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SORGHUM FLOUR CHARACTERIZATION AND EVALUATION IN GLUTEN-FREE FLOUR TORTILLA

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ABSTRACT

Four sorghum hybrids (Fontanelle-625 [F-625]), Fontanelle-1000 [F-1,000], ATx631xRTx2907 [NE#20] and 5,040C) were characterized and evaluated for kernel characteristics, proximate analysis, flour characterization (particle size distributions, starch damage, amylose content and starch pasting properties) and end product in gluten-free tortilla. A commercial sorghum flour (TVM) was used as a control. Significant differences were found ($P < 0.05$) among hybrids for kernel and flour composition except total starch ($P > 0.05$). NE#20 had the largest particle diameter for both flour and starch. F-1000 had significantly higher starch damage compared with the other hybrids. Flours with smaller particle size and higher starch damage contributed to softer and more extensible tortilla. Amylose content ranged from 20.2 (NE#20) to 27.3 (F-1000). Tortilla made with TVM flour had the highest extensibility, while the F-625 tortilla had the lowest. F-625 tortilla had the lightest color with L^* value of 70.38, while the 5,040C tortilla had the darkest with L^* value of 61.68. Descriptive sensory results showed significant differences for tortilla grain specks, angle of bend, rancidity, sweetness, springiness, hardness and grittiness. The results have shown that sorghum hybrids can differ in kernel and flour properties, which could help predict sorghum flour quality for the purpose of gluten-free products.

PRACTICAL APPLICATIONS

Sorghum is a gluten-free grain tolerated by patients with celiac disease, that has potential in the gluten-free food market. Despite considerable scientific progress in understanding celiac disease, to date, a strict gluten-free diet for life is the only treatment for patients with celiac disease. With an increasing number of people being diagnosed with celiac disease and with the market for gluten-free products growing, there is a great opportunity to create new products using sorghum flour. There are many sorghum hybrids that have not been characterized for grain, flour or end-product quality. Therefore, understanding the quality attributes of sorghum varieties is critical in translating to end-product use. The results have shown that sorghum hybrids can differ in kernel and flour characteristics, which could help predict end-product quality and application in gluten-free products.

INTRODUCTION

Celiac disease is an autoimmune inflammatory disease of the upper small intestine resulting from the ingestion of gluten protein fractions, which are mainly present in wheat, barley and rye (Case 2006). One out of 133 Americans has celiac disease, and an estimated 3 million Americans across all races, ages and genders suffer from the disease. A gluten-free diet is the only treatment for celiac disease. The increased awareness and better diagnosis for celiac disease has caused a bigger demand for gluten-free products. In 2012, the U.S. market for gluten-free foods and beverages reached more than $4.2 billion, with a growth rate of 28% over the 2008–2012 period, and the U.S. sales are expected to exceed $6.6 billion by 2017 (Packaged Facts 2012).

Sorghum is a gluten-free grain with a great deal of potential in the gluten-free food market. According to the U.S. Grain Council, grain sorghum is the fifth most important cereal crop grown in the world and the third most important in the U.S.A. (U.S. Grains Council 2012). Most of the grain in the U.S.A. is either exported or used for feed. In Africa and Asia, sorghum is a major food crop (Serna-Saldivar and Rooney 1995), and an estimated 30–40% of sorghum is consumed by humans (Murty and Kumar 1995). Sorghum has a great potential in foods and beverages. Sorghum has been studied in many food products, including breads (Schober *et al.* 2005, 2007), tortilla chips (Rooney and Waniska 2000), cookies (Morad *et al.* 1984), ground beef patties (Huang *et al.* 1999), chicken nuggets (Devatkal *et al.* 2011) and noodles (Suhendro *et al.* 2000; Liu *et al.* 2012).

Flour tortillas have been used in burritos, tacos and fajitas. According to the Tortilla Industry Association, 78% of fine dining restaurants have tortillas in a menu item (Petrak 2006a). In 2011, tortilla sales were estimated to be $11 billion, making it the second most popular baked item in the U.S.A. after bread (Hartman 2011). Sorghum has been used to replace some or all of the maize in corn tortillas where masa is formed with an alkaline process and then made into a tortilla (Rooney and Waniska 2000). The literature is scarce on the use of sorghum in flour tortillas, and there needs to be an understanding of functionality of different hybrids. There are many sorghum hybrids that have not been characterized for grain, flour or end-product quality. Therefore, the objectives of this research were to characterize four sorghum hybrids both as a kernel and as a flour and to evaluate their physicochemical and sensory properties in a gluten-free flour tortilla.

MATERIALS AND METHODS

Grain Sorghum Samples and Flour Preparation

Four nontannin hybrids, two white (Fontanelle-625 [F-625] and Fontanelle-1000 [F-1,000]), a heterowaxy white (ATx631 × RTx2907 [NE#20]) and one red (5,040C) grown in Nebraska during 2007 were selected for use in this study. The hybrids were decorticated with a tangential abrasive dehulling device (TADD) until 20% of the initial weight was removed, then further processed with a Bliss Hammer mill (Venebles Machine Works, Saskatoon, Canada) according to Oomah *et al.* (1981). In addition, a commercial sorghum flour (TVM, Twin Valley Mills, LLC, Ruskin, NE) was used as a control for comparing final product quality with the hybrids.

Kernel Characterization

Physical properties of the sorghum kernels were characterized with the single kernel characterization system (SKCS 4100 Perten Instruments, Huddinge, Sweden) according to Bean *et al.* (2006). A TADD (Venebles Machine Works, Saskatoon, Canada) with an 80-grit abrasive, supplied by the manufacturer, was used to determine the abrasive hardness index (AHI) of the kernels as described in Oomah *et al.* (1981).

Flour Analysis

Proximate analysis on the flour was performed according to the following standard methods: protein (AACC 2000), ash (AACC 2000) and moisture (AOAC 2005). Flour particle size distribution was determined with an LS 13,320 single wavelength laser diffraction particle size analyzer using the Tornado dry powder system (Beckman-Coulter, Inc., Miami, FL). Amylose and amylopectin content of the starch were determined by the method of Gibson *et al.* (1995) using a Megazyme amylose/amylopectin assay kit (K-AMYL 04/06, Megazyme International Ireland Ltd., Co., Wicklow, Ireland). The total starch content of the sorghum flours was determined by Megazyme Total Starch Assay kit, K-TSTA 05/06 (Megazyme International Ireland Ltd., Co.), which is based on the amyloglucosidase/a-amylase method (AOAC Method 996.11). As sorghum starch may have high levels of resistant starch, a pretreatment with dimethyl sulfoxide was performed. Starch damage was measured by the method of Gibson *et al.* (1993) using Starch Damage Assay kit (Megazyme International Ireland Ltd., Co.).

Starch Isolation

High-intensity ultrasound (sonication) was used to purify starch from sorghum flour following the procedure of Park *et al.* (2006). The isolated starch was dried in a Labconco Freezone 6 Freeze Dryer (Labconco Corporation, Kansas City, MO).

Starch Particle Size Distribution

Starch particle size distribution was determined using an LS Laser Diffraction Particle Size Analyzer (Beckman-Coulter, Inc.) following Approved Method 55–40 (AACC 2000) in a universal liquid module with an integrated sonicator.

Starch Pasting Properties

Pasting properties of sorghum starch from the four sorghum hybrids were assessed using the rapid visco analyzer (RVA Model 4, Newport Scientific, Warriewood, Australia) method of Lee *et al.* (2002). The pasting curve is a result of the starch slurry being subjected to a specified thermal profile. In the RVA, the short temperature profile (13 min) was used and the mixture was stirred at 960 rpm for 10 s, and then at 160 rpm for the remainder of the test. The starting temperature of the test was 50C, which was held for 1 min, after which it was ramped up to 95C over 3 min and 45 s. The sample was held at 95C for 2 min and 30 s before decreasing the temperature back down to 50C over 3 min and 45 s and holding the sample again at that temperature for 2 min.

Tortilla Preparation

The gluten-free tortilla was produced by the hot-press procedure. Sorghum flour was 100% substituted for wheat flour. Ingredients used were: 200 g sorghum flour, 5 g salt (Kroger, Cincinnati, OH), 2 g xanthan gum (Grindsted Xanthan 200, Danisco USA, Inc., New Century, KS), 1.5 g baking powder (Clabber Girl, Terre Haute, IN), 1 g citric acid (Gold Coast Ingredients, Inc., Commerce, CA), 30 g granulated sugar (Extra Fine, Great Value, Walmart Stores, Inc., Bentonville, AR), 4.5 g monoglycerides (Dimodan PH 300 K-A, Danisco USA, Inc.), 23 g shortening (Crisco, J. M. Smucker Company, Orrville, OH), 13.5 g glycerin (Kosher Superol Glycerine USP, Procter & Gamble Chemicals, New Milford, CT) and water. The amount of water needed was determined using a farinograph and were 70, 82, 85, 78, and 130 g for F-625, F-1,000, NE#20, 5,040C, and TVM, respectively.

The dry ingredients (sorghum flour, salt, xanthan gum, baking powder, citric acid, sugar and monoglycerides) were mixed for 1 min and 30 s on speed 1 in a KitchenAid mixer (KitchenAid, St. Joseph, MI). Shortening and glycerin were added and mixed for 45 s at speed 1. The ingredients were mixed for another 45 s at speed 2 until no clumps were visible. Warm water (38C) was slowly added while mixing at speed 1 and increasing to speed 3 for a total mixing time of 1 min and 30 s.

The dough was kneaded using a dough hook for 30 s and then placed in a sealed container in order to retain moisture. Twenty-five grams of dough were weighed out and rounded into a smooth ball by hand. Each dough ball was kept in the sealed container during preparation. For pressing, a TXA-SS DoughXpress (Perten Instruments, Inc., Springfield, IL) was used with settings of 230C and a 6 s press time. Two pieces of parchment paper were used to avoid sticking. One sheet was placed on the bottom plate and the dough ball set on top of the paper. The second sheet was then laid on top of the dough ball and pressed. The tortilla was then placed on a DoughPro griddle (Model TW1520, Proprocess Corporation, Paramount, CA) set at 176.7C by removing the top piece of parchment paper, laying the tortilla on the griddle, and removing the second piece of parchment paper. The tortilla was cooked for 30 s on each side and then put on a cooling rack for 2 min before being stored in a sealable plastic Ziplock bag (C. Johnson & Son, Inc., Racine, WI). Physical and chemical measurements were taken after 4 h.

Tortilla Extensibility

Extensibility of tortillas was determined using a TA.XT. plus Texture Analyzer (Texture Technologies Corporation, Scarsdale, NY) equipped with TA-96 tensile grips (Texture Technologies Corporation). The analyzer was set at a pretest speed of 1 mm/s, test speed of 1 mm/s, post-test speed of 5 mm/s, distance of 25 mm, and force of 5 g. For each tortilla, two pieces were cut out of the center using a carving knife and a template measuring 3.5×3.7 cm. Each piece was placed in the tensile grips with the longer side in the vertical direction. The grips were tightened by hand as tight as possible, and the test ran by pulling the tortilla piece vertically. The maximum peak force and distance values were recorded.

Tortilla Stretchability/Flexibility

The puncture test was used to evaluate the stretchability and flexibility of a tortilla. Tortillas were tested using a TA.XT.plus Texture Analyzer (Texture Technologies Corporation). The American Institute of Baking provided a standard procedure for flour tortilla stretchability/flexibility measurement to determine the breaking point and rupture force. The TA-108 Tortilla/Film Fixture and TA-108a 18 mm diameter probe with rounded edge (Texture Technologies Corporation) were used with the following settings: pretest speed of 6 mm/s, test speed of 1.7 mm/s, post-test speed of 10 mm/s, distance of 30 mm, force of 20 g and acquisition of 200 pps.

Tortilla Rollability

Tortilla rollability was determined using a 1-cm wooden dowel. The tortilla was wrapped around the dowel and cracking and breaking was evaluated. A scale from 1 to 5 was used with 1 meaning breaks immediately or unrollable and 5 meaning no cracks or breakage. This procedure was used by Waniska *et al.* (2004) for the evaluation of wheat tortilla quality.

Tortilla Color

A HunterLab MiniScan (Model MS/S-4000S, Hunter Associates Laboratory Inc., Reston, VA) was used to measure the color of the tortilla samples. The color values L^*, a^*, and b^* were determined in three places on each tortilla with a C illuminant and a 10° standard observer. The dimension L^* means lightness with 100 for white and 0 for black, while a^* indicates redness when positive and greenness when negative, and b^* indicates yellowness when positive and blueness when negative.

Tortilla Water Activity and Moisture Content

Water activity measurements were determined using an AquaLab water activity meter (Model Series 3, Decagon Devices, Inc., Pullman, WA, USA). The moisture content of each tortilla sample was obtained using the AACC method 44–40 (AACC 2000).

Sensory Descriptive Analysis

Seven trained panelists participated in the descriptive analysis for the sorghum flour tortillas. The panelists were recruited and chosen based on their availability and willingness to participate in the project, and all signed a consent form for their participation. A total of four sessions were held for training and development of attributes. The panelists met once a week for 2–3 h. The first session consisted of tasting a sorghum flour tortilla made with commercial flour and determining attributes in terms of appearance, texture on the hand, odor, flavor and texture in the mouth. First, each panelist created a list of attributes individually. Then, these attributes were shared and a consensus made of all the attributes found in the sorghum flour tortilla. These attributes were compared with those found in grain sorghum (Brannan *et al.* 2001) and wheat flour tortillas (Bejosano *et al.* 2005) in order to confirm all characteristics were accounted for. Finally, each attribute was defined and references suggested for the next session. In the second and third sessions, all suggested references were available and the panelists decided on which references to keep, assigned references to appropriate attributes and scored the references on a scale from 1 to 15. This was done individually first, then as a group to develop a consensus. The fourth session was used to practice evaluating a sorghum flour tortilla with the descriptive terms, definitions and references the panelists had developed (Table 1). Distilled water and unsalted saltine crackers were given to cleanse the palate during tasting. Once training was complete, two more sessions were held to test the five treatments of prepared sorghum flour tortillas. Two samples were scored at the first session and three samples at the second in order to eliminate panelist fatigue. The samples were given to the panelists with random three-digit number codes. Samples were tested in the same way as the fourth session of training.

Statistical Analysis

Three replications with three subsamples per replication were performed. Triplicate readings of each physical, chemical and textural test were performed with the exception of water activity in which duplicate readings were taken. Treatments were analyzed in a complete block design. Sensory analysis was performed only once for the descriptive analysis. When treatment effects were found significantly different, the least square means with Tukey–Kramer groupings were used to differentiate treatment means. Significant differences were determined at the α level of 0.05. All data were analyzed using SAS Software version 9.1 (SAS Institute Inc., Cary, NC).

RESULTS AND DISCUSSION

Kernel Properties

The physical properties of the sorghum kernels that were characterized with the SKCS are shown in Table 2. Significant differences were found among the sorghum hybrids ($P < 0.05$) for hardness index, kernel weight and kernel diameter. F-625 and NE#20 had hardness index averages that were significantly higher than F-1,000 and 5,040C. The average hardness indexes ranged from 72.1 (5,040C) to 82.7 (NE#20). F-625 had the lowest average kernel weight (23.1 mg) and NE#20 the highest (29.5 mg). Significant differences ($P < 0.05$) were found among the hybrids, but F-1,000 and NE#20 were not significantly different from each other in terms of kernel weight (Table 2). Kernel diameter averages were the highest for NE#20 (2.44 mm) and F-1,000 (2.41 mm). NE#20 and F-1,000 were significantly ($P < 0.05$) different from F-625 and 5,040C (Table 2). Kernel size and weight affect the flour particle size and the amount of starch damage (Liu *et al.* 2012).

An AHI was used to calculate the amount of kernel removed over time. The SKCS and AHI are only loosely correlated (Bean *et al.* 2006) and provide different measures of kernel strength or hardness (Liu *et al.* 2012). Significant differences were found ($P < 0.05$) for the averages of AHI (Table 2). F-625 had the highest average AHI (12.7) and 5,040C had the lowest average AHI (8.4), but F-1,000 and NE#20 were not significantly different from each other. F-625 and NE#20 were significantly different in terms of AHI, but not significantly different in terms of the SKCS hardness index. This suggests that different factors influence AHI values compared with those which influence the SKCS

TABLE 1. ATTRIBUTES DEFINITION AND REFERENCE FOR SENSORY DESCRIPTIVE ANALYSIS

Attribute	Definition	References
Appearance		
Yellow color	The hue of that portion of the visible spectrum lying between orange and green.	Sliced Swiss cheese = 2, butter = 7, Lemon rind = 15
Brown color	A dark tertiary color with a yellowish or reddish hue.	Cannellini bean = 1, whole wheat flour tortilla = 7, milk chocolate bar = 15
Evenness of color	Degree to which the color is free from variations or fluctuations. Tortilla placed on white paper.	Mission flour tortilla = 2, whole wheat flour tortilla = 13
Opacity	Degree to which a substance is transparent or translucent. Place hand behind tortilla and hold up to light.	Parchment paper = 3, napkin = 13
Shape (round)	Being such that every part of the surface or the circumference is equidistant from the center.	Whole wheat flour tortilla = 14
Surface	Degree to which the outer face presents variations or fluctuations by means of blistering and puffing.	Whole wheat flour tortilla = 5, mission flour tortilla = 11
Grain specks	A small spot of grain differing in color or substance from that of the surface upon which it lies.	Mission flour tortilla (fajita size) = 1, whole wheat flour tortilla = 15
Glossiness	The property of having a shiny or lustrous surface.	Cardboard = 1, magazine = 15
Texture (in the hand)		
Roughness	The property of having a surface marked by irregularities, protuberances or ridges.	Kool-aid gels = 1, orange peel = 6, potato chip = 10, crunchy granola bar = 14
Angle of bend	Degree to which the tortilla will bend in half before breaking.	0° = 1, 90° = 7.5, 180° = 15
Tearability	Amount of force required to pull the tortilla apart. With a strip of tortilla, hold the top with one hand and pull down on the bottom of the strip with the other hand.	Mission flour tortilla = 8, pita pocket bread = 14
Odor		
Sweet	Aromatic associated with sugar, such as sucrose or honey.	Extra fine granulated sugar = 2, honey maid graham cracker = 8, clover honey = 14
Rancid	Aromatic associated with decomposition of fats or oils.	All-vegetable shortening = 2, stale saltine cracker = 14
Musty	Aromatic associated with a dust or earth from grain.	Bag of sorghum grain = 11
Flavor		
Sour	A fundamental taste factor of which citric, malic, phosphoric and other acid solutions are typical.	0.05% citric acid solution = 2, 0.10% citric acid solution = 7, 0.15% citric acid solution =11, 0.20% citric acid solution = 15
Salty	A fundamental taste factor of which sodium chloride solution is typical.	0.2% NaCl solution = 4, 0.4% NaCl solution = 7, 0.8% NaCl solution = 15
Sweet	A fundamental taste factor of which sucrose solution is typical.	1.0% sucrose solution = 3, 2.0% sucrose solution = 6, 4.0% sucrose solution = 11, 8.0% sucrose solution = 15
Bitter	A fundamental taste factor of which caffeine solution is typical.	0.02% caffeine solution = 2, 0.04% caffeine solution = 7, 0.06% caffeine solution = 14
Doughy	A flavor associated with wet flour or dough.	Savory butter roll = 5, canned biscuit dough = 15
Nutty	A sweet, light brown, slightly musty and/or earthy flavor associated with nuts, grains and seeds.	Toasted wheat germ = 10
Mouth coating	A layer of substance, typically fat and oil, spread over the mouth after chewing.	Potato chip = 7, canned biscuit dough = 12
Texture (by the mouth)		
Springiness	Degree to which the sample can be condensed and return to its original shape. Compress partially without breaking using front teeth.	Cream cheese = 2, Oscar Meyer wiener = 7, jet-puffed marshmallow = 14
Hardness	The relative resistance to deformation. Bite down evenly using front teeth.	Cream cheese = 1, cheddar cheese = 4, peanuts = 13
Cohesiveness of mass	Degree to which sample holds together during mastication. Measure after three to four chews with molars.	Triscuit = 4, Cheerio = 8
Fracturability	Force with which sample breaks. Bite down evenly using front teeth until sample breaks.	Corn muffin = 2, graham cracker = 7
Moisture absorption	Amount of saliva absorbed during mastication. Measure after three to four chews with molars.	Twizzlers candy = 2, potato chip = 5, popcorn (butter) = 7, unsalted tops saltine cracker = 13
Grittiness	Amount of gritty particles perceived in the sample during mastication. Measure after five to seven chews with molars.	Post grape nuts = 14
Tooth packing	Amount of sample packed in and between the teeth after swallowing.	Honey Maid graham cracker = 7, peanuts = 10, Wonka Laffy Taffy candy = 15

TABLE 2. COMPARISON OF GRAIN PHYSICAL PROPERTIES AND FLOUR† COMPOSITION OF SORGHUM HYBRIDS

	SKCS‡									
Sample	Single kernel hardness	Kernel weight (mg)	Kernel diameter (mm)	Abrasive hardness index	Moisture content (%)	Protein (% db)	Ash (% db)	Total starch (% db)	Starch damage (%)	Amylose (% db)
F-625	81.1 ± 0.8^{a}	23.1 ± 0.4^{c}	2.09 ± 0.03^{b}	12.8 ± 0.2^{a}	15.00 ± 0.12^{a}	9.85 ± 0.08^{b}	1.45 ± 0.01^{a}	72.5 ± 2.2^{a}	2.7 ± 0.1^{b}	25.6 ± 2.3^{ab}
F-1,000	75.0 ± 0.6^{b}	29.4 ± 0.4^{a}	2.41 ± 0.03^{a}	12.2 ± 0.1^{b}	11.91 ± 0.14^{bc}	8.61 ± 0.05^{c}	1.20 ± 0.00^{c}	66.6 ± 8.6^{a}	3.0 ± 0.1^{a}	27.3 ± 0.6^{a}
NE#20	82.7 ± 0.7^{a}	29.5 ± 0.7^{a}	2.44 ± 0.06^{a}	12.3 ± 0.1^{b}	11.44 ± 0.19^{c}	10.53 ± 0.05^{a}	1.40 ± 0.02^{b}	72.6 ± 1.6^{a}	2.8 ± 0.1^{b}	20.2 ± 0.7^{c}
5,040C	72.1 ± 1.5^{b}	27.0 ± 0.7^{b}	2.12 ± 0.01^{b}	8.4 ± 0.1^{c}	12.45 ± 0.38^{b}	9.87 ± 0.05^{b}	1.41 ± 0.01^{b}	71.5 ± 2.6^{a}	2.8 ± 0.1^{b}	24.1 ± 1.4^{b}

Means with different letters in columns indicate significant differences among treatments ($P < 0.05$).
† Flours were obtained from 20% decorticated kernels.
‡ Single Kernel Characterization System.

hardness index values. Factors effecting AHI are kernel shape, kernel size and pericarp thickness (Lawton and Faubion 1989).

Sorghum Flour Analysis

Significant differences ($P < 0.05$) in the crude protein contents were found among the sorghum hybrids (Table 2). The protein values ranged from 8.61 (% db) to 10.53 (% db) with F-1,000 having the lowest and NE#20 having the highest protein content. F-625 and 5,040C were not significantly different from each other. Ash content (% db) ranged from 1.20 (F-1,000) to 1.45 (F-625) (Table 2). All hybrids were significantly different from each other except NE#20 and 5,040C ($P < 0.05$). These flour protein and ash values are in agreement with those reported by Schober *et al.* (2005) and Liu *et al.* (2012). Ash content is an indication of the amount of bran and germ contamination in milling (Kim and Flores 1999). In terms of flour quality, ash content is an important indicator of flour color (Kim and Flores 1999), and bakers continue to look at ash content as a factor of flour grade. Sorghum quality was related to ash in a study by Aboubacar and Hamaker (1999). They reported that sorghum cultivars have high couscous yields when the flour has a low ash content and high proportion of course particles. Suroso *et al.* (2000) used ash content of sorghum grits as a factor in determining bran contamination. The lower ash content was thought to have more potential for utilization in human food. F-625 had a significantly higher moisture content (15%) than the other hybrids. The lowest moisture content coincided with NE#20 (11.44%). Buffo *et al.* (1998) found unground sorghum seeds to have a moisture content from 13.80 to 13.95%.

The total starch content of the sorghum flour was not significantly ($P < 0.05$) different among hybrids (Table 2). Total starch ranged from 66.6% (F-1,000) to 72.6% (NE#20) on a dry basis. Buffo *et al.* (1998) reported an average starch content of 73.12 (% db) for sorghum grain. F-1,000 had significantly higher starch damage at 3.0% ($P < 0.05$) compared with the other three hybrids (Table 2). F-625, NE#20 and 5,040C were not significantly different from each other. The starch damage results were similar to those of Liu *et al.* (2012) who reported starch damage values between 2.6 and 3.3% for sorghum hybrids. Starch damage affects water absorption, mixing properties and end-product quality. There is a positive correlation between damaged starch and water absorption (Evers and Stevens 1985). Damaged starch also affects rheology and fermentation of leavened wheat products (Stasio *et al.* 2007). Too much starch damage can produce slack dough, but too little starch damage causes low bread volumes and heavy texture (Mao and Flores 2001). Amylose content (%) ranged from 20.2 (NE#20) to 27.3 (F-1,000). Significant differences were found ($P < 0.05$) (Table 2). NE#20 was significantly lower than the other hybrids. This was expected as NE#20 is a heterowaxy sorghum. Waxy grains contain lower amylose content compared with their counterpart. These results are similar to those reported by Liu *et al.* (2012). The amylose/amylopectin ratio is a property of cereal starches that affects the end product by varying gelatinization, gelation, solubility, resistant starch formation and textural characteristics (Leloup *et al.* 1991). Park and Baik (2004) reported amylose content effecting water absorption, lightness, fat absorption, cooking time and texture properties of cooked instant noodles. In bread making, waxy and partial waxy wheat flour have greater resistance to retrogradation during storage (Sasaki *et al.* 2000).

Sorghum Flour and Starch Particle Size Distribution

Significant differences were found ($P < 0.05$) in the average flour particle diameter for each sample at five different volume percents: 10, 25, 50, 75 and 90 (Table 3). The average flour particle diameters ranged from 27.9 to 33.9 μm, 83.8 to 101.8 μm, 154.4 to 191.8 μm, 244.3 to 299.6 μm, and 320.5 to 367.1 μm, for 10, 25, 50, 75, and 90 volume percents, respectively. NE#20 had the largest particle diameter at each volume. F-625 had the smallest particle diameter at each volume, except at 10% in which 5,040C had the smallest. All four hybrids produced a sigmoidal distribution. Schober *et al.* (2007) found lower values for sorghum flour particle size compared with the values found in this study. The particle diameter was 21.7, 118.6, and 276.6 μm, for 10, 50, and 90 volume percents, respectively.

Significant differences were also found ($P < 0.05$) for the average starch particle diameters for each sample at five different volume percents: 10, 25, 50, 75 and 90 (Table 3). The average starch particle diameters ranged from 6.2 to 7.3 μm, 11.7 to 13.7 μm, 17.6 to 20.8 μm, 24.5 to 28.7 μm, and 31.7 to 37.1 μm, for 10, 25, 50, 75, and 90 volume percents, respectively. NE#20 had the largest particle diameter at each volume, except at 10% in which F-1,000 had the largest. F-625 had the smallest particle diameter at each volume. All four hybrids produced a sigmoidal distribution. Liu *et al.* (2012) reported average flour particle diameter of sorghum hybrids ranging from 38.78 to 177.0 m at 50 volume percent.

Sorghum Starch Pasting Properties

As starch can express differences in properties from even the same plant cultivar and species (Fujita *et al.* 1996), analyzing and understanding the pasting properties of each variety or hybrid is important. Significant differences were found ($P < 0.05$) at each parameter of the RVA curve, except the

TABLE 3. COMPARISON OF FLOUR AND STARCH PARTICLE SIZE DISTRIBUTIONS FOR SORGHUM HYBRIDS

	Flour particle size distribution (μm)					Starch particle size distribution (μm)				
Sample	10	25	50	75	90	10	25	50	75	90
F-625	28.6 ± 0.6^{c}	83.8 ± 1.1^{c}	154.4 ± 0.8^{d}	244.3 ± 0.9^{c}	320.5 ± 1.7^{b}	6.2 ± 0.3^{b}	11.7 ± 0.7^{b}	17.6 ± 0.6^{c}	24.5 ± 0.8^{b}	31.7 ± 1.4^{b}
F-1,000	31.5 ± 0.3^{b}	88.8 ± 1.5^{b}	163.1 ± 1.2^{c}	250.2 ± 0.0^{c}	324.6 ± 1.0^{b}	7.3 ± 0.1^{a}	13.2 ± 0.1^{a}	19.5 ± 0.0^{ab}	26.2 ± 0.1^{b}	32.3 ± 0.2^{b}
NE#20	33.9 ± 0.3^{a}	101.8 ± 0.7^{a}	191.8 ± 3.4^{a}	299.6 ± 3.7^{a}	367.1 ± 4.5^{a}	7. ± 0.2^{a}	13.7 ± 0.2^{a}	20.8 ± 0.3^{a}	28.7 ± 0.7^{a}	37.1 ± 1.3^{a}
5,040C	27.9 ± 0.8^{c}	88.9 ± 0.5^{b}	177.8 ± 1.9^{b}	278.1 ± 2.1^{b}	356.7 ± 5.0^{a}	6.3 ± 0.1^{b}	12.5 ± 0.0^{ab}	18.7 ± 0.1^{bc}	25.4 ± 0.5^{b}	32.9 ± 0.6^{b}

Means with different letters in columns indicate significant differences among treatments ($P < 0.05$).

TABLE 4. STARCH PASTING PROPERTIES FOR SORGHUM HYBRIDS USING RAPID VISCO ANALYZER (RVU)

Sample	Peak viscosity (RVU)	Trough (RVU)	Breakdown (RVU)	Final viscosity (RVU)	Setback (RVU)	Peak time (min)	Pasting temp (°C)
F-625	428.7 ± 2.7[b]	85.5 ± 1.8[a]	324.3 ± 0.2[b]	236.5 ± 5.6[a]	151.0 ± 7.4[a]	3.78 ± 0.00[bc]	70.50 ± 0.00[b]
F-1,000	476.8 ± 4.4[a]	77.5 ± 1.6[b]	380.4 ± 1.8[a]	255.3 ± 0.9[a]	177.9 ± 0.6[a]	3.81 ± 0.00[b]	71.60 ± 0.28[ab]
NE#20	380.1 ± 8.6[c]	84.0 ± 1.1[a]	296.1 ± 7.5[c]	266.5 ± 5.0[a]	182.5 ± 4.0[a]	4.14 ± 0.00[a]	72.15 ± 0.57[a]
5,040C	417.8 ± 3.5[b]	83.5 ± 1.9[ab]	318.5 ± 3.2[b]	256.8 ± 13.1[a]	173.3 ± 15.0[a]	3.77 ± 0.02[c]	71.33 ± 0.04[ab]

Means with different letters in columns indicate significant differences among treatments ($P < 0.05$).

final viscosity and set back (Table 4). F-1,000 had the highest peak viscosity (428.7 RVU) and breakdown (380.4 RVU). The lowest peak viscosity (380.1 RVU) and breakdown (296.1 RVU) were from NE#20. The results reported are similar to that of Beta and Corke (2001) with average peak average viscosity data for 95 sorghum hybrids grown in Zimbabwe was 324 RVU. Suhendro *et al.* (2000) reported higher peak viscosity (456–810 RVU) and longer peak development time (6.42–7.25 min) than the four hybrids. Trough viscosity, an indication of holding strength, ranged from 77.5 RVU (F-1,000) to 85.5 RVU (F-625). Pasting temperature ranged from 70.50C (F-625) to 72.15C (NE#20). Our results are comparable to those of Liu *et al.* (2012) who reported pasting temperature ranging from 69.73C to 75.18C. Lower pasting temperatures were found to be associated with faster particle swelling and higher peak viscosity (Liu *et al.* 2012). The protein content and liberation of free fatty acids during storage of whole grain sorghum flour are the reasons for different pasting properties during cooling (Zhang and Hamaker 2005).

Evaluation of Sorghum Tortilla

For tortilla extensibility, TVM tortilla had significantly ($P < 0.05$) the lowest force value (534.9g; Table 5). F-625 and TVM tortillas had significantly higher rupture distance values (0.52 and 0.47 mm, respectively). F-1,000, NE#20 and 5,040C tortillas were not significantly different from each other for both force and distance. A low force value and longer distance of extension indicates soft and extensible tortillas. On the other hand, hard and brittle tortillas show higher force values and shorter rupture distances (Suhendro *et al.* 1999). TVM tortilla had a significantly lower force value and higher distance. F-625 tortilla had a significantly lower rupture distance value, but the force was high. These higher distance values were probably due to the smaller particle size of the flours and starch damage. F-625 had the smallest flour particle size (<154.4 μm at 50%) among sorghum hybrids and after testing TVM flour even smaller values were found (<114.6 μm at 50%). Finer particle size in the correct amount of water produces more cohesion (Hoseney 1994). In gluten-free products, the cohesiveness of dough relies on inert particles held together by water through surface tension. Also, starch damage was found to be much higher for TVM (12.2%) than the other four samples. Damaged starch increases water absorption (Evers and Stevens 1985), allowing more water to flow in the system to create a more pliable product because water act as a plasticizer. Particle size and starch damage affect water absorption and end-product quality. Liu *et al.* (2012) reported that water absorption in gluten-free sorghum noodles was significantly affected by flour particle size, starch particle size and starch damage. In bread making, too much starch damage produced slack dough, but too little starch damage caused low bread volumes and heavy texture (Mao and Flores 2001).

For tortilla stretchability, TVM tortilla had a significantly ($P < 0.05$) lower force (67.5 g) and F-625 tortilla had a significantly higher force (130.4 g) compared with all samples (Table 5). F-1,000, NE#20 and 5,040C force values were not significantly different from each other. Significant differences ($P < 0.05$) were found among samples for distance with values ranging from 4.06 mm (TVM) and 5.43 mm (F-625). As the distance of rupture increased, the force increased. A higher force indicates greater stretchability. Mao and Flores (2001) found higher stretchability in wheat flour tortillas with lower starch damage and coarser particle size. After testing TVM for starch damage, our results agree with Mao and Flores (2001). TVM (with the lowest force) had an average value of 12.2 compared with the low 2.7 for F-625. However, particle size was smallest for F-625, which contradicts Mao and Flores (2001). The stretchability test may not be a good indicator of sorghum flour quality for tortillas as the gluten-network in wheat tortillas is what creates a flexible product. Therefore, the goal in gluten-free tortillas is more a means of softness in order to roll. A higher force in this test could mean the tortilla is harder and not as conducive to rolling because of the lack of gluten network in sorghum flour.

The sorghum samples received an average score of 1.00 for rollability as they could not roll around a 1-cm dowel without breaking (data not shown). Using simply both hands to roll the tortillas, it was found that tortilla made with TVM could roll to a diameter of about 3 cm without cracking. The other sorghum hybrids could roll to a diameter of about 5 cm with 5,040C having the most cracking.

TABLE 5. PHYSICAL PROPERTIES OF SORGHUM FLOUR TORTILLAS

	Extensibility		Stretchability		Color			Water	Moisture
Sample	Force (g)	Distance (mm)	Force (g)	Distance (mm)	L^*	a^*	b^*	activity	content (%)
F-625	664.7 ± 56.4[a]	0.52 ± 0.07[a]	130.4 ± 12.6[a]	5.43 ± 0.38[a]	70.38 ± 1.32[a]	1.73 ± 0.29[d]	22.14 ± 1.22[ab]	0.78 ± 0.01[b]	17.31 ± 0.60[b]
F-1,000	629.7 ± 72.0[a]	0.39 ± 0.05[b]	96.3 ± 5.5[b]	4.58 ± 0.42[bc]	69.29 ± 1.66[a]	3.91 ± 0.40[c]	20.85 ± 1.07[bc]	0.78 ± 0.04[b]	16.93 ± 0.89[b]
NE#20	611.2 ± 48.6[a]	0.40 ± 0.04[b]	110.5 ± 8.6[b]	4.98 ± 0.39[ab]	64.71 ± 1.34[b]	5.57 ± 0.31[b]	22.28 ± 0.82[a]	0.79 ± 0.02[b]	16.90 ± 1.73[b]
5,040C	617.9 ± 92.2[a]	0.39 ± 0.07[b]	104.1 ± 15.4[b]	4.92 ± 0.42[ab]	61.68 ± 1.83[c]	11.11 ± 1.08[a]	17.94 ± 0.54[d]	0.77 ± 0.02[b]	16.06 ± 2.47[b]
TVM	523.9 ± 42.3[b]	0.47 ± 0.04[a]	67.5 ± 9.6[c]	4.06 ± 0.50[c]	62.81 ± 2.07[bc]	2.27 ± 0.27[d]	21.12 ± 1.17[ac]	0.89 ± 0.00[a]	25.29 ± 0.99[a]

Means with different letters in columns indicate significant differences among treatments ($P < 0.05$).

This could be attributed to the flour particle size and starch damage as TMV flour had a finer particle size (<114.6 μm at 50%) and higher starch damage (12.2%) than the other sorghum flours. Because of the small particle size and high starch damage, TVM flour required more water in the tortilla production and hence more rollable tortillas than the other sorghum hybrids.

Significant differences ($P < 0.05$) were found among all sorghum tortillas for L^*, a^* and b^* color values (Table 5). F-625 and F-1,000 tortillas were significantly lighter than the other samples with L^* values of 70.38 and 69.29, respectively. 5,040C (61.68) and TVM (62.81) tortillas were the darkest samples. For the a^* values, 5,040C tortilla (11.11) was significantly higher than the other samples. This result was expected as 5,040C hybrid is red sorghum. NE#20, white sorghum, is the second highest in redness with an a^* value of 5.57. NE#20 had the highest particle size distribution (191.766 μm at 50%) which could be an indication of large pieces of bran. Bran pieces would increase the red color. The b^* values ranged from 17.94 (5,040C) to 22.28 (NE#20). 5,040C tortilla had a lower yellow color as it is a red sorghum.

TVM tortilla was significantly higher in both water activity and moisture content with values of 0.89 and 25.29, respectively (Table 5). No significant differences were found among the other four samples. These higher water values are due to the greater amount of water needed to make the dough with TVM flour. In making the tortillas, TVM flour required 130 g of water while the other four samples required water content between 70 and 85 g. TVM flour required more water because of the small particle size and high starch damage. Our results are in agreement with Liu *et al.* (2012) who reported that high starch damage and small particle size flour required more water than low starch damage and coarse flours. The particle size distribution for TVM flour was 114.6 μm at 50% volume, while the other four samples had a range of 154.4 μm to 177.9 μm at 50% volume. Smaller particles in the flour allow for a greater surface area for water to fill around. Also, the starch damage for TVM flour was 12.2%. The other four samples had a starch damage ranging from 2.7 to 3.0%. Damaged starch increases water absorption (Evers and Stevens 1985). Disruption of the crystalline region in starch granules allows water access to the whole granule (Multon *et al.* 1980).

Sensory Evaluation

Significant differences were found ($P < 0.05$) for some attributes in descriptive analysis (Table 6). For appearance, the only significant difference was in grain specks. TVM tortilla had a significantly lower score (5.67). The smaller flour particle size distribution (114.55 μm at 50% volume) of TVM

TABLE 6. MEANS VALUES OF SENSORY ATTRIBUTES† OF SORGHUM FLOUR TORTILLAS AS EVALUATED BY A TRAINED DESCRIPTIVE PANEL

Appearance								
Sample	Yellow color	Brown color	Evenness of color	Opacity	Shape (round)	Surface	Grain specks	Glossiness
F-625	3.57 ± 0.79^{a}	2.71 ± 1.11^{a}	8.86 ± 3.63^{a}	8.43 ± 1.72^{a}	12.43 ± 0.98^{a}	3.29 ± 2.69^{a}	9.00 ± 4.69^{a}	2.86 ± 1.21^{a}
F-1,000	3.14 ± 1.07^{a}	3.00 ± 1.63^{a}	8.00 ± 5.45^{a}	8.86 ± 1.68^{a}	12.86 ± 1.46^{a}	6.86 ± 4.88^{a}	10.29 ± 4.50^{a}	3.00 ± 1.63^{a}
NE#20	3.17 ± 2.56^{a}	3.67 ± 1.63^{a}	10.17 ± 1.83^{a}	9.33 ± 2.94^{a}	12.00 ± 2.53^{a}	4.33 ± 3.14^{a}	11.17 ± 2.71^{a}	2.67 ± 1.03^{a}
5,040C	1.67 ± 1.21^{a}	4.33 ± 5.32^{a}	11.17 ± 1.33^{a}	9.50 ± 2.74^{a}	11.17 ± 3.31^{a}	2.67 ± 1.37^{a}	12.83 ± 2.48^{a}	2.67 ± 1.03^{a}
TVM	3.80 ± 1.33^{a}	3.83 ± 0.98^{a}	10.00 ± 0.00^{a}	6.00 ± 2.19^{a}	13.83 ± 0.75^{a}	3.33 ± 1.37^{a}	5.67 ± 1.51^{b}	4.33 ± 2.16^{a}
Flavor								
Sample	Sour	Salty	Sweet	Bitter	Doughy	Nutty	Mouth coating	
F-625	3.14 ± 2.04^{a}	2.71 ± 1.38^{a}	6.86 ± 1.07^{a}	3.71 ± 0.95^{a}	4.14 ± 2.04^{a}	6.43 ± 2.23^{a}	4.43 ± 2.23^{a}	
F-1,000	2.29 ± 1.11^{a}	2.86 ± 1.35^{a}	6.14 ± 0.90^{ab}	4.29 ± 0.76^{a}	4.57 ± 1.72^{a}	7.14 ± 2.04^{a}	4.43 ± 2.51^{a}	
NE#20	2.33 ± 1.21^{a}	2.83 ± 0.98^{a}	4.67 ± 0.52^{cd}	4.00 ± 1.26^{a}	3.67 ± 0.82^{a}	5.67 ± 2.16^{a}	3.33 ± 0.82^{a}	
5,040C	2.5 ± 1.76^{a}	2.67 ± 1.21^{a}	5.33 ± 0.82^{bc}	4.00 ± 1.26^{a}	3.83 ± 0.75^{a}	7.00 ± 2.90^{a}	4.67 ± 1.63^{a}	
TVM	3.50 ± 1.76^{a}	2.50 ± 1.22^{a}	4.83 ± 0.75^{bd}	3.17 ± 0.98^{a}	4.33 ± 1.37^{a}	6.50 ± 1.05^{a}	4.83 ± 2.79^{a}	
Texture (in the mouth)								
Sample	Springiness	Hardness	Cohesiveness of mass	Fracturability	Moisture absorption	Grittiness	Tooth packing	
F-625	1.29 ± 0.49^{c}	8.00 ± 1.41^{a}	5.57 ± 0.79^{a}	4.5 ± 0.76^{a}	7.29 ± 2.14^{a}	4.00 ± 2.31^{bc}	6.21 ± 1.95^{a}	
F-1,000	2.00 ± 0.89^{bc}	6.71 ± 1.80^{ac}	6.86 ± 2.04^{a}	4.57 ± 2.07^{a}	6.71 ± 1.70^{a}	4.57 ± 2.94^{bc}	5.36 ± 1.60^{a}	
NE#20	2.83 ± 0.41^{ab}	5.33 ± 1.51^{bcd}	8.00 ± 3.16^{a}	4.50 ± 0.84^{a}	7.17 ± 1.60^{a}	6.17 ± 2.93^{ab}	5.50 ± 1.64^{a}	
5,040C	2.33 ± 0.52^{ac}	7.17 ± 1.83^{ab}	4.83 ± 1.72^{a}	4.50 ± 1.64^{a}	7.17 ± 2.14^{a}	8.92 ± 1.69^{a}	5.33 ± 1.63^{a}	
TVM	3.50 ± 1.05^{a}	3.83 ± 0.98^{d}	8.00 ± 1.26^{a}	4.17 ± 0.75^{a}	6.00 ± 0.00^{a}	6.00 ± 2.10^{ac}	4.75 ± 1.47^{a}	
Texture (in the hand)								
Sample	Roughness	Angle of ben^{d}	Tearability					
F-625	3.43 ± 0.98^{a}	8.43 ± 1.90^{ab}	7.50 ± 2.93^{a}					
F-1,000	2.93 ± 0.84^{a}	9.71 ± 1.47^{ab}	6.71 ± 2.56^{a}					
NE#20	2.83 ± 0.41^{a}	10.25 ± 2.36^{bc}	7.50 ± 1.38^{a}					
5,040C	2.67 ± 0.52^{a}	10.42 ± 0.92^{ac}	6.50 ± 2.17^{a}					
TVM	2.33 ± 0.52^{a}	12.92 ± 1.69^{c}	5.67 ± 2.58^{a}					
Odor								
Sample	Sweet	Ranci^{d}	Musty					
F-625	3.57 ± 1.13^{a}	1.83 ± 0.75^{ab}	6.79 ± 2.16^{a}					
F-1,000	4.00 ± 2.31^{a}	2.14 ± 0.90^{ab}	7.14 ± 1.21^{a}					
NE#20	3.67 ± 0.52^{a}	1.67 ± 0.52^{bc}	6.67 ± 1.75^{a}					
5,040C	4.17 ± 0.98^{a}	3.17 ± 0.75^{ac}	7.17 ± 2.32^{a}					
TVM	4.67 ± 1.21^{a}	4.00 ± 2.45^{c}	7.17 ± 2.79^{a}					

Means with different latters in columns indicate significant differences among treatments ($P < 0.05$).
† Attributes were scored on a 15-point scale.

means there are less large particles or "specks" visible to the human eye.

The sweet attribute was the only flavor descriptor with significant differences. The values ranged from 4.67 (NE#20) to 6.86 (F-625). The differences are probably due to the variations in maturity level of the sorghum caryopses (Newton *et al.* 1980). Springiness, hardness and grittiness showed significant differences in texture by the mouth. Springiness ranged from 1.29 (F-625) to 3.50 (TVM). Hardness ranged from 3.83 (TVM) to 8.00 (F-625). Grittiness ranged from 4.00 (F-625) to 8.92 (5,040C). The TVM hardness is in agreement with the extensibility results from the texture analyzer, which showed that force required to rupture the tortillas was the lowest for TVM. The angle bend was the attribute with significant differences found for texture in the hand. TVM tortilla had the highest score (12.92), while F-625 tortilla had the lowest score (8.43). The TVM sample's high score can be related to the extensibility values. With a low force and high distance values, the TVM tortilla is more extensible making it easier to bend without breaking. In odor attributes, significant differences were found for rancid. TVM tortilla had the highest score (4.00) for rancidity and NE#20 tortilla had the lowest (1.67). These differences are most likely due to the release of free fatty acids during storage. The flour samples were stored in a freezer to delay the unset of fat oxidation. The storage of the commercial flour prior to purchase is unknown, while the other four samples were stored in a freezer to delay the unset of fat oxidation.

CONCLUSIONS

Understanding quality characteristics of sorghum varieties is very important in translating to end-product use. The results of this study have shown that sorghum hybrids can differ in kernel and flour properties, which could help predict sorghum flour quality for the purpose of gluten-free products. Flour with smaller particle size and greater starch damage have yielded better gluten-free tortillas. Through control of sorghum flour quality characteristics, gluten-free tortilla could be prepared with acceptable quality attributes.

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