.2b	26.4d	7.0b	3.0c	0.01b	260.0a	108.8b
Casselton	0.03a	6.4b	52.4d	29.0a	7.8a	4.2a	0.12a	248.8c	110.8a
Dickinson	0.02a	1.2c	59.2a	27.7bc	7.6a	4.2a	0.04ab	246.6cd	104.6c
Langdon	0.03a	7.1a	54.5c	27.2c	7.5ab	3.7b	0.03b	254.8b	111.0a
Minot	0.05a	1.2c	58.8a	27.9b	7.7a	4.3a	0.10ab	245.9d	104.6c

[a] d_{gw} = geometric mean diameter; s_{gw} = standard deviation of geometric mean diameter.
[b] Mean values followed by different letters in the columns of each experiment are significantly different at $P \leq 0.05$.

Dziki et al. (2017) stated that the particle size and size distribution were important from technical point of view and that there was an inverse relationship between kernel hardness and finely ground particles. In this experiment, D13899 in experiment 1 had the softest kernels (lowest hardness index) and had the smallest dgw of semolina particles which agreed with previous research (Matsuo and Dexter, 1980; Tsuge, 1985; Pauly et al., 2013; Oury et al., 2017). Break rolls are expected to break hard kernels into large particles and produce few fine particles. The effect of hardness on semolina size distribution was not obvious enough to be detected in experiment 2 when averaged across location or genotype. But it was observed that hardness

index was negatively correlated to small particle fractions, and negatively correlated with geometric mean diameter (r=0.817, *P*=0.0072 and r=0.453, *P*=0.0033, respectively) in experiment 1 and experiment 2.

Specks in semolina were the result of small particles of bran or other material escaping the cleaning and purifying process. Speck count of semolina is an important indicator of milling quality, and a small number is preferred. In experiment 1, genotype differed from 53 for Maier to 64 specks/dm^2 for Mountrail (Table 10). All nine genotypes had a much higher speck count compared to the 5-year average (42 specks/dm^2). In experiment 2, genotypes did not differ in their speck counts. For location, speck count in semolina was lowest for grain from Minot and Dickinson (47 and 50/dm^2, respectively); intermediate for grain from Carrington and Langdon (56 and 60/dm^2, respectively), and highest for grain from Casselton (67/dm^2).

Protein content and ash content are known to relate to milling yield because they both have greater accumulation in the periphery of the endosperm compared to the center of the endosperm (Dexter and Matsuo, 1978; Abecassis et al., 1987; Li and Posner, 1989). Thus, the more endosperm near the aleurone layer removed, the higher amount of protein and ash in semolina (Hareland, 1998). Protein content in semolina varied with genotype and location in this experiment (Table 10). In experiment 1, protein content ranged from 9.8 (D13541) to 12.8% (Maier). In experiment 2, protein content ranged from 12.1 (ND Riveland) to 13.4% (Maier) for genotype, and 10.6 (Casselton) to 13.8% (Dickinson and Minot) for location. Thus, protein content differed more among locations than among genotypes.

Table 10. Semolina quality properties[a] related to milling of nine genotypes grown in Casselton in 2017 (Experiment 1) and eight genotypes grown in three locations in ND in 2018 (Experiment 2)[b].

Experiment 1	Specks	Protein	Ash	Starch Damage	CIE L	CIE b
Genotype	No./dm^2	%	%			
Carpio	56ab	11.5d	0.70ab	2.6cd	83.98c	27.75a
D131090	60ab	11.3e	0.68abc	2.8abc	84.64ab	24.99d
D13541	54ab	9.8g	0.71ab	2.7bc	84.18bc	27.28abc
D13899	59ab	10.3f	0.65d	2.3d	84.02c	25.29d
Divide	57ab	12.7a	0.66cd	2.8abc	84.10c	25.86bcd
Joppa	59ab	11.2e	0.66cd	2.8abc	84.87a	25.78bcd
Maier	53b	12.8a	0.71a	2.9ab	84.12c	27.56ab
Mountrail	64a	11.8c	0.67bcd	3.0a	84.23bc	25.61cd
ND Riveland	59ab	12.1b	0.65d	2.7abc	84.93a	25.46d
Experiment 2						
Genotype						
Carpio	57a	12.7bcd	0.80bc	3.3ab	83.04ab	30.57a
D13541	54a	12.4cd	0.81bc	3.2b	83.20ab	30.06ab
D13899	54a	13.1ab	0.75c	3.0c	83.64a	29.74ab
Divide	57a	12.9abc	0.79bc	3.4ab	83.65a	27.94c
Joppa	56a	12.2d	0.80bc	3.5a	83.61a	30.05ab
Maier	60a	13.4a	0.90a	3.3ab	82.75b	29.17b
Mountrail	54a	12.9abc	0.84b	3.5a	83.68a	24.62d
ND Riveland	56a	12.1d	0.81b	3.4ab	83.34ab	29.42b
Location						
Carrington	56bc	12.4c	0.90a	3.4a	82.80d	31.67a
Casselton	67a	10.6d	0.89a	3.5a	84.24a	28.01b
Dickinson	50c	13.8a	0.77b	3.1b	83.36bc	28.55b
Langdon	60ab	13.0b	0.78b	3.4a	83.49b	28.20b
Minot	47c	13.8a	0.74b	3.2b	82.93cd	28.32b

[a] Protein and ash on 14% moisture basis.
[b] Mean values followed by different letters in the columns of each experiment are significantly different at $P \leq 0.05$.

Ash content is considered as an indicator of bran contamination in semolina because bran contains relatively high levels of ash (Manthey and Hareland, 2001). Ash contents for genotypes were lower in experiment 1 than in experiment 2. In experiment 1, ash content varied from 0.65% (D13899 and ND Riveland) to 0.71% (Maier and D13541). In experiment 2, ash content varied from 0.75% (D13899) to 0.90% (Maier). Genotype ranking was similar in experiment 1

and experiment 2. Ash content varied with growing location with lowest ash content in Minot (0.74%) to highest ash content in Casselton (0.89%) and Carrington (0.90%). This could be the result from either more bran contamination or higher level of ash in endosperm. Speck count was negatively correlated with protein content (r=-0.553, *P*=0.0002), kernel vitreousness (r=-0.512, *P*=0.0007), kernel hardness index (r=-0.419, *P*=0.0071), germ length (r=-0.377, *P*=0.0165) and positively correlated with semolina ash content (r=0.315, *P*=0.0480) and first break release (r=0.596, *P*=0.0021) in experiment 2.

Starch damage varied with genotype from 2.3 to 3.0% in experiment 1 and 3.0 to 3.5% in experiment 2. Starch damage was about 0.6 percentage units greater in experiment 2 than in experiment 1(Table 10). In both experiments, D13899 had lowest amount of starch damage (2.3 and 3.0% respectively) and Mountrail had greatest amount of starch damage (3.0 and 3.5% respectively). It was observed by Dexter and Matsuo (1978) that starch damage of semolina was positively correlated to semolina extraction. There was no correlation between starch damage and semolina extraction in experiment 1 but there was a positive in experiment 2 (r=0.410, *P*=0.0087). Starch damage was positively correlated with kernel hardness (r=0.637, *P*=0.0648) and kernel vitreousness (r=0.6336, *P*=0.0669) in experiment 1. Baasandorj et al. (2016) also reported a positive correlation between starch damage and kernel vitreousness.

CONCLUSIONS

Much research has been carried out on the milling properties of durum grain and the relation between physical kernel characteristics and milling performance. However, limited information is available concerning the kernel characteristics and milling properties of commercially available genotypes grown in North Dakota. The results showed that kernel shape and size varied with genotype and growing location. Kernel shape and size were strongly associated with first break in Bühler milling. Larger and rounder kernels tended to result in better milling extraction with more release from first break. The data also confirmed that kernel hardness and vitreousness favored the production of large particles producing less flour in first break. There was no correlation between grain characteristics and total extraction in Bühler milling. A single major grain trait was not identified that could be used as a reliable predictor of durum milling. Although, some correlations occurred between kernel physical and mechanical characteristics and semolina extraction which indicates that these parameters contributed to the milling process, these characteristics did not act as dominant factors influencing the milling. For example, kernel hardness and vitreousness were strongly associated with semolina extraction and quality, but they were not consistently reliable in predicting semolina extraction. Harder and more vitreous kernels have more chance to have superior semolina extraction with fewer specks. Interestingly, kernel hardness and vitreousness appeared to contribute negatively to large bran percentage which meant that harder and more vitreous kernels tended to produce fewer large bran flakes.

FUTURE RESEARCH AND INDUSTRIAL APPLICATION

Future research can be set to focus on: 1) the investigation of environmental variables; and 2) the investigation of starch in bran. Because this study showed that growing location was of significant importance on grain characteristics and collecting the weather data during grain filling, maturity, and harvesting days can be done to have a better understanding of what environment produces favored grain traits. Another research direction can be testing the bran flakes collected from milling, because the starch in the bran could be a major factor determining the difficulty of separating bran from endosperm and germ.

From the data of this research, a suggestion to milling company, especially for quality control settings, is that monitoring kernel shape and size is very important. This includes investigating the growing environment of durum grains because it appeared to contribute to the kernel characteristics such as protein and ash content, kernel shape and size in this study. By monitoring kernel shape and size, roll gap can be adjusted to optimize the breakage. In addition, monitoring break release in break system in durum mill is also suggested which ensures an appropriate material flow within the mill. Grains that are large and round, hard and more vitreous should be a good choice for buyers in milling company to have favorable milling yields.

LITERATURE CITED

Abecassis, J., Autran, J. C., and Kobrehel, K. 1987. Composition and quality of durum wheat mill streams. Pages 300-312 in: *Cereals in a European Context: First European Conference on Food Science and Technology*. I. D. Morton, eds. VCH Publishers.

Abercrombie, E. 1980. Durum milling. *Association of Operative Miller-Bulletin*, 3808-3813.

Al-Mahasneh, M. A. and Rababah, T. M. 2007. Effect of moisture content on some physical properties of green wheat. *Journal of Food Engineering, 79,* 1467-1473.

American Association of Cereal Chemists International. 2010. Approved Methods of Analysis, 11th ed. Methods (08-01.01), (26-10.02), (26-41.01), (38-12.02), (44-11.01), (44-15.02), (46-30.01), (54-40.02), (55-10.01), (56-81.03), and (76-31.01). American Association of Cereal Chemists International: St. Paul, MN.

American Society of Agricultural and Biological Engineers. 2012. S319.4: Method of determining and expressing fineness of feed materials by sieving. American Society of Agricultural and Biological Engineers: St. Joseph, MI.

Baasandorj, T., Ohm, J. B., and Simsek, S. 2016. Effects of kernel vitreousness and protein level on protein molecular weight distribution, milling quality, and breadmaking quality in hard red spring wheat. *Cereal Chemistry*, *93*, 426-434.

Beach Cooperative Grain Company. 2016. Durum discount schedule. https://inetsgi.com/customer/733/e3ea1290.pdf.

Bizzarri, O., and Morelli, A. 1988. Milling of durum wheat. Pages 161-189 in: *Durum Wheat: Chemistry and Technology.* G. Fabriani and C. Lintas, eds. American Association of Cereal Chemists International, St. Paul, MN.

Caffe-Treml, M., Glover, K. D., Krishnan, P. G., Hareland, G. A., Bondalapati, K. D., and Stein, J. 2011. Effect of wheat genotype and environment on relationships between dough extensibility and breadmaking quality. *Cereal Chemistry, 88*, 201-208.

Campbell, G. M., Bunn, P. J., Webb, C., and Hook, S. C. 2001. On predicting roller milling performance Part II. The breakage function. *Powder Technology, 115*, 243-255.

Chaurand, M., Lempereur, I., Roulland, T. M., Autran, J. C., and Abecassis, J. 1999. Genetic and agronomic effects on semolina milling value of durum wheat. *Crop Science, 39,* 790-795.

Cubadda, R. 1988. Evaluation of durum wheat, semolina, and pasta in Europe. Pages 217-228 in: *Durum Wheat: Chemistry and Technology*. G. Fabriani and C. Lintas, eds. American Association of Cereal Chemists International, St. Paul, MN.

Dal-Pastro, F., Facco, P., Bezzo, F., Zamprogna, E., and Barolo, M. 2016. Data-driven modeling of milling and sieving operations in a wheat milling process. *Food and Bioproducts Processing, 99,* 99–108.

de la Peña, E., Ohm, J. B., Simsek, S., and Manthey, F. A. 2015. Physicochemical changes in nontraditional pasta during cooking. *Cereal Chemistry, 92*, 578-587.

Deng, L., and Manthey, F. A. 2017. Effect of single-pass and multipass milling systems on whole wheat durum flour and whole wheat pasta quality. *Cereal Chemistry, 94*, 963-969.

Dexter, J. E., Doust, M. A., Raciti, C. N., Lombardo, G. M., Clarke, F. R., Clarke, J. M., Marchylo, B. A., Schlichting, L. M., and Hatcher, D. W. 2004. Effect of durum wheat (*Triticum turgidum* L. var. *durum*) semolina extraction rate on semolina refinement, strength indicators and pasta properties. *Canadian Journal of Plant Science, 84*, 1001–1013.

Dexter, J. E., Marchylo, B. A., MacGregor, A. W., and Tkachuk, R. 1989. The structure and protein composition of vitreous, piebald and starchy durum wheat kernels. *Journal of Cereal Science, 10,* 19-32.

Dexter, J. E., and Matsuo, R. R. 1978. Effect of semolina extraction rate on semolina characteristics and spaghetti quality. *Cereal Chemistry, 55*, 841-852.

Dexter, J. E., and Matsuo, R. R. 1981. Effect of starchy kernels, immaturity and shrunken kernels on durum wheat quality. *Cereal Chemistry, 58,* 395-400.

Dexter, J. E., Matsuo, R. R., and Kruger, J. E. 1990. The spaghetti-making quality of commercial durum wheat samples with variable α-amylase activity. *Cereal Chemistry*, *67*, 405-412.

Dexter, J. E., Williams, P. C., Edwards, N. M., and Martin, D. G. 1988. The relationships between durum wheat vitreousness, kernel hardness and processing quality. *Journal of Cereal Science, 7,* 169-181.

Dick, J. W., and Youngs, V. L. 1988. Evaluation of durum wheat, semolina, and pasta in the United States. Pages 237-248 in: *Durum Wheat: Chemistry and Technology*. G. Fabriani and C. Lintas, eds. American Association of Cereal Chemists International, St. Paul, MN.

Dobraszczyk, B. J., Whitworth, M. B., Vincent, J. F., and Khan, A. A. 2002. Single kernel wheat hardness and fracture properties in relation to density and the modelling of fracture in wheat endosperm. *Journal of Cereal Science, 35*, 245-263.

Doehlert, D. C., and McMullen, M. S. 2008. Oat grain density measurement by sand displacement and analysis of physical components of test weight. *Cereal Chemistry, 85,* 654-659.

Dursun, E., and Dursun, I. 2005. Some physical properties of caper seed. *Biosystems Engineering*, *92,* 237-245.

Dziki, D., Cacak-Pietrzak, G., Gawlik-Dziki, U., Świeca, M., Miś, A., Różyło, R., and Jończyk, K. 2017. Physicochemical properties and milling characteristics of spring wheat from different farming systems. *Journal of Agricultural Science and Technology, 19*, 1253-1266.

Dziki, D., Cacak-Pietrzak, G., Miś, A., Jończyk, K., and Gawlik-Dziki, U. 2014. Influence of wheat kernel physical properties on the pulverizing process. *Journal of Food Science and Technology, 51*, 2648-2655.

Dziki, D., and Laskowski, J. 2004. Influence of kernel size on grinding process of wheat at respective grinding stages. *Polish Journal of Food and Nutrition Sciences, 54*, 29-33.

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

Elias, E. M., and Manthey, F. A. 2005. Registration of 'Divide' durum wheat. *Journal of Plant Registrations, 1,* 7-8.

Elias, E. M., and Manthey, F. A. 2016. Registration of 'Joppa' durum wheat. *Journal of Plant Registrations, 10,* 139-144.

Elias, E. M., and Manthey, F. A. 2019. Registration of 'ND Riveland' durum wheat. *Journal of Plant Registrations, 13*. doi:10.3198/jpr2019.01.0001crc.

Elias, E. M., Manthey, F. A., and AbuHammad, W. A. 2014. Registration of 'Carpio' durum wheat. *Journal of Plant Registrations, 9,* 78-82.

Elias, E. M., and Miller, J. D. 2000a. Registration of 'Maier' durum wheat. *Crop Science, 40,* 1489-1490.

Elias, E. M., and Miller, J. D. 2000b. Registration of 'Mountrail' durum wheat. *Crop Science, 40*, 1499-1500.

El-Khayat, G. H., Samaan, J., Manthey, F. A., Fuller, M. P., and Brennan, C. S. 2006. Durum wheat quality I: Some physical and chemical characteristics of Syrian durum wheat genotypes. *International Journal of Food Science and Technology, 41,* 22-29.

Fang, C., and Campbell, G. M. 2002. Effect of roll fluting disposition and roll gap on breakage of wheat kernels during first-break roller milling. *Cereal Chemistry, 79,* 518-522.

Fang, C., and Campbell, G. M. 2003. On predicting roller milling performance V: Effect of moisture content on the particle size distribution from first break milling of wheat. *Journal of Cereal Science, 37,* 31-41.

Fowler, M. 2012. Balancing the mill. World-Grain. February 23. www.worldgrain.com/articles/10199-balancing-the-mill.

Fowler, M. 2014. The complexities of durum milling. July 2. www.world-grain.com/articles/10208-the-complexities-of-durum-milling.

Fu, B., Wang, K., Dupuis, B., Taylor, D., and Nam, S. 2018. Kernel vitreousness and protein content: Relationship, interaction and synergistic effects on durum wheat quality. *Journal of Cereal Science, 79,* 210-217.

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

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

Haddad, Y., Mabille, F., Mermet, A., Abecassis, J., and Benet, J. C. 1999. Rheological properties of wheat endosperm with a view on grinding behaviour. *Powder Technology, 105,* 89-94.

Haque, E. 1991. Application of size reduction theory to roller mill design and operation. *Cereal Foods World, 36,* 368-375.

Haraszi, R., Sissons, M., Juhasz, A., Kadkol, G., Tamas, L., and Anderssen, R. S. 2016. Using rheological phenotype phases to predict rheological features of wheat hardness and milling potential of durum wheat. *Cereal Chemistry, 93*, 369-376.

Hareland, G. A. 1998. Effects of break-roll speed differential on product yield and semolina granulation in a durum pilot mill system. *Cereal Chemistry, 75*, 836-840.

Hareland, G. A., and Shi, Y. 1997. Interaction effects of five milling variables on durum wheat in the first break system. *Association of Operative Millers, Feb*, 6871-6874.

Hatcher, D. W., Dexter, J. E., Bellido, G. G., Clarke, J. M., and Anderson, M. J. 2009. Impact of genotype and environment on the quality of amber durum wheat alkaline noodles. *Cereal Chemistry, 86,* 452-462.

Hlynka, I., and Bushuk, W. 1959. The weight per bushel. *Cereal Science Today, 4,* 239-240.

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,* 1-12.

Hrušková, M., and Švec, I. 2009. Wheat hardness in relation to other quality factors. *Czech Journal of Food Sciences, 27,* 240–248.

Hsieh, F. H., Martin, D. G., Black, H. C., and Tipples, K. H. 1980. Some factors affecting the first break grinding of Canadian wheat. *Cereal Chemistry, 57,* 217-233.

Katyal, M., Virdi, A. S., Singh, N., Kaur, A., Rana, J. C., and Kumari, J. 2018. Diversity in protein profiling, pasting, empirical and dynamic dough rheological properties of meal

from different durum wheat accessions. *Journal of Food Science and Technology, 55,* 1256-1269. https://doi.org/10.1007/s13197-018-3036-y.

Khan, M. R., Anjum, F. M., Hussain, S., and Nadeem, M. 2010. A review of wheat quality assessment. *International Journal of BioSciences, Agriculture and Technology, 2,* 12-20.

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

Koo, T. K., and Li, M. Y. 2016. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine, 15,* 155-163.

Kunerth, W. H., and Youngs, V. L. 1984. Effect of variety and growing year on the constituents of durum bran fiber. *Cereal Chemistry, 61,* 350-352.

Li, Y. Z., and Posner, E. S. 1989. An experimental milling technique for various flour extraction levels. *Cereal Chemistry, 66,* 324-328.

Mabille, F., Gril, J., and Abecassis, J. 2001. Mechanical properties of wheat seed coats. *Cereal Chemistry, 78,* 231-235.

MacMasters, M. M, Bradbury, D., and Hinton, J. J. C. 1964. Microscopic structure and composition of the wheat kernel. Pages 55-110 in: *Wheat: Chemistry and Technology*. I. Hlynka, eds. American Association of Cereal Chemists International, St. Paul, MN.

Mahmoud, A. A., Mohdaly, A. A. A., and Elneairy, N. A. A. 2015. Wheat germ: An overview on nutritional value, antioxidant potential and antibacterial characteristics. *Food and Nutrition Sciences, 6,* 265-277. http://dx.doi.org/10.4236/fns.2015.62027.

Manthey, F. A., and Hareland, G. A. 2001. Effects of break-roll differential on semolina and spaghetti quality. *Cereal Chemistry, 78,* 368-371.

Manthey, F. A., and Twombly, W. 2005. Extruding and drying of pasta. Pages 158.1-158.15 in: *Handbook of Food Science, Technology, and Engineering, Volume 4*. Y. H. Hui, eds. Taylor and Francis, Boca Raton, FL.

Mariani, B. M., D'Egidio, M. G., and Novaro, P. 1995. Durum wheat quality evaluation: Influence of genotype and environment. *Cereal Chemistry, 72*, 194-197.

Markowski, M., Z˙uk-Gołaszewska, K., and Kwiatkowski, D. 2013. Influence of variety on selected physical and mechanical properties of wheat. *Industrial Crops and Products, 47*, 113-117.

Marshall, D. R., Mares, D. J., Moss, H. J., and Ellison, F. W. 1986. Effects of grain shape and size on milling yields in wheat. II. Experimental studies. *Australian Journal of Agricultural Research, 37,* 331-342.

Marti, A., Seetharaman, K., and Pagani, M. A. 2013. Rheological approaches suitable for investigating starch and protein properties related to cooking quality of durum wheat pasta. *Journal of Food Quality, 36*, 133-138.

Martin, C. R., Rousser, R., and Brabec, D. L. 1993. Development of a single-kernel wheat characterization system. *Transactions of the American Society of Agricultural Engineers, 36*, 1399-1404.

Matsuo, R. R. 1988. Evaluation of durum wheat, semolina, and pasta in Canada. Pages 249-262 in: *Durum Wheat: Chemistry and Technology*. G. Fabriani and C. Lintas, eds. American Association of Cereal Chemists International, St. Paul, MN.

Matsuo, R. R., and Dexter, J. E. 1980. Relationship between some durum wheat physical characteristics and semolina milling properties. *Canadian Journal of Plant Science, 60*, 49-53.

McCorkle, F. D. 1973. Development and operation of modern roller mill. *Bulletin of Association of Operative Millers, May,* 3362.

Miller Jones, J., Adams, J., Harriman, C., Miller, C., and Van der Kamp, J. W. 2015. Nutritional impacts of different whole grain milling techniques: A review of milling practices and existing data. *Cereal Foods World, 60,* 130-139.

Miller Magazine. Pre-milling grain cleaning process and what to know. September 13, 2016. http://www.millermagazine.com/english/pre-milling-grain-cleaning-process-and-what-to-know/.html.

Mohammadi, R., Armion, M., Sadeghzadeh, D., Amri, A., and Nachit, M. 2011. Analysis of genotype-by-environment interaction for agronomic traits of durum wheat in Iran. *Plant Production Science, 14,* 15-21.

Mohsenin, N. N. 1986. Physical properties of plant and animal materials. New York: Gordon and Breach Science Publishers.

NDWC. 2018. U.S. durum wheat regional quality report. www.ndwheat.com/uploads/6/durum18.pdf.

Novaro, P., Colucci, F., Venora, G., and D'Egidio, M. G. 2001. Image analysis of whole grains: A noninvasive method to predict semolina yield in durum wheat. *Cereal Chemistry, 78,* 217-221.

Nuttall, J. G., O'Leary, G. J., Panozzo, J. F., Walker, C. K., Barlow, K. M., and Fitzgerald, G. J. 2017. Models of grain quality in wheat-A review. *Field Crops Research, 202,* 136-145.

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

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

Osborne, B. G., Henry, R. J., and Southan, M. D. 2007. Assessment of commercial milling potential of hard wheat by measurement of the rheological properties of whole grain. *Journal of Cereal Science, 45*, 122-127.

Oury, F. X., Lasme, P., Michelet, C., Dubat, A., Gardet, O., Heumez, E., Rolland, B., Rousset, M., Abecassis, J., L'Helgouac'h, C. B., and Lullien‐Pellerin, V. 2017. Bread wheat milling behavior: Effects of genetic and environmental factors, and modeling using grain mechanical resistance traits. *Theoretical and Applied Genetics, 130,* 929-950.

Pasha, I., Anjum, F. M., and Morris, C. F. 2010. Grain hardness: A major determinant of wheat quality. *Food Science and Technology International, 16*, 511-522.

Patel, J. B., Ukani, J. D., Babariya, C. A., and Ramani, P. S. 2016. Characterization of wheat varieties (*Triticum* spp.) through seed morphology. *Journal of Applied and Natural Science, 8*, 464-468.

Pauly, A., Pareyt, B., Fierens, E., and Delcour, J. A. 2013. Wheat (*Triticum aestivum* L. and *T. turgidum* L. ssp. *durum*) kernel hardness: II. Implications for end-produce quality and role of puroindolines therein. *Comprehensive Reviews in Food Science and Food Safety, 12*, 427-438.

Peyron, S., Mabille, F., Devaux, M. F., and Autran, J. C. 2003. Influence of structural characteristics of aleurone layer on milling behavior of durum wheat (*Triticum durum* Desf.). *Cereal Chemistry, 80,* 62-67.

Pinheiro, N., Costa, R., Almeida, A. S., Coutinho, J., Gomes, C., and Maçãs, B. 2013. Durum wheat breeding in Mediterranean environments - influence of climatic variables on quality traits. *Emirates Journal of Food and Agriculture, 25*, 962-973.

Posner, E. S., and Hibbs, A. N. 2005. Milling of durum wheat. Pages 329-351 in: *Wheat Flour Milling*. American Association of Cereal Chemists International: St. Paul, MN.

Psaroudaki, A. 2007. An extensive survey of the impact of tropospheric ozone on the biochemical properties of edible plants. *World Scientific and Engineering Academy and Society Transactions on Environment and Development, 3*, 99-110.

Samson, M. F., Mabille, F., Chéret, R., Abécassis, J., and Morel, M. H. 2005. Mechanical and physicochemical characterization of vitreous and mealy durum wheat endosperm. *Cereal Chemistry, 82*, 81-87.

Saulnier, L., Guillon, F., Sado, P.-E., Chateigner-Boutin, A. –L., Rouau, X. 2007. Plant Cell Wall Polysaccharides in Storage Organs: Xylans (Food Applications). *Comprehensive GlycoScience , 2*, 653-689. https://doi.org/10.1016/B978-044451967-2/00147-1.

Sebastian, R. 2018. The importance of break system in flour milling process. Miller Magazine. September 13, 2018. http://www.millermagazine.com/english/the-importance-of-break-system-in-flour-milling-process/.html.

Shinezorigt, D. 2019. Debranning affects durum wheat milling properties and semolina quality (master's thesis). North Dakota State University, Fargo, ND.

Shuey, W. C. 1960. A wheat sizing technique for predicting flour milling yield. *Cereal Science Today, 5*, 71-75.

Simmons, L. and Meredith, P. 1979. Width, weight, endosperm, and bran of the wheat grain as determinants of flour milling yield in normal and shrivelled wheats. *New Zealand Journal of Science, 22,* 1-10.

Sissons, M. J., and Hare, R. A. 2002. Tetraploid wheat-A resource for genetic improvement of durum wheat quality. *Cereal Chemistry*, *79*, 78-84.

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

Ştefan, M. E., Voicu, G., Constantin, G. A., Munteanu, M., and Ionescu, M. 2018. Effects of wheat seeds characteristics on roller milling process-a review. Pages 361-366 in: conference paper presented at 7th International Conference on Thermal Equipment, Renewable Energy and Rural Development, Drobeta-Turnu Severin, România.

Taghouti, M., Gaboun, F., Nsarellah, N., Rhrib, R., El-Haila, M., Kamar, M., Abbad-Andaloussi, F., and Udupa, S. M. 2010. Genotype x environment interaction for quality traits in durum wheat cultivars adapted to different environments. *African Journal of Biotechnology*, *9*, 3054-3062.

Troccoli, A., Borrelli, G. M., De Vita, P., Fares, C., and di Fonzo, N. 2000. Durum wheat quality: A multidisciplinary concept. *Journal of Cereal Science, 32*, 99-113.

Troccoli, A., and di Fonzo, N. 1999. Relationship between kernel size features and test weight in *Triticum durum. Cereal Chemistry, 76,* 45-49.

Tsuge, N. 1985. The effects of the first break roller mill differentials and speeds (master's thesis). Kansas State University, Manhattan, KS.

USDA. 2014. Grain Inspection Handbook Book II, Chapter 13 Wheat Grain Inspection, Packers and Stockyards Administration: Washington, DC. https://www.gipsa.usda.gov/fgis/handbook/grain-insp/grbook2/wheat.pdf.

USDA. 2019. Crop production 2018 summary. National Agricultural Statistics Service. https://www.nass.usda.gov/Publications/Todays_Reports/reports/cropan19.pdf.

Varnamkhasti, M. G., Mobli, H., Jafari, A., Keyhani, A. R., Soltanabadi, M. H., Rafiee, S., and Kheiralipour, K. 2008. Some physical properties of rough rice (*Oryza Sativa* L.) grain. *Journal of Cereal Science, 47*, 496-501.

Yan, D., Duermeyer, L., Leoveanu, C., and Nambara, E. 2014. The functions of the endosperm during seed germination. *Plant and Cell Physiology, 55*, 1521-1533.

Yu, J., Wang, S., Wang, J., Li, C., Xin, Q., Huang, W., Zhang, Y., He, Z., and Wang, S. 2015. Effect of laboratory milling on properties of starches isolated from different flour millstreams of hard and soft wheat. *Food Chemistry, 172*, 504-514.