Effects of Hand Pounding, Abrasive Decortication–Hammer Milling, Roller Milling, and Sorghum Type on Sorghum Meal Extraction and Quality

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ABSTRACT

Twelve sorghum types with diverse physicochemical properties were milled using two-stage roller milling (RM), abrasive decortication–hammer milling (ADHM), and hand pounding (HP), and the effects on meal extraction and quality were evaluated. Grain hardness correlated significantly with extraction rate for ADHM and HP but not for RM. Pericarp thickness and whole-grain oil content were significantly correlated with meal purity for RM and ADHM. RM gave the darkest meal, followed by HP. Grain weathering significantly affected extraction rate for ADHM but not for RM and HP. RM produced fine meals with slightly more ash and oil and gave higher protein and higher meal extraction (836 compared to 757 g kg^{-1}) than ADHM. HP produced coarser meals with the lowest ash and oil contents but gave the lowest extraction rates (742 g kg^{-1}). Overall, RM seems more advantageous than ADHM and HP for sorghum milling because of its much higher extraction rate and production throughput.

Sorghum (*Sorghum bicolor* (L.) Moench) is an important cereal crop in the developing countries of Africa and Asia (7). In Africa, sorghum ranks second in production, after maize. It is grown predominantly by subsistence farmers for household food security (15,19).

Preparation of most sorghum products starts with milling of the grain to separate the outer fibrous pericarp layer and the oil-rich germ from the starchy endosperm and to reduce the clean starchy endosperm into a meal. Traditionally, sorghum meal is produced by hand-pounding grain using a wooden pestle and mortar. This process is still practiced in rural households but is declining. In recent years, mechanized milling, commonly using the Prairie Research Laboratory (PRL) type of abrasive dehuller (decorticator) and a hammer mill, has become popular for commercial small and medium-scale sorghum meal production throughout southern Africa (15,19). However, this milling system is characterized by high milling losses, inconsistent quality, and low production rates (19,20).

The lack of an efficient sorghum milling technology has been identified as a major constraint to the establishment of a vibrant sorghum food industry (19). According to Taylor and Dewar (20), early attempts to process sorghum by roller milling, the industrial milling technology used for wheat and maize, resulted in poor separation of the grain components, giving poorly refined products that lacked consumer appeal. These problems were attributed to several sorghum kernel characteristics, notably, the extremely friable pericarp, the large integral germ, and the highly variable endosperm texture (20).

Several studies have reported the advantages of tempering sorghum before roller milling (5,9,11). Cecil (5) described a semiwet milling process that entailed tempering the grain to 26% at 60°C for 6 hr before milling. This process was reported to improve degermination and bran separation, but it resulted in poor extraction rates and high residual moisture in flour. In another study, tempering the grain to 16% at 4°C for 24 hr improved extraction rates and reduced final meal residual moisture to microbiologically safe levels (9).

Fig. 1. Hand pounding of sorghum in Botswana. Foreground, pounding of grain using wooden pestle and mortar; background, separation of bran by winnowing.

Fig. 2. Small sorghum mill in Botswana. Foreground, hammer mill; background, Prairie Research Laboratory type of dehuller.

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These findings suggest that roller milling has potential for sorghum milling. However, there is insufficient information about how roller milling performs compared to other conventional sorghum milling processes. Also, knowledge is limited about how the milling process and the sorghum kernel characteristics affect meal quality. Such information could serve as a powerful tool for breeders and millers in supplying premium-quality sorghum products to consumers. This study, therefore, investigated the effect of the milling process (hand-pounding, abrasive decortication–hammer milling, and roller milling) and the sorghum type on sorghum meal extraction rate and quality.

MATERIALS AND METHODS

Grain

Twelve sorghum types with varied kernel characteristics were procured from farmers in different areas of Botswana. Six types were indigenous (Kanye standard, Lekgeberwa, Marupantsi, Sefofu, Segaolane, and Town) and six types (BSH1, Phofu, Mmabaitse, LARSVYT, SNK, and Buster) had been introduced over the past 10 years. All the samples were harvested during the 2004 crop season and were stored at 7°C until they were used.

Grain Characterization

Kernel size was characterized by sieving 100-g samples of clean grain through two test sieves with 3.35- and 2.80-mm openings (10). Endosperm texture was rated subjectively on a scale of 1 (most corneous) to 5 (very floury) by visually examining longitudinal sections of half cuts of 20 randomly selected mature grains (16). Kernel hardness was evaluated using the Tangential Abrasive Dehulling Device (TADD) fitted with 60-grit sand paper (Norton R284 metalite, Saint-Gobain Abrasives, Isando, South Africa), as described by Reichert et al (13), by measuring yield when 30-g grain samples were decorticated for 4 min. Pericarp thickness was rated subjectively by observing longitudinal sections of half kernels (20 kernels per sorghum type) using a light stereomicroscope. Thousand-kernel weight (TKW) was determined by weighing 1,000 randomly counted unbroken kernels. Color of the whole grains was assessed visually (16) and was also measured in L^*, a^*, b^* CIELAB units on milled whole-grain flour, produced by milling with a Falling Number 3100 mill (Huddinge, Sweden) fitted with a screen having 0.8-mm openings, using a tristimulus color meter (Minolta Chroma Meter CR-400/410, Konica Minolta Sensing, Japan). The parameters a^* and b^* were used to calculate C^*_{ab} (chroma) and h^*_{ab} (hue), which were then used with L^* to describe the color of the meal samples (22). Glume color was assessed by observing the inside of the glume after peeling it from the kernel (16). The presence or absence of a pigmented testa was established using the bleach test, performed as described by Taylor (18). Weathered grain was estimated as percent-

Fig. 3. Roller mill tested for sorghum milling at the University of Pretoria. The mill comprises two pairs of rolls and a sieving assembly.

Table I. Physical characteristics of kernels of 12 selected sorghum grain types grown in Botswana[a,b]

Sorghum Type	Grain Size (mm)[c] %>3.35	Grain Size (mm)[c] 3.35 <%>2.80	Pericarp Thickness	Visual Hardness Score[d]	Visual Hardness Class[e]	TKW[f] (g)	TADD[g] Decortication Yield at 4 min (g kg^{-1})
BSH1	45.4 e (2.2)	50.0 c (1.5)	Medium	1.7 b (0.7)	C	29.0 i (0.4)	875.1 f (6.7)
Kanye standard[h]	66.5 f (2.5)	30.5 b (2.7)	Thick	3.7 h (0.7)	I	30.4 j (0.4)	792.6 b (12.1)
LARSVYT	6.4 b (0.9)	86.1 ij (0.7)	Thin	2.1 c (0.6)	C	22.8 c (0.3)	853.6 d (11.2)
Lekgeberwa	0.7 a (0.4)	82.9 hi (4.1)	Thick	1.3 a (0.4)	C	20.7 a (0.1)	863.8 de (6.1)
Buster	36.3 d (3.7)	55.1 d (2.5)	Thick	3.2 fg (0.6)	I	27.2 g (0.5)	875.3 f (10.4)
Marupantsi[h]	37.2 d (2.4)	59.9 e (2.9)	Thick	2.9 ef (0.7)	I	28.1 h (0.5)	813.1 c (9.6)
Mmabaitse[h]	14.1 c (0.7)	79.4 f (0.2)	Thick	3.7 h (0.7)	I	23.2 d (0.1)	732.3 a (8.2)
Phofu	8.7 b (1.6)	82.6 gh (1.2)	Medium	2.3 c (0.4)	C	21.9 b (0.3)	863.8 de (8.3)
Sefofu	76.2 g (2.0)	21.4 a (1.8)	Medium	2.2 c (0.4)	C	33.4 k (0.7)	872.6 ef (9.3)
Segaolane	3.1 a (0.4)	89.3 j (1.0)	Thin	2.5 cd (0.5)	I	24.3 e (0.4)	880.9 f (7.3)
SNK	14.8 c (0.3)	78.8 f (0.7)	Thick	3.4 gh (0.6)	I	24.4 e (0.4)	820.0 c (12.6)
Town	13.6 c (0.9)	82.9 hi (0.6)	Thin	2.7 de (0.4)	I	25.5 f (0.5)	864.1 de (7.5)

[a] Figures in parentheses are standard deviations.
[b] Figures in columns with different letter notations are significantly different at $P < 0.05$.
[c] All classified as medium-size in accordance with scheme described by Gomez et al (10).
[d] Scale 1–5, with 1 denoting corneous (hard) and 5 representing floury (soft) endosperm.
[e] Classification: C = corneous, I = intermediate.
[f] Thousand-kernel weight.
[g] Tangential Abrasive Dehulling Device.
[h] Grain partially weathered (Marupantsi, 19%; Kanye standard, 24%; and Mmabaitse, 33%).

Table II. Color characteristics of kernels of 12 selected sorghum grain types grown in Botswana[a,b]

Sorghum Type	Glume Color	Grain Color (phenotype)	Color Measurement (whole-grain meal color) L^*	C^*_{ab}	h^*_{ab} (deg.)
BSH1	Sienna	White	78.8 f (0.2)	13.3 g (0.2)	88.7 ef (0.2)
Kanye standard[c]	Purple	Bright white, mottled	69.8 b (0.6)	9.3 a (0.2)	67.9 b (0.6)
LARSVYT	Sienna	White	75.6 e (0.9)	13.4 g (0.3)	88.6 ef (0.7)
Lekgeberwa	Purple	White	75.9 e (0.6)	12.4 ef (0.1)	87.0 e (0.3)
Buster	Red	Red	71.9 c (0.1)	13.2 g (0.2)	69.9 b (0.6)
Marupantsi[c]	Purple	Reddish white	71.5 bc (1.1)	10.2 b (0.3)	67.6 b (0.9)
Mmabaitse[c]	Purple	White, mottled	62.7 a (0.7)	9.3 a (0.8)	51.5 a (4.4)
Phofu	Sienna	White	76.9 e (1.8)	12.6 f (0.4)	90.4 f (0.1)
Sefofu	Red	White	76.8 e (1.5)	11.9 de (0.3)	81.4 d (0.4)
Segaolane	Purple	Cream-white, mottled	73.7 d (1.4)	10.5 b (0.1)	76.9 c (0.6)
SNK	Red	Red	70.8 bc (0.6)	11.3 c (0.1)	68.7 b 0.6)
Town	Red	Red	72.4 cd (0.6)	11.8 d (0.2)	68.7 b (0.3)

[a] Figures in parentheses are standard deviations.
[b] Figures in columns with different letter notations are significantly different at $P < 0.05$.
[c] Grain partially weathered (Marupantsi, 19%; Kanye standard, 24%; and Mmabaitse, 33%).

age of kernels with visible mold patches. Moisture content was determined by oven drying using AACC International method 44-15A (1). Total ash was determined using AACC International method 08-01 (1). Oil content was determined by petroleum ether extraction with AACC International method 30-25 (1). Protein (N × 6.25) was determined by the Dumas combustion method.

Hand Pounding

Three adult women with hand-pounding experience were employed to pound 4 kg of each sorghum type in a typical traditional Botswana process (Fig. 1). Clean grain (2.0 kg) was soaked in about 2 kg of water for approximately 15–20 min. Drained grain portions of between 500 and 800 g of 30–40% moisture (depending on the sorghum type) were decorticated by pounding with wooden pestles in a mortar for 10–15 min. Bran was immediately separated from the endosperm material by winnowing with a traditional basket winnower. Hard-to-decorticate grains were reprocessed until decorticated to the satisfaction of the person doing the pounding. The decorticated grain was then conditioned to 25–30% moisture and pounded into a meal in portions of approximately 500–800 g. Each portion took about 10–15 min to process. The milled stock was separated into fine and coarse grits using a winnowing basket. Additional water was added to the coarse grits to soften them, and they were then pounded again. All the milled-grit portions of a batch were blended together and spread on jute bags in the open sun to dry for 18–24 hr.

Abrasive Decortication and Hammer Milling

A commercial mill in Botswana was engaged to mill the 12 sorghum types in accordance with the mill's production-quality standards. Milling equipment comprised a Rural Industries Innovation Centre (RIIC, Kanye, Botswana) PRL-type dehuller and hammer mill similar to those shown in Figure 2. A cleaned, dry 10-kg batch of each sorghum type was fed into the barrel of the dehuller through a hopper fitted with a flow regulator. The bran was progressively abraded off and removed by means of a cyclone fan. The grain was decorticated to the operator's satisfaction. Decorticating time for each batch ranged from 3 to 8 min, depending on the sorghum type. The grain was then milled using a hammer mill fitted with a screen with 2.0-mm openings. Bran and meal were weighed to determine extraction rates. Each sorghum type was milled in duplicate.

Roller Milling

A small commercial roller mill (Fig. 3) with two pairs of fluted rolls and a rated throughput of 500 kg h^{-1} was used. The top rolls (coarse break rolls) had eight flutes per 25 mm, and the bottom rolls (fine break rolls) had 22 flutes per 25 mm. Both roll pairs operated at a differential of 1.5:1. A milling process previously optimized for acceptable meal quality (results not shown) was used. The process involved tempering 5-kg batches of clean grain to 16% moisture for 15 min in tightly closed plastic buckets at ambient temperature. The grain was thoroughly mixed at intervals of 5 min to uniformly distribute added water and was roller milled immediately using top and bottom roller gaps of 0.80 and 0.30 mm, respectively. The feed rate was main-

Table III. Protein, oil, and ash content (g kg^{-1} dry basis) of 12 selected sorghum types grown in Botswana[a,b]

Sorghum type	Protein	Oil	Ash
BSH1	129.5 f (2.7)	36.3 e (0.6)	16.4 g (0.3)
Kanye standard	113.9 d (2.3)	33.4 c (0.4)	11.4 a (0.6)
LARSVYT	106.8 b (2.0)	33.1 c (0.5)	14.3 d (0.2)
Lekgeberwa	131.4 f (1.6)	46.7 i (0.6)	13.8 cd (0.4)
Buster	104.7 a (1.2)	34.7 d (0.2)	14.2 cd (0.2)
Marupantsi	126.2 e (1.5)	33.8 c (0.5)	11.6 a (0.9)
Mmabaitse	143.2 h (0.6)	28.2 a (0.4)	15.8 fg (0.2)
Phofu	110.2 c (1.5)	30.3 b (0.9)	13.6 bc (0.4)
Sefofu	155.7 i (1.3)	42.0 h (0.4)	15.0 e (0.2)
Segaolane	136.8 g (1.7)	38.7 g (0.5)	13.2 b (0.2)
SNK	129.6 f (1.6)	36.5 e (0.4)	14.3 d (0.2)
Town	130.4 f (0.9)	37.9 f (0.3)	15.5 ef (0.3)
Mean	126.5 (14.9)	39.8 (5.5)	14.1 (1.5)
Literature values[c]			
Range	44–211	21–76	13–33
Mean	114	33	19

[a] Figures in brackets are standard deviation.
[b] Figures in columns with different letter notations are significantly different at P <0.05.
[c] Data from Serna-Saldivar and Rooney (17).

Table IV. Effect of sorghum type and milling process on the extraction rate of sorghum meal[a,b]

Sorghum Type	Meal Extraction (g kg^{-1}): Hand Pounding	Abrasive Decortication and Hammer Milling	Roller Milling	Main Sorghum Type Effect	Main Sorghum Type Effect[c]
BSH1	797.0 f (15.6)	830.9 cd (59.4)	816.0 ab (15.6)	814.6 cd (32.1)	814.6 e–g (32.1)
Kanye Standard[d]	772.0 ef (12.7)	708.6 ab (9.1)	856.0 gh (11.3)	778.9 bc (66.7)	…
LARSVYT	634.5 a (6.4)	795.6 b–d (52.3)	822.0 bc (8.5)	750.7 ab (93.9)	750.7 ab (93.9)
Lekgeberwa	871.0 g (33.9)	800.0 b–d (52.4)	855.0 gh (1.4)	842.0 d (43.5)	842.0 g (43.5)
Buster	734.5 cd (12.0)	743.8 a–c (61.7)	843.0 e–g (4.2)	773.8 bc (60.7)	773.8 cd (60.7)
Marupantsi[d]	746.0 de (11.3)	731.8 a–c (20.5)	839.0 d–f (2.8)	772.3 bc (53.1)	…
Mmabaitse[d]	711.0 bc (17.0)	679.2 a (74.2)	831.5 c–e (3.5)	740.6 ab (79.5)	…
Phofu	728.0 cd (12.7)	814.0 cd (56.8)	807.0 a (7.1)	783.0 bc (50.1)	783.0 c–e (50.1)
Sefofu	792.5 f (12.0)	772.4 a–d (71.6)	848.0 fg (2.8)	804.3 cd (47.8)	804.3 d–f (47.8)
Segaolane	799.5 f (10.6)	848.4 d (2.3)	867.5 h (0.7)	838.4 d (31.7)	838.4 fg (31.7)
SNK	634.0 a (11.3)	675.4 a (9.2)	832.5 c–e (2.1)	714.0 a (93.9)	714.0 a (93.9)
Town	682.0 b (9.9)	685.4 a (7.1)	825.5 b–d (3.5)	731.0 ab (73.5)	731.0 ab (73.5)
Main milling effect	741.8 a (69.7)	757.1 a (69.3)	836.9 b (18.2)	778.6	…
Main milling effect (excluding weathered grain)	741.4 a (81.1)	774.0 b (69.2)	835.2 c (19.7)	…	783.5

[a] Figures in brackets are standard deviations.
[b] Means in columns and the two bottom rows with different letter notations are significantly different at P <0.05.
[c] Excluding weathered grain.
[d] Weathered grain.

tained constant. The milled stock was separated on vibrating sieves of mesh sizes 1.00, 0.850, 0.710, and 0.710 mm (Tyler standard 16, 20, 26, and 26, respectively) arranged in descending order by size (top to bottom). The first two sieves retained the bran fraction, which was designated "coarse," while the last two sieves fractionated the meal into three streams designated "medium-coarse," "medium-fine," and "fine," respectively. All three meal streams were recombined for subsequent analysis. The meals were packed in sealed polythene "zipper-locked" bags and stored at 7°C until analyzed.

Analysis of Meals

Meal particle size was determined by sifting 20-g meal samples for 3 min, using a sieve shaker, through a series of test sieves with opening sizes of 106, 150, 250, 500, 710, 1,000, and 1,400 μm. Meal color, moisture, ash, and oil were determined as described above.

Statistical Analysis

The data were analyzed by multifactor analysis of variance, and the means were compared by Fisher's least significant differences (LSD). Pearson correlation coefficients between selected data sets were also determined. All calculations were performed using Statgraphics Centurion XV (StatPoint, Herndon, VA).

RESULTS AND DISCUSSION

Grain Characterization

As shown in Table I, all the sorghum types were medium in size, as classified according to Gomez et al (10). Lekgeberwa was the lightest (20.7 g per 1,000 kernels), and Sefofu was the heaviest (33.4 g per 1,000 kernels). Fifty percent of the sorghum types had thick pericarps, while three had medium-thick and the rest thin.

Table V. Significant Pearson correlation coefficients between sorghum type characteristics and the characteristics of the meals obtained by hand pounding, abrasive decortication–hammer milling, and roller milling[a]

		Meal Characteristic						
	Milling Process[b]	Extraction Rate	Ash	Oil	Protein	L^* Value (lightness)	C^*_{ab} Value (chroma)	h^*_{ab} Value (hue)
Grain visual hardness	HP	–0.57*				–0.74***		–0.76***
	ADHM	–0.79***	–0.55*	–0.50*		–0.64**	–0.51*	–0.73***
	RM			–0.58**		–0.74***	–0.52*	–0.80***
Grain abrasive (hardness TADD yield)	HP		–0.62**			0.92****		0.86****
	ADHM	0.72***	0.64**	0.58**		0.89****	0.67**	0.89****
	RM			0.59**			0.60**	0.83****
Whole grain oil	HP	0.61**				0.53*		
	ADHM			0.92****		0.54*		
	RM	0.52*		0.93****		0.54*		
Whole grain ash	HP						0.50*	
	ADHM		0.65**				0.61**	
	RM		0.91****				0.65**	
Whole grain protein	HP				0.85****			
	ADHM				0.97****			
	RM				0.99****			
Pericarp thickness	HP							
	ADHM		–0.59**					
	RM		–0.57*					
Whole grain L^* value	HP					0.95****		
	ADHM					0.91****		
	RM					0.97****		
Whole grain C^*_{ab} value	HP					0.87****		
	ADHM					0.81****		
	RM					0.82****		
Whole grain h^*_{ab} value	HP					0.90****		
	ADHM					0.85****		
	RM					0.94****		
Meal ash	HP					–0.63**		–0.54*
	ADHM	0.61**				0.53*	0.83***	0.66**
	RM						0.74**	
Meal oil	HP				0.57*		–0.72***	
	ADHM					0.51*		
	RM	0.53*				0.55*		
Meal L^* value	HP		–0.63**					
	ADHM	0.67**	0.53*	0.51*				
	RM			0.55*				
Meal C^*_{ab} value	HP							
	ADHM		0.83****	–0.72***		0.60**		
	RM		0.74***			0.59**		
Meal h^*_{ab} value	HP		–0.54*			0.98****		
	ADHM	0.74**	0.66**			0.96****	0.75***	
	RM					0.97****	0.68**	

[a] Significance: *P <0.10, **P <0.05, ***P <0.01, ****P <0.001.

[b] HP = Hand pounding, ADHM = abrasive decortication and hammer milling, RM = roller milling.

Visual hardness scores ranged from 1.3 (Lekgeberwa) to 3.7 (Kanye standard). Based on these hardness scores, and using the classification scheme proposed by Rooney and Miller (16), BSH1, LARSVYT, Lekgeberwa, Phofu, and Sefofu were classified corneous while the rest were intermediate (Table I). The TADD decortication yield (abrasive kernel hardness) for all sorghum types (except Kanye standard and Mmabaitse) were above 800 g kg^{-1}. Kanye standard and Mmabaitse were slightly weathered, which probably accounted for their lower decortication yield.

All the sorghum types had pigmented glumes (Table II), with five having purple glumes, four red, and three sienna. Grain color (phenotype color) ranged from white to red. Some white-colored sorghum types (Kanye standard, Mmabaitse, and Segaolane) were mottled, indicating that they were weathered. Grain overall color is genetically controlled and is affected by several factors, including pericarp color and thickness, testa pigmentation (if present), and endosperm color (16). Relative lightness (L^*) ranged from 62.7 to 78.8 units, while C^*_{ab} (chroma) and h^*_{ab} (hue) ranged from 9.3 to 13.4 and 51.5° to 90.4°, respectively. Lower values of L^* indicate darker colors, whereas C^*_{ab} signifies the intensity of the color. Hue is expressed on a 360° grid, where 0° and 90° reflect bluish-red and yellow, respectively (22). The two lightest sorghum types were BSH1 and Phofu, whereas Mmabaitse was the darkest.

As shown in Table III, mean protein content ranged from 104.7 g kg^{-1} (Buster) to 155.7 g kg^{-1} (Sefofu), while oil content varied from 28.2 g kg^{-1} (Mmabaitse) to 42.0 g kg^{-1} (Sefofu). Ash content ranged from 11.4 g kg^{-1} (Kanye standard) to 16.4 g kg^{-1} (BSH1) and was consistently lower than the average reported for sorghum in the literature (Table III). It is known that the mineral content of sorghum is greatly influenced by the availability of phosphorus in the soil (8); therefore, the low ash in these grains may be attributable to the phosphorus-deficient sandy soils of Botswana (14).

Extraction Rates

There were significant variations ($P < 0.05$) in mean extraction rates between hand pounding (HP), abrasive decortication and hammer milling (ADHM), and roller milling (RM) (Table IV), showing that the milling process affected the extraction rate. When all sorghum types were considered, HP and ADHM were not significantly different, giving mean extraction rates of 742 and 757 g kg^{-1}, respectively. RM performed substantially better, giving an 11% (78 g kg^{-1}) yield advantage over ADHM. However, when the three weathered sorghum types were excluded from the data, ADHM performed significantly better than HP, although still substantially worse than RM. The extraction rates for HP and RM remained essentially unchanged, indicating that grain weathering does not affect milling yields with HP and RM as much as it does with ADHM.

Interestingly, RM extraction rates did not correlate significantly with visual grain hardness and abrasive hardness (TADD decortication yield), indicating that grain hardness is not important for achievement of good extraction rates with RM. Hammond (11) also did not find any correlation between sorghum hardness and extraction rate in roller milling studies involving four sorghum types with varied endosperm texture. However, this finding should be interpreted with caution, as the sorghum types used in the present study did not include types that had completely floury endosperms. In contrast to RM, there were significant correlations (Table V) between ADHM extraction rate and grain visual hardness ($r = -0.79$, $P < 0.01$) and abrasive hardness ($r = 0.72$, $P < 0.01$). Similarly, extraction rates with HP correlated significantly with visual hardness ($r = -0.57$, $P < 0.10$) but not with abrasive hardness. The highest extraction rates were achieved with the relatively harder sorghum types Lekgeberwa, BSH1, and Segaolane. The softer types, SNK and Mmabaitse, gave the lowest extraction rates. This confirmed findings reported by Bassey and Schmidt (3) that, for abrasive decortication and hand pounding, grains with harder endosperms give higher flour yields than those with softer endosperms.

Color of the Meals

Light-colored sorghum products are usually preferred by consumers (2,4,9). Table VI shows that the milling process significantly ($P < 0.05$) affected the color of the meals, with ADHM producing the lightest colored meals (as indicated by L^*), followed by HP. RM produced slightly darker meals. However, in terms of hue,

Table VI. Effect of sorghum type and milling process on the color properties (L^*, C^*_{ab}, and h^*_{ab}) of sorghum meal[a,b]

	L^* (lightness)			C^*_{ab} (chroma)			h^*_{ab} (hue)		
Sorghum Type	Hand Pounding	Abrasive Decortication and Hammer Milling	Roller Milling	Hand Pounding	Abrasive Decortication and Hammer Milling	Roller Milling	Hand Pounding	Abrasive Decortication and Hammer Milling	Roller Milling
BSH1	89.2 j (0.1)	87.6 gh(0.1)	87.2 i (0.2)	10.8 d (0.2)	11.6 g (0.2)	12.4 ef (0.2)	84.3 k (0.4)	80.2 g (0.1)	81.8 i (0.2)
Kanye Standard[c]	78.7 b (0.2)	82.7 b (0.2)	79.6 c (0.1)	10.2 c (0.1)	9.2 a (0.3)	10.0 a (0.2)	59.8 c (0.5)	58.4 b (0.8)	57.0 b (0.4)
LARSVYT	87.4 i (0.1)	87.4 g (0.1)	85.8 g (0.2)	9.5 a (0.2)	11.2 f (0.2)	11.8 d (0.4)	79.7 i (0.4)	81.6 h (0.2)	81.4 i (0.1)
Lekgeberwa	87.1 h (0.1)	87.7 h (0.1)	86.4 h (0.2)	10.2 c (0.0)	10.7 e (0.2)	11.8 d (0.2)	80.6 j (0.3)	80.0 g (0.3)	78.9 h (0.3)
Buster	85.6 f (0.1)	86.7 f (0.2)	82.7 f (0.2)	11.4 e–g (0.3)	11.7 g (0.1)	12.5 f (0.2)	70.4 g (0.3)	75.0 f (0.3)	67.3 e (0.7)
Marupantsi[c]	78.7 b (0.1)	83.2 c (0.2)	78.5 b (0.1)	10.0 bc (0.1)	9.7 b (0.0)	10.7 b (0.2)	56.4 b (0.2)	63.2 c (0.1)	59.2 c (0.3)
Mmabaitse[c]	70.5 a (0.2)	74.4 a (0.0)	71.4 a (0.3)	11.3 ef (0.3)	10.1 c (0.1)	11.3 c (0.2)	39.9 a (0.3)	44.1 a (0.4)	44.3 a (0.4)
Phofu	86.1 g (0.0)	86.4 e (0.1)	85.7 g (0.1)	10.9 de (0.5)	11.7 g (0.2)	12.4 ef (0.2)	81.1 j (0.2)	81.0 h (0.3)	81.2 i (0.1)
Sefofu	86.8 h (0.1)	86.2 e (0.1)	85.6 g (0.1)	10.3 c (0.3)	11.4 fg (0.2)	12.1 de (0.2)	74.4 h (0.5)	75.6 f (0.4)	74.5 g (0.1)
Segaolane	83.7 e (0.1)	84.6 d (0.1)	82.4 e (0.2)	9.7 ab (0.1)	10.3 cd (0.2)	11.2 c (0.1)	68.6 f (0.3)	70.0 e (0.4)	68.5 f (0.6)
SNK	81.6 c (0.3)	84.5 d (0.1)	81.5 d (0.4)	11.5 fg (0.3)	10.6 de (0.1)	11.4 c (0.2)	65.6 e (0.2)	68.6 d (0.2)	64.9 d (0.6)
Town	82.6 d (0.2)	84.6 d (0.3)	81.7 d (0.2)	11.8 g (0.3)	10.7 e (0.4)	11.4 c (0.1)	64.6 d (0.2)	68.3 d (0.6)	64.6 d (0.5)
Mean	83.2 b (5.1)	84.6 c (3.5)	82.4 a (4.3)	10.6 a (0.8)	10.8 b (0.8)	11.6 c (0.7)	68.8 a (12.4)	70.5 b (10.8)	68.6 a (11.3)
Mean (excluding weathered grains)	85.6 b (2.4)	86.2 c (1.3)	84.3 a (2.1)	10.7 a (0.8)	11.1 b (0.5)	11.9 c (0.5)	74.4 a (7.1)	75.6 b (5.3)	73.7 a (7.1)

[a] Where the means for a particular color property have different letter notations, they are significantly different from each other ($P < 0.05$).
[b] Figures in brackets are standard deviations.
[c] Weathered grain.

HP and RM meals were not significantly (P <0.05) different (Table VI). This may be because, unlike ADHM, the other two processes had a tempering stage that probably stained the grain endosperm by leaching dark-colored pigments from pericarps of the pigmented sorghum types. The color intensity (chroma) of the meals was lowest with HP and highest with RM. This could be associated with the concentration of the dark-colored pigments in the meal and therefore with the level of bran contamination of the meal. Excluding the weathered sorghum types improved the lightness color (increased L^* and h^*) of the meals with all the milling processes and maintained the same color ranking order obtained for all 12 sorghum types, indicating that weathered grains affect meal color in the same manner for all milling processes.

Sorghum type also caused significant variations in the color properties of the meals (Table VI). Light-colored sorghum types, such as BSH1, LARSVYT, and Phofu produced light-colored meals (i.e., higher L^* and h^*_{ab} values) regardless of the milling process used. In contrast, pigmented sorghum types, such as SNK and Town, produced meals with comparatively lower L^* and h^*_{ab} values, indicating that the dark pericarp pigments discolored the meals. Meal lightness (L^*) correlated positively with the color characteristics (L^*, C^*_{ab}, and h^*_{ab}) of the whole grain (Table V), indicating that the color properties of the final meal depend on the color of the whole grain. Unlike the light-colored types, pigmented sorghum types produced meals with higher chroma values, reflecting the higher color intensity contributed by the colored pigments (Table VI). There were significant positive correlations (Table V) between meal C^*_{ab} and meal ash content (bran contamination) with ADHM and RM (r = 0.83, P <0.01 and r = 0.74, P <0.05, respectively). The weathered grains (Mmabaitse, Kanye standard, and Marupantsi) generally gave meals with low L^* values

Table VII. Effects of sorghum type and milling process on the ash content of sorghum meal[a,b]

	Ash Content of the Meal (g kg^{-1})				
Sorghum Type	Hand Pounding	Abrasive Decortication and Hammer Milling	Main Sorghum Roller Milling	Main Sorghum Type Effect	Type Effect[c]
BSH1	10.1 ef (0.3) [49.2]	13.8 f (0.2) [70.1]	14.9 f (0.4) [74.3]	12.9 e (2.2) [64.2]	12.9 d (2.2)
Kanye Standard[d]	9.1 cd (0.2) [61.7]	10.0 a (0.4) [62.2]	10.4 a (0.3) [78.2]	9.8 a (0.6) [67.0]	…
LARSVYT	8.2 a (0.3) [36.3]	13.1 e (0.3) [72.8]	14.2 e (0.1) [81.5]	11.9 cd (2.7) [62.4]	11.9 c (2.7)
Lekgeberwa	8.8 bc (0.2) [56.2]	11.1 b (0.3) [64.4]	12.5 b (0.2) [77.5]	10.8 b (1.6) [66.0]	10.8 a (1.6)
Buster	8.4 ab (0.2) [43.3]	12.3 d (0.1) [64.3]	13.3 cd (0.7) [78.8]	11.3 bc (2.3) [61.4]	11.3 b (2.3)
Marupantsi[d]	9.0 cd (0.2) [57.9]	10.1 a (0.2) [63.8]	10.4 a (0.2) [75.3]	9.9 a (0.7) [66.0]	…
Mmabaitse[d]	12.9 g (0.4) [57.0]	11.0 b (0.1) [45.5]	13.3 cd (0.4) [69.9]	12.4 de (1.1) [58.0]	…
Phofu	10.4 f (0.2) [55.5]	12.1 d (0.3) [72.1]	12.7 bc (0.5) [75.1]	11.8 cd (1.1) [67.7]	11.8 c (1.1)
Sefofu	9.0 cd (0.2) [47.4]	12.4 d (0.2) [62.7]	13.8 de (0.6) [77.8]	11.7 cd (2.1) [62.6]	11.7 c (2.1)
Segaolane	9.2 d (0.4) [56.0]	12.2 d (0.2) [78.7]	12.8 bc (0.5) [84.5]	11.4 bc (1.7) [72.7]	11.4 b (1.7)
SNK	9.2 cd (0.2) [40.8]	11.2 b (0.2) [52.9]	12.3 b (0.3) [71.7]	10.9 b (1.4) [54.5]	10.9 a (1.4)
Town	9.8 de (0.6) [43.2]	11.6 c (0.4) [51.4]	14.1 e (0.4) [75.2]	11.8 cd (1.9) [55.8]	11.8 c (1.9)
Main milling effect	9.5 a (1.2) [50.4]	11.8 b (1.1) [63.4]	12.9 c (1.4) [76.6]	11.4 [63.2]	…
Main milling effect (excluding weathered grain)	9.2 a (0.8)	12.2 b (0.8)	13.4 c (0.9)	…	11.6

[a] Figures in parentheses are standard deviations. Figures in square brackets are amounts (%) of whole-grain ash retained in the meal.
[b] Means in columns with different letter notations are significantly different at P <0.05.
[c] Excluding weathered grain.
[d] Weathered grain.

Table VIII. Effects of sorghum type and milling process on the oil content of sorghum meal[a,b]

	Oil Content of the Meal (g kg^{-1})				
Sorghum Type	Hand Pounding	Abrasive Decortication and Hammer Milling	Roller Milling	Main Sorghum Type Effect	Main Sorghum Type Effect[c]
BSH1	16.8 b (1.2) [36.9]	25.3 g (1.4) [57.9]	25.6 d (0.5) [57.5]	22.6 cd (4.4) [50.7]	22.6 cd (4.4)
Kanye Standard[d]	19.0 d (0.9) [43.9]	21.4 cd (0.1) [45.4]	22.2 b (0.2) [56.9]	20.9 a–c (1.5) [48.7]	…
LARSVYT	24.0 g (0.2) [46.0]	20.4 bc (0.9) [49.0]	23.1 bc (0.4) [57.4]	22.5 cd (1.7) [51.0]	22.5 cd (1.7)
Lekgeberwa	24.6 g (0.5) [45.9]	34.4 i (0.1) [58.9]	36.2 h (1.1) [66.3]	31.7 f (5.4) [57.2]	31.7 fg (5.4)
Buster	15.5 a (0.7) [32.8]	23.6 f (0.4) [50.6]	26.8 e (0.8) [65.1]	22.0 b–d (5.0) [49.1]	22.0 bc (5.0)
Marupantsi[d]	19.5 de (0.5) [43.0]	22.8 ef (0.4) [49.4]	23.8 c (0.7) [59.1]	22.0 b–d (2.0) [50.3]	…
Mmabaitse[d]	20.2 e (0.4) [50.1]	16.7 a (0.8) [38.8]	20.6 a (0.3) [60.7]	19.1 a (1.9) [50.2]	…
Phofu	18.0 c (0.2) [43.2]	19.9 b (0.8) [53.5]	23.7 c (1.3) [63.1]	20.5 ab (2.6) [53.0]	20.5 a (2.6)
Sefofu	22.6 f (0.8) [42.6]	31.7 h (1.2) [57.4]	34.0 g (0.5) [68.6]	29.5 e (5.2) [56.5]	29.5 f (5.2)
Segaolane	22.2 f (0.5) [45.9]	31.9 h (0.6) [69.9]	30.3 f (0.5) [67.9]	28.1 e (4.5) [60.9]	28.1 e (4.5)
SNK	17.2 bc (0.3) [30.0]	25.6 g (0.3) [47.4]	25.7 d (0.5) [58.6]	22.9 d (4.2) [44.8]	22.9 d (4.2)
Town	18.0 c (0.5) [32.4]	21.8 de (1.2) [39.4]	25.3 d (0.6) [55.1]	21.7 b–d (3.2) [41.9]	21.7 b (3.2)
Main milling effect	19.8 a (2.9) [41.1]	24.6 b (5.3) [51.5]	26.4 c (4.6) [61.4]	23.6 [51.2]	…
Main milling effect (excluding weathered grain)	19.9 a (3.3)	26.1 b (5.2)	27.9 c (4.5)	…	24.6

[a] Figures in parentheses are standard deviations. Figures in square brackets are amounts (%) of whole-grain oil retained in the meal.
[b] Means in columns with different letter notations are significantly different at P <0.05.
[c] Excluding weathered grain.
[d] Weathered grain.

and correspondingly low hue values, showing that weathering caused darkening of the meals. However, ADHM produced slightly lighter meals from these sorghum types, again indicating that the tempering process aggravated the color problems of weathered and pigmented grains.

Ash Content of the Meals

Ash content is an indicator of the level of bran contamination in milled products (12). The meal ash content obtained with each of the milling processes was lower than the ash content of the whole grains (Tables III and VII), indicating that substantial amounts of the aleurone tissue and the germ (the main location of the minerals [17]) were removed, as expected. The lowest meal ash contents were obtained with HP and the highest with RM (Table VII). HP retained 36–62% of the whole-grain ash content in the meal, with the amount retained depending on the sorghum type. In comparison, ADHM and RM retained 46–79% and 70–84% ash content, respectively (Table VII). Excluding the weathered grain types did not affect meal ash content substantially, indicating that slight weathering had no serious effect on the efficiency of bran separation.

The lowest meal ash contents were obtained from the sorghum types Marupantsi and Kanye standard, while the highest were from BSH1 and Mmabaitse. These variations can be accounted for by the amount of ash originally present in the whole grain of each sorghum type (Table III). There were significant correlations (Table V) between whole-grain ash and the ash content of the meals obtained with ADHM (r = 0.65, P <0.05) and RM (r = 0.91, P <0.001) but not those obtained with HP. Pericarp thickness also correlated significantly with ash content for ADHM (r = –0.59, P <0.05) and RM (r = –0.57, P <0.10). The fact that, for HP, meal ash content did not correlate significantly with whole-grain ash and pericarp thickness (unlike for ADHM and RM) suggests that HP was effective in removing the aleurone tissue and the germ in all the sorghum types, whereas this was not the case with ADHM and RM. Meal ash content also correlated significantly and negatively with grain visual hardness for ADHM (r = –0.55, P <0.10), and with grain abrasive hardness for HP (r = –0.62, P <0.05), indicating that the softer the grain, the more the meal was contaminated with bran.

Oil Content of the Meals

As with ash content, the meal oil content obtained with all the milling processes was also lower than the whole-grain oil content, because the oil is concentrated in the germ (17) (Tables III and VIII). HP gave lower meal oil contents than ADHM and RM (Table VIII). Oil content of the meal is of importance because sorghum oil is high in unsaturated fatty acids (17), which are prone to oxidation and therefore could limit meal shelf life. About 30–50% of the oil originally present in the whole grain was retained in the meal with HP. However, ADHM and RM retained rather more, 39–70% and 55–69%, respectively (Table VIII). The amount of oil retained was correlated positively with extraction rate, indicating that high meal purity was achieved at the expense of extraction rate. Also as with ash, excluding data on weathered grains did not affect the oil content of the meals considerably, indicating that weathering had little or no effect on the extent of degermination of the grains, and hence on the oil content of the meals. The lowest oil contents were obtained with Mmabaitse and Phofu, whereas Lekgeberwa and Sefofu gave the highest oil in their meals. As with ash, these meal oil contents were related to the whole-grain oil contents of the respective sorghum types (Table III). There were significant correlations (Table V) between meal oil and whole-grain oil with ADHM and RM (r = 0.92 and 0.93, respectively, P <0.001). In addition, meal oil contents obtained with these two processes had lower but significant correlations with abrasive grain hardness (r = 0.58, P <0.05 and r = 0.59, P <0.05 with ADHM and RM, respectively), indicating that the harder the grain, the less germ was removed.

Protein Content of the Meals

Unlike meal ash and oil content, the meal protein content obtained with all the milling processes was higher than the whole-grain protein content (Tables III and IX) because the grain pericarp, which is relatively poor in protein, was removed. According to Taylor and Schussler (21), approximately 80, 16, and 3% of whole-grain protein is contained in the endosperm, germ, and pericarp, respectively. As expected, the amount of protein retained in the meal was a consequence of the extraction rate. Thus, RM, which had the highest extraction rate, correspondingly retained the highest amount (93.7%)

Table IX. Effects of sorghum type and milling process on the protein content of sorghum meal[a,b]

	Protein Content of the Meal (g kg^{-1})				
Sorghum Type	Hand Pounding	Abrasive Decortication and Hammer Milling	Roller Milling	Main Sorghum Type Effect	Main Sorghum Type Effect[c]
BSH1	147.6 e (1.0) [90.8]	133.2 d (1.3) [85.5]	145.8 d (0.4) [91.9]	142.2 e (6.8) [89.4]	142.2 d (6.8) [89.4]
Kanye Standard[d]	132.7 c (1.2) [89.9]	126.5 bc (0.6) [78.7]	125.9 b (1.1) [94.6]	128.3 bc (3.3) [87.7]	…
LARSVYT	147.9 e (0.2) [87.9]	122.1 b (0.4) [91.0]	120.7 a (0.7) [92.9]	130.2 c (13.3)[91.5]	130.2 c (13.3)[91.5]
Lekgeberwa	143.6 d (2.1) [95.2]	148.5 f (3.2) [90.4]	148.9 de (1.6) [96.9]	147.0 f (3.3) [94.2]	147.0 e (3.3) [94.2]
Buster	116.2 a (0.7) [81.5]	114.2 a (1.4) [81.1]	117.7 a (1.2) [94.8]	116.0 a (1.8) [85.7]	116.0 a (1.8) [85.7]
Marupantsi[d]	134.0 c (0.2) [79.2]	139.9 e (0.6) [81.1]	140.5 c (1.0) [93.4]	138.1 d (3.1) [84.5]	…
Mmabaitse[d]	163.4 g (0.7) [79.8]	158.8 g (1.1) [72.6]	162.8 f (0.9) [94.5]	161.7 h (2.3) [83.6]	…
Phofu	127.1 b (0.7) [84.0]	127.0 c (1.5) [93.8]	127.5 b (1.8) [93.4]	127.2 b (1.2) [90.4]	127.2 b (1.2) [90.4]
Sefofu	173.0 h (0.2) [88.1]	165.9 h (1.7) [81.0]	173.0 g (1.4) [94.2]	170.6 i (3.7) [88.1]	170.6 g (3.7) [88.1]
Segaolane	159.6 f (2.4) [93.3]	147.0 f (1.8) [91.2]	150.3 e (1.5) [95.3]	152.3 g (5.9) [93.3]	152.3 f (5.9) [93.3]
SNK	144.5 de (1.0) [70.7]	137.8 de (1.0) [71.8]	145.9 d (0.3) [93.7]	142.7 e (3.8) [78.6]	142.7 d (3.8) [78.6]
Town	142.8 d (1.1) [74.7]	140.0 e (1.2) [73.6]	140.6 c (0.2) [89.0]	141.1 e (1.5) [79.1]	141.1 d (1.5) [79.1]
Main milling effect	144.4 c (15.5) [84.6]	138.4 a (14.7) [82.6]	141.6 b (16.2) [93.7]	141.5 [87.2]	…
Main milling effect (excluding weathered grain)	144.7 c (15.9)	137.3 a (15.0)	141.2 b (16.5)	…	

[a] Figures in parentheses are standard deviations. Figures in square brackets are amounts (%) of whole-grain protein retained in the meal.
[b] Means in columns with different letter notations are significantly different at P <0.01.
[c] Excluding weathered grain.
[d] Weathered grain.

of protein in the meal (Table IX). In comparison, HP and ADHM, which gave equal extraction rates, retained similar but lower amounts of protein in the meal (84.6 and 82.6%, respectively).

The protein content in sorghum has been shown to correlate with grain hardness (6). It was therefore expected that grain hardness would significantly correlate with the meal protein content, but surprisingly that was not found to be the case.

Particle Size Distribution of the Meals

Figure 4 shows that RM produced finer meals, with all the particles passing through a 710-µm sieve opening. In comparison, HP produced much coarser meals, with approximately 50% of the particles falling in the size range 1,180–1,700 µm. ADHM meals were slightly finer than HP meals but coarser than meals obtained with RM. Grain type affected particle size distribution slightly with RM but more with ADHM; the effect was even more pronounced with HP. Differences in the particle sizes were more evident in the size range above 500 µm, with the more-corneous sorghum type (BSH1) giving a higher proportion of the larger meal particles. This confirms earlier reports that hard-endosperm sorghum grains produce relatively coarser meals when subjected to the same milling conditions (21).

CONCLUSIONS

This study confirms that the physicochemical properties of sorghum grain generally affect the quality of meal produced by milling. Sorghum types with hard endosperm are advantageous for achieving high extraction rates with HP and ADHM milling processes but apparently not with RM. Generally, all the milling processes produce darker meals from sorghum types with pigmented pericarps, and weathered grains tend to darken the color of the meals.

Milling process affects sorghum meal quality. HP produces coarser meals with low ash, low oil, and high protein concentration but with low extraction rate. ADHM produces less-coarse meals with slightly higher ash and oil content than HP, but it gives lighter-colored meals. RM produces meals with slightly darker color and higher ash and oil contents than ADHM, but this slight loss in meal purity is offset by a substantial gain (11%) in extraction rate. Because of its higher extraction rate and production throughput, RM holds great potential as a milling process for sorghum.

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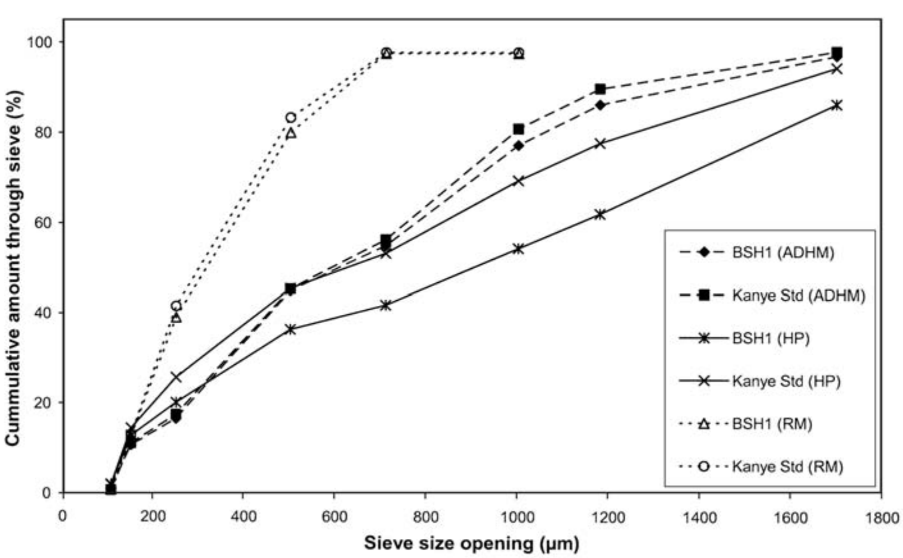

Fig. 4. Effect of milling process on the particle size distribution of sorghum meals produced from corneous (BSH1) and intermediate (Kanye Std.) endosperm grains by hand pounding (HP), abrasive decortication-hammer milling (ADHM), and roller milling (RM).

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