3 RESEARCH

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

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ABSTRACT

Limited knowledge about the effects of sorghum type and milling process on the quality of sorghum meal hampers expansion of sorghum utilisation as food. Twelve sorghum types with diverse physico-chemical 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 with ADHM and HP, but not with RM. Pericarp thickness and whole grain oil content were significantly correlated with meal purity with RM and ADHM. RM gave the darkest meal, followed by HP. Grain weathering significantly affected extraction rate with ADHM but not with RM and HP. RM produced fine meals with slightly more ash and oil, and gave higher protein and higher meal extraction (84 g/100 g compared to 76 g/100 g) than ADHM. HP produced coarser meals with the lowest ash and oil contents, but gave the lowest extraction rates (74 g/100 g). Overall, RM seems advantageous over ADHM and HP for sorghum milling because of its much higher extraction rate and production throughput.

Keywords: sorghum, meal, flour, milling

3.1.1 INTRODUCTION

Sorghum [*Sorghum bicolor* (L.) Moench] is an important cereal crop in the developing countries of Africa and Asia (Dendy 1995). In Africa, sorghum ranks second in production, after maize. It is grown predominantly by subsistence farmers for household food security (Rohrbach 2003, Taylor 2003).

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 commonly 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, mechanised milling, commonly using the Prairie Research Laboratory (PRL) type abrasive dehuller (decorticator) and a hammer mill, has become popular for commercial small- and medium-scale sorghum meal production throughout southern Africa (Rohrbach 2003, Taylor 2003). However, this milling system is characterised by high milling losses, inconsistent quality and low production rates (Taylor 2003, Taylor and Dewar 2001).

The lack of an efficient sorghum milling technology has been identified as a major constraint to the establishment of a vibrant sorghum food industry (Taylor 2003). According to Taylor and Dewar (2001), 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 (Taylor and Dewar 2001).

Several studies have reported the advantages of tempering sorghum prior to roller milling (Cecil 1992, Gomez 1993, Hammond 1996). Cecil (1992) described a semi-wet milling process which entailed tempering the grain to 26% at 60ºC for 6 hr before milling. This process was reported to improve degermination and bran separation, but resulted in poor extraction rates and high residual moisture in flour. In another study, tempering the grain to 16% at 4ºC for 24 hr improved extraction rates and reduced final meal residual moisture to microbiologically safe levels (Gomez 1993).

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, there is limited knowledge on 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.

3.1.2 MATERIALS AND METHODS

3.1.2.1 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) were introduced over the past ten years. All the samples were harvested during the 2004 crop season and were stored at 7°C until they were used.

3.1.2.2 Grain characterisation

Kernel size was characterised by sieving 100 g samples of clean grain through two test sieves with 3.35 mm and 2.80 mm openings (Gomez et al 1997). 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 (Rooney and Miller 1982). Kernel hardness was evaluated using a Tangential Abrasive Dehulling Device (TADD), fitted with a 60 grit sand paper (Norton R284 metalite, Saint-Gobain Abrasives, Isando, South Africa) as described by Reichert et al (1982) 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 stereo-microscope. Thousand kernel weight (TKW) was determined by weighing 1000 randomly counted unbroken kernels. Colour of the whole grains was assessed visually (Rooney and Miller 1982), 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 a 0.8 mm opening screen, using a tristimulus colour 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 colour of the meal samples (22). Glume colour was assessed by observing the inside of the glume after peeling it from the kernel (Rooney and Miller 1982). The presence or absence of a pigmented testa was established using the Bleach Test, performed as described by Taylor (2001).

Weathered grain was estimated as percentage of kernels with visible mould patches. Moisture content was determined by oven drying (AACC (2000) method 44-15A). Total ash was determined using AACC (2000) method 08-01. Oil content was determined by petroleum ether extraction (AACC (2000) method 30-25). Protein (N x 6.25) was determined by the Dumas combustion method.

3.1.2.3. Hand pounding

Three adult ladies with hand-pounding experience were employed to pound 4 kg of each sorghum type in a typical traditional Botswana process (Fig. 2.3). Clean grain (2 kg) was soaked in about 2 kg 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 grits portions of a batch were blended together and spread on jute bags in the open sun to dry for 18-24 hr.

3.1.2.4. Abrasive decortication and hammer milling

A commercial mill in Botswana was engaged to mill the twelve 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 Fig. 3.1.1. 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 2.0 mm opening screen. Bran and meal were weighed to determine extraction rates. Each sorghum type was milled in duplicate.

Fig. 3.1.1. **PRL-type Abrasive decorticator (a) and hammer mill (b) similar to those used to produce abrasive decortication-hammer mill meal samples. Picture photographed in 2007 in Kanye, Botswana, by L Kwape.**

3.1.2.5. Optimising the roller milling process for sorghum

An assumption was made that because of their long existence, the hand pounding and abrasive decortication and hammer milling processes were already optimised in terms of meal quality. Therefore, only the roller milling process needed to be optimised before meaningful comparisons between all the processes could be drawn.

Conditioning (tempering)

To determine a suitable tempering period, 1 kg batches of Phofu (corneous endosperm grain) and SNK (intermediate endosperm texture) were tempered to 16% moisture in tightly closed plastic buckets at ambient temperature for 15 min and 18 hr. The grain was mixed at intervals of 5 min for the first 15 min, to evenly distribute the added water. The grain was roller milled immediately after tempering as described below, using top and bottom roller gaps of 0.80 mm and 0.30 mm, respectively.

Roll gaps

To determine suitable roller gap combinations, a two factor experiment involving the factors (i) sorghum type (corneous (Phofu)) and intermediate (SNK) endosperm texture) and (ii) top and bottom roller gap settings 0.80 mm/ 0.30 mm, 0.80 mm/ 0.40 mm, 0.80 mm/ 0.60 mm, 1.50 mm/ 0.30 mm, 1.50 mm/ 0.40 mm, and 1.50 mm/ 0.60 mm was carried out. For the gaps 0.80 mm/ 0.40 mm, 0.80 mm/ 0.60 mm, 1.50 mm/ 0.40 mm and 1.50 mm/ 0.60 mm, test sieves with opening sizes 1.4 mm and 1.7 mm were used to separate the endosperm and bran fractions. Extraction rates, particle size distribution, ash, and oil content of the meals were determined.

3.1.2.6. Roller milling

A small commercial roller mill (Fig. 3.1.2) with two pairs of fluted rolls and rated throughput of 500 kg/hr was used. The top rolls (coarse break rolls) had 8 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. All 12 sorghum types were milled using the ‘optimised’ roller milling process established from the above experiments. The process involved tempering 5000 g 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 mm and 0.30 mm, respectively. Feed rate was maintained constant. The milled stock was separated on vibrating sieves of mesh sizes 1.00 mm, 0.850 mm, 0.710 mm 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 the three meal streams were recombined for subsequent analysis. The meals were packed in sealed polythene “zipper-locked” bags and stored at 7°C until analysed.

Fig. 3.1.2. Two roll roller mill used to produce roller milled meal samples. Picture photographed in 2007 at the University of Pretoria, South Africa, by L Mugode.

3.1.2.7. Estimation of the amount of endosperm in ‘‘bran’’

To assess how efficient the milling processes were in separating the endosperm particles from the bran, the amount of endosperm material in bran was quantified. About 100 g (accurately weighed) of “Bran” samples obtained with the different milling processes were winnowed using a plastic tray to separate endosperm particles (dense material) from bran (less dense material). Weights of the two fractions were then determined.

3.1.2.8. 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 106, 150, 250, 500, 710, 1000 and 1400 μm. Meal colour, moisture, ash, and oil were determined as described above.

3.1.2.9. Statistical analysis

The data were analysed 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,Virginia, USA).

3.1.3. RESULTS AND DISCUSSION

3.1.3.1. Grain characterisation

As shown in Table II, all the sorghum types were medium in size, as classified according to Gomez et al (1997). Lekgeberwa was the lightest (20.7 g 1000 per kernels) and Sefofu was the heaviest (33.4 g per 1000 kernels). Fifty percent of the sorghum types had thick pericarps, while three had medium-thick and the rest thin. Visual hardness score 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 (1982), BSH1, LARSVYT, Lekgeberwa, Phofu and Sefofu were classified corneous while the rest were intermediate (Fig. 3.1.3 and Table II). The TADD decortication yield (abrasive kernel hardness) for all sorghum types, except Kanye standard and Mmabaitse, were above 80 g/100 g. Kanye standard and Mmabaitse were slightly weathered, which probably accounted for their lower decortication yield.

All the sorghum types had pigmented glumes, with five having purple glumes, four red and three siena. Grain colour (phenotype colour) ranged from white to red. Some white coloured sorghum types (Kanye standard, Mmabaitse and Segaolane) were mottled, indicating that they were weathered. Grain overall colour is genetically controlled and is affected by several factors, including pericarp colour and thickness, testa pigmentation (if present), and endosperm colour (Rooney and Miller 1982). 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 colours, whereas C^*_{ab} signifies the intensity of the colour. Hue is expressed on 360° grid, where 0° and 90° reflect bluish-red and yellow, respectively (Wrolstad et al 2005). The two lightest sorghum types were BSH1 and Phofu, whereas Mmabaitse was the darkest.

Fig. 3.1.3. **Cross sectional micrographs of the kernels of the twelve selected sorghum types grown in Botswana. FE – Floury Endosperm, CE – Corneous Endosperm, and P – Pericarp. Magnification – X3**

Table II
Physical Characteristics of Kernels of Twelve Selected Sorghum Types Grown in Botswana

Sorghum type	Grain Size (mm)[1]		Pericarp Thickness	Visual Hardness		TKW[3] (g)	TADD Decortication Yield at 4 min (g /100 g)	Glume colour	Grain colour[4]	Colour measurement (whole grain meal colour)		
	%>3.35	3.35 <%>2.80		Score[2]	Classification					L*	C^*_{ab}	h^*_{ab} (deg)
BSH1	45.4e (2.2)	50.0c (1.5)	Medium	1.7b (0.7)	Corneous	29.0i (0.4)	87.5f (0.7)	Siena	White	78.8f (0.2)	13.3g (0.02)	88.7ef (0.2)
Kanye standard[5]	66.5f (2.5)	30.5b (2.7)	Thick	3.7h (0.7)	Intermediate	30.4j (0.4)	79.3b (1.2)	Purple	Bright white, mottled	69.8b (0.6)	9.3a (0.2)	67.9b (0.6)
LARSVYT	6.4b (0.9)	86.1ij (0.7)	Thin	2.1c (0.6)	Corneous	22.8c (0.3)	85.4d (1.1)	Siena	White	75.6e (0.9)	13.4g (0.3)	88.6ef (0.7)
Lekgeberwa	0.7a (0.4)	82.9hi (4.1)	Thick	1.3a (0.4)	Corneous	20.7a (0.1)	86.4de (0.6)	Purple	White	75.9e (0.6)	12.4ef (0.1)	87.0e (0.3)
Buster	36.3d (3.7)	55.1d (2.5)	Thick	3.2fg (0.6)	Intermediate	27.2g (0.5)	87.5f (1.0)	Red	Red	71.9c (0.1)	13.2g (0.2)	69.9b (0.6)
Marupantsi[5]	37.2d (2.4)	59.9e (2.9)	Thick	2.9ef (0.7)	Intermediate	28.1h (0.5)	81.3c (1.0)	Purple	Reddish-white	71.5bc (1.1)	10.2b (0.3)	67.6b (0.9)
Mmabaitse[5]	14.1c (0.7)	79.4fg (0.2)	Thick	3.7h (0.7)	Intermediate	23.2d (0.1)	73.2a (0.8)	Purple	White, mottled	62.7a (0.7)	9.3a (0.8)	51.5a (4.4)
Phofu	8.7b (1.6)	82.6gh (1.2)	Medium	2.3c (0.4)	Corneous	21.9b (0.3)	86.4de (0.8)	Siena	White	76.9e (1.8)	12.6f (0.4)	90.4f (0.1)
Sefofu	76.2g (2.0)	21.4 a (1.8)	Medium	2.2c (0.4)	Corneous	33.4k (0.7)	87.3ef (0.9)	Red	White	76.8e (1.5)	11.9de (0.3)	81.4d (0.4)
Segaolane	3.1a (0.4)	89.3 j (1.0)	Thin	2.5cd (0.5)	Intermediate	24.3e (0.4)	88.1f (0.7)	Purple	Cream-white, mottled	73.7d (1.4)	10.5b (0.1)	76.9c (0.6)
SNK	14.8c (0.3)	78.8 f (0.7)	Thick	3.4 gh (0.6)	Intermediate	24.4e (0.4)	82.0c (1.3)	Red	Red	70.8bc (0.6)	11.3c (0.1)	68.7b (0.6)
Town	13.6c (0.9)	82.9hi (0.6)	Thin	2.7de (0.4)	Intermediate	25.5f (0.5)	86.4de (0.8)	Red	Red	72.4cd (0.6)	11.8d (0.2)	68.7b (0.3)

Figures in brackets are standard deviations
Figures in columns with different letter notations are significantly different at $P < 0.05$.
[1]All classified as medium-size in accordance with scheme described by Gomez et al (1997)
[2]Scale 1-5, with 1 denoting corneous (hard) and 5 representing floury (soft) endosperm
[3]Thousand Kernel Weight (TKW)
[4]Phenotype colour
[5]Grain partially weathered (Marupantsi – 19%, Kanye standard – 24% and Mmabaitse – 33%)

Table III
Protein, Oil and Ash Content (g/100 g Dry Basis) of Twelve Selected Sorghum Types Grown in Botswana

Sorghum type	Protein	Oil	Ash
BSH1	13.0f (0.3)	3.63e (0.06)	1.64g (0.03)
Kanye standard	11.4d (0.2)	3.34c (0.04)	1.14a (0.06)
LARSVYT	10.7b (0.2)	3.31c (0.05)	1.43d (0.02)
Lekgeberwa	13.1f (0.2)	4.67i (0.06)	1.38cd (0.04)
Buster	10.5a (0.1)	3.47d (0.02)	1.42cd (0.02)
Marupantsi	12.6e (0.2)	3.38c (0.05)	1.16a (0.09)
Mmabaitse	14.3h (0.1)	2.82a (0.04)	1.58fg (0.02)
Phofu	11.0c (0.2)	3.03b (0.09)	1.36bc (0.04)
Sefofu	15.6i (0.1)	4.20h (0.04)	1.50e (0.02)
Segaolane	13.7g (0.2)	3.87g (0.05)	1.32b (0.02)
SNK	13.0f (0.2)	3.65e (0.04)	1.43d (0.02)
Town	13.0f (0.1)	3.79f (0.03)	1.55ef (0.03)
Mean	12.6 (1.5)	3.98 (0.55)	1.41 (0.15)
Literature values[1]			
Range	4.4–21.1	2.1–7.6	1.3–3.3
Mean	11.4	3.3	1.9

Figures in brackets are standard deviations
Figures in columns with different letter notations are significantly different at P < 0.05
[1]Data from Serna-Saldivar and Rooney (1995)

As shown in Table III, mean protein content ranged from 10.5 g/100 g (Buster) to 15.6 g/100 g (Sefofu), while oil content varied from 2.82 g/100 g (Mmabaitse) to 4.20 g/100 g (Sefofu) among the sorghum types. Ash content ranged from 1.14 g/100 g (Kanye standard) to 1.64 g/100 g (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 (FAO 1995), and therefore, the low ash in these grains may be attributable to the phosphorus-deficient sandy soils of Botswana (Remmelzwaal 1989).

3.1.3.2. Optimisation of roller milling

For both sorghum endosperm types (corneous and intermediate) tempering for 15 min generally increased residual moisture of the meals to about 14.0 g/100 g (Fig. 3.1.4). Conditioning for longer (18 hr) caused equilibrium moisture distribution within the kernels, thus increasing residual moisture in the meals to over 15.0 g/100 g. Thus, tempering for 15 min selectively wetted the pericarp layers, leaving the endosperm relatively dry, while tempering for longer raised the moisture content of the endosperm as well. Residual moisture in the meal is of considerable importance with regard to the keeping quality, as high moisture content raises water activity of the meals, thus favouring rapid spoilage due to increased microbial activity. In a production setup tempering for 18 hr would necessitate drying of the product to 15% moisture or lower to conform to sorghum flour quality standards recommended by the Codex Alimentarius Commission (FAO and WHO 2006).

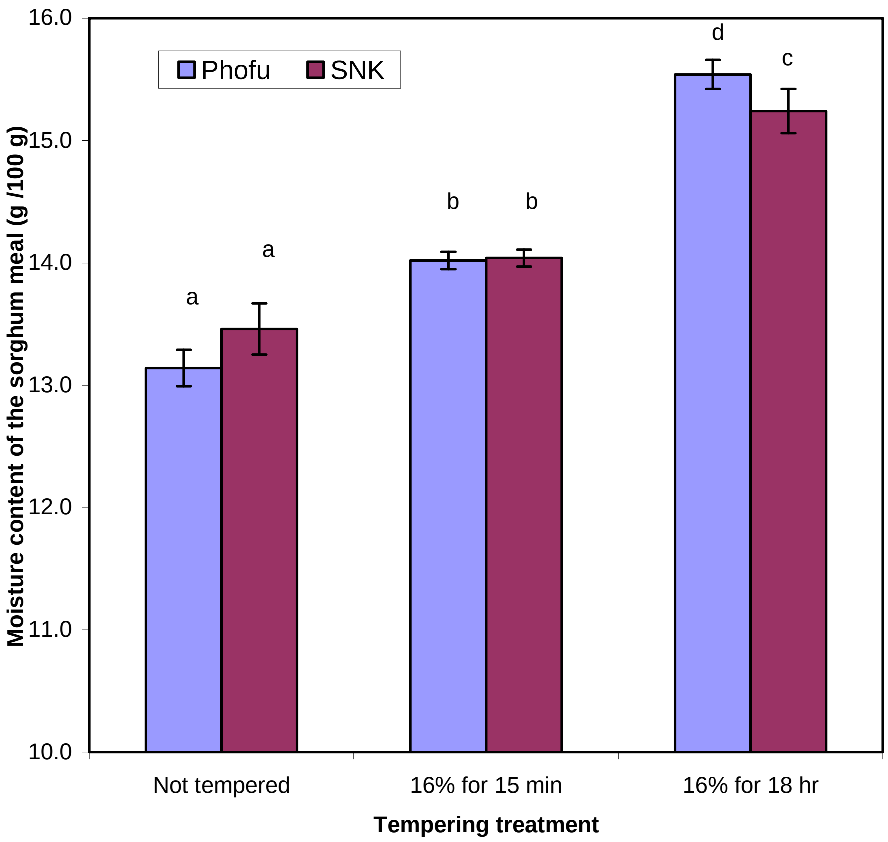

Figure 3.1.4. **Effect of tempering sorghum grain to 16% for 15 min and 18 hr on the moisture content of sorghum meal produced by two-stage roller milling (Data bars with different letter notations are significantly different at $p<0.05$ and the error bars are standard deviations).**

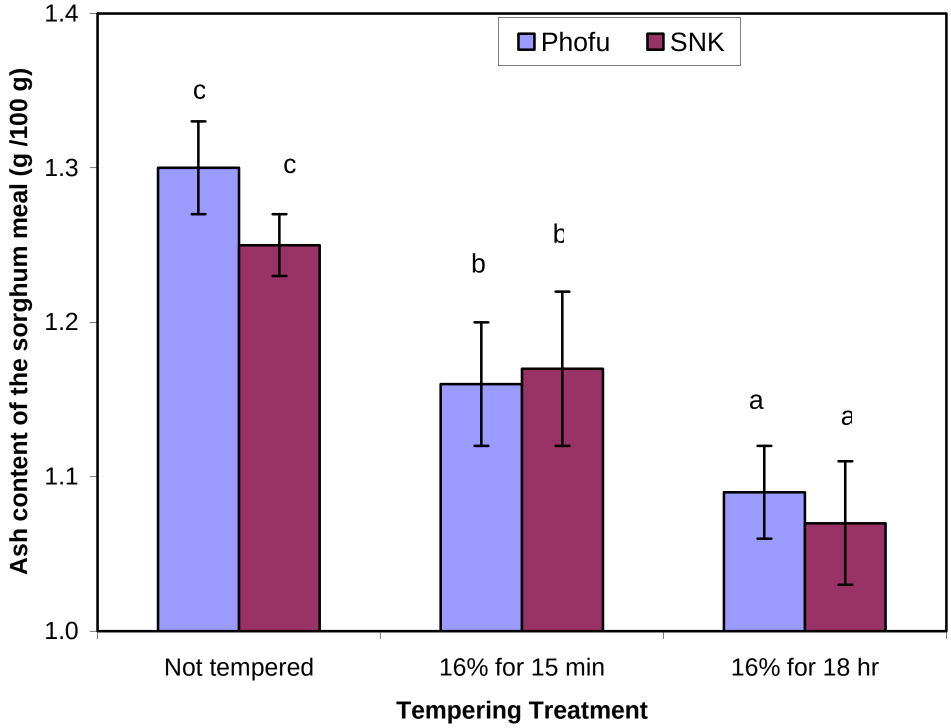

Fig. 3.1.5. **Effect of tempering sorghum grain to 16% for 15 min and 18 hr on the ash content of sorghum meal produced by two-stage roller milling (Data bars with different letter notations are significantly different at p<0.05 and the error bars are standard deviations).**

Tempering the grain for 15 min caused 6 to 11% (0.08 to 0.14 g/100 g) reduction in the ash content (Fig. 3.1.5), while longer conditioning reduced the ash content further by 6 to 9% (up to 0.1 g/100 g). This shows that separation of the bran from the endosperm was significantly enhanced by tempering. This agrees with the findings of Gomez (1993) that compared to non-tempered grain, tempering to 16% moisture significantly reduced the ash content in fine roller milled sorghum flour (<212 µm) by 20 to 45%. A similar trend was obtained for the oil content of the meals (Fig. 3.1.6). The 15 min tempering caused about 5% reduction in oil content, while longer tempering induced an additional 8% reduction. In studies by Gomez (1993), tempering reduced the oil content of the flours by about 14 to 57%, depending on the hardness of the grain. The reduction in meal oil content with tempering suggests that tempering the grain longer allowed water to penetrate the strong cementing layer that exists between the scutellum and the endosperm (described by Rooney (1973)) , thus facilitating degermination.

Thus, tempering for 18 hr was advantageous over the 15 min tempering period in that it produced more refined meals, but as stated, in practical milling this advantage could be offset by microbial growth problems.

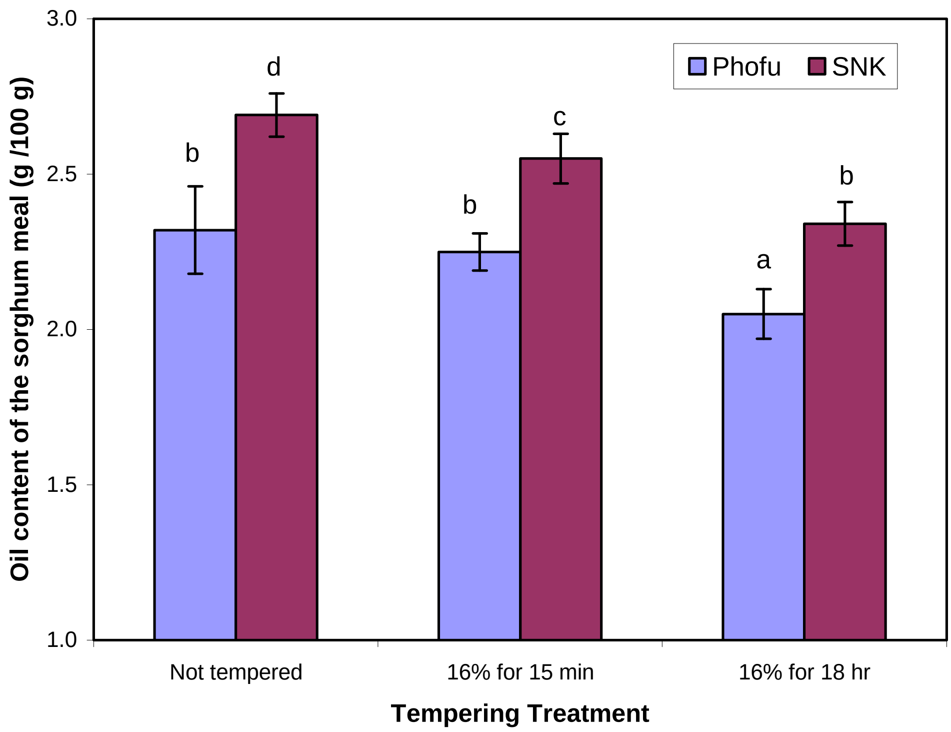

Fig. 3.1.6. **Effect of tempering sorghum grain to 16% for 15 min and 18 hr on the oil content of sorghum meal produced by two-stage roller milling (Data bars with different letter notations are significantly different at $p<0.05$ and the error bars are standard deviations).**

Generally, varying the gap of the top break rolls did not significantly affect the extraction rate of the grain (Fig. 3.1.7). For example, extraction rates for SNK obtained with the roller gaps 0.80 mm/ 0.30 mm and 1.50 mm/ 0.30 mm (about 84.0 g/100 g and 85.0 g/100 g, respectively) were not statistically different. Likewise, for each sieve opening size, no significant differences were found between mean ash content for both Phofu and SNK meals obtained with the 0.80 mm/0.40 mm and 1.50 mm/ 0.40 mm gaps (Fig. 3.1.7). Studies on wheat revealed that severe grinding in the early break rolls adversely affects flour ash and colour (Dexter and Martin 1986), hence, the fact that there were no significant differences in the ash content of the meals produced with the different top roll gaps possibly suggests that there was no severe grinding in the first set of rolls. Setting the top roller gap to 0.80 mm and 1.50 mm while keeping the bottom gap wide open (2.50 mm) produced stock (meal stream) which comprised mainly large broken kernels, which had pericarp fragments still attached. This showed that the break rolls were, as expected, just breaking the kernels open such that the endosperm could subsequently be scraped off in the succeeding rollers (Kent and Evers 1994).

Unlike the top roller gap, narrowing the bottom gap generally increased the extraction rate significantly. For example, for the 0.80 mm top gap and 1.4 mm sieve opening, reducing the bottom gap from 0.60 mm to 0.40 mm increased extraction rate for Phofu from about 71.0 g/100 g to 87.0 g/100 g (Fig. 3.1.7). This increase was possibly caused by the fact that more endosperm was released from the bran flakes using the narrow roller gap than with the wider gap. Thus, grinding the grain fine is probably critical for complete separation of bran from the endosperm to attain maximum extraction rates. Meals produced with the 0.30 mm bottom gap were satisfactorily sieved with a 1.0 mm sieve opening, but gap settings greater than 0.30 mm required sieves with larger openings (1.40 mm and 1.70 mm). As was expected, extraction rates increased with the increasing sieve opening (Fig. 3.1.7).

Changing both the top and bottom roll gaps did not affect the ash content of the meal (Fig. 3.1.8). However, the ash content increased with increasing sieve opening, particularly with the 1.40 mm and 1.70 mm sieve openings. This was significant ($p<0.05$) for the sorghum type SNK, probably indicating that the pericarp for SNK was more friable than that of Phofu, and hence was fragmenting excessively, causing more contamination of the meal. For example, for the 0.80 mm/ 0.40 mm roller gaps (Fig. 3.1.8), the 1.40 mm and 1.70 mm sieve openings produced SNK meals which differed significantly in ash content (1.25 g/100 g and 1.32 g/100 g, respectively), but not for Phofu. A similar trend was observed for the roll gaps 0.80 mm/ 0.60 mm. For the gaps 1.50 mm/ 0.60 mm, the effect was significant for both sorghum types, showing that the size difference between bran flakes and the endosperm particles obtained with these gaps did not permit effective separation of bran with the 1.70 mm sieve opening.

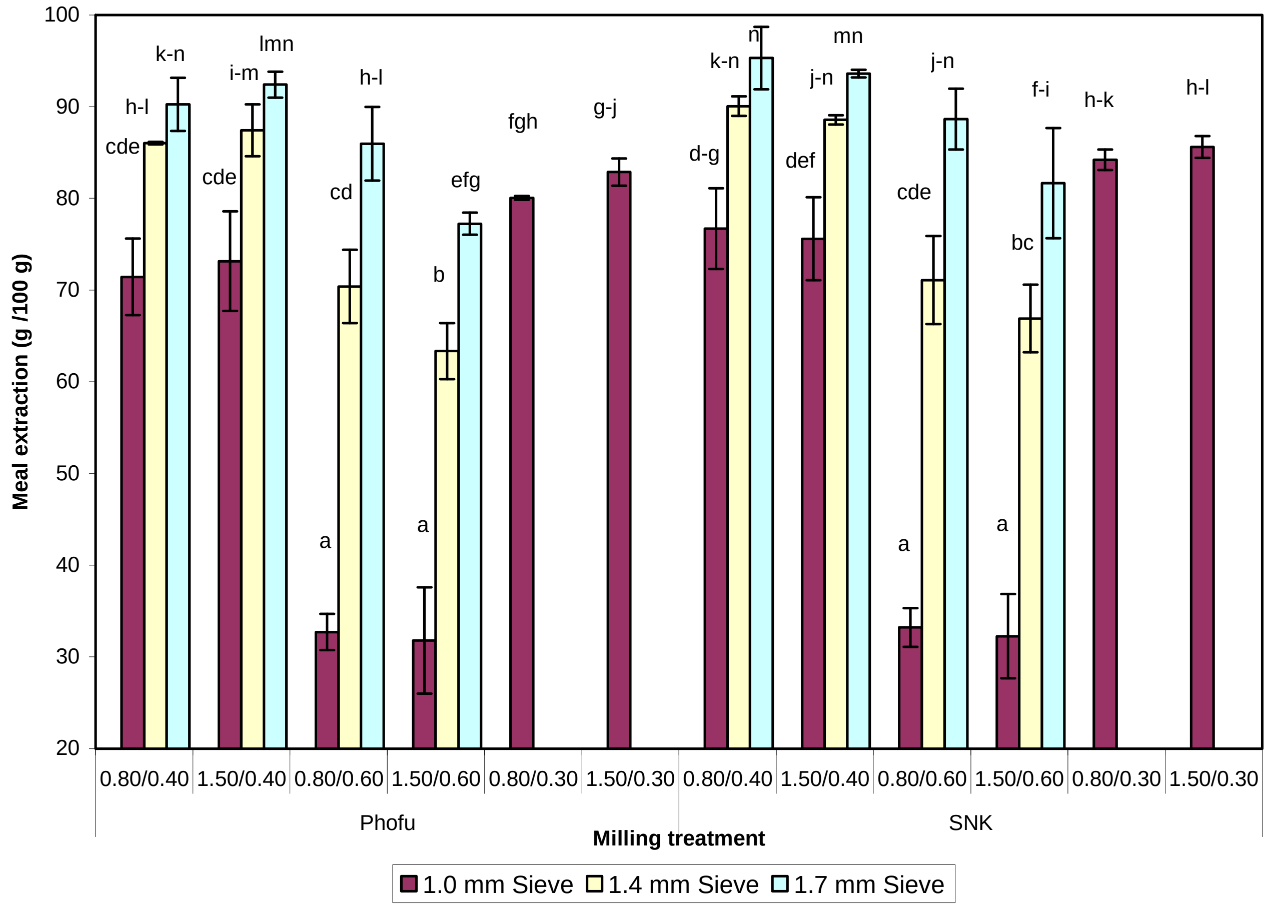

Fig. 3.1.7. **Effect of roll gap size (first number top gap, second number bottom gap) and sieve opening on the extraction rates of corneous (Phofu) and intermediate (SNK) endosperm sorghum types milled using a two-stage roller mill (Data bars with different letter notations are significantly different at p<0.05 and the error bars are standard deviations).**

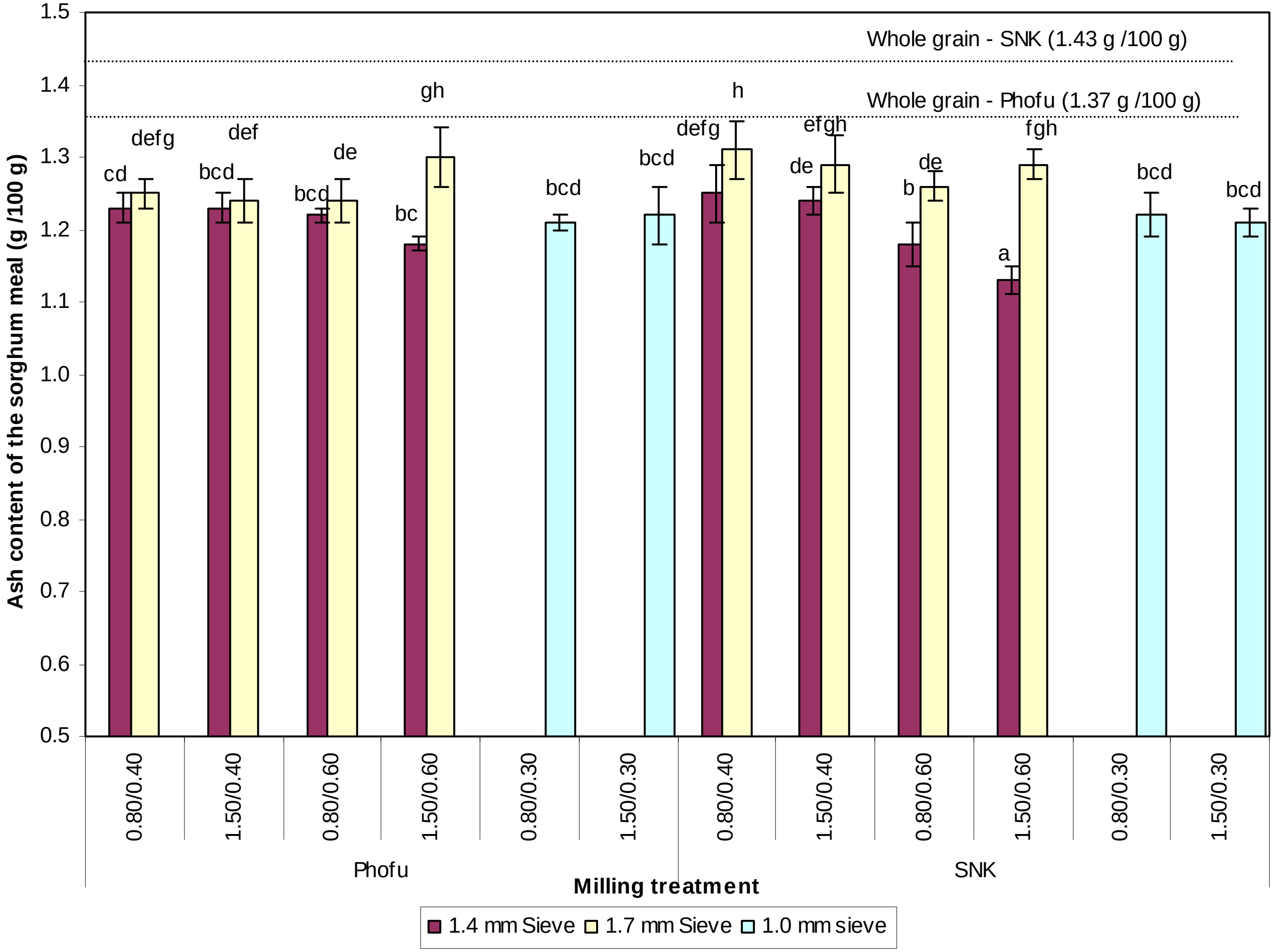

Fig. 3.1.8. **Effect of roll gap size (first number top gap, second number bottom gap) and sieve opening on the ash content of meals produced from corneous (Phofu) and intermediate (SNK) endosperm sorghum types milled using a two-stage roller mill (Data bars with different letter notations are significantly different at p<0.05 and the error bars are standard deviations).**

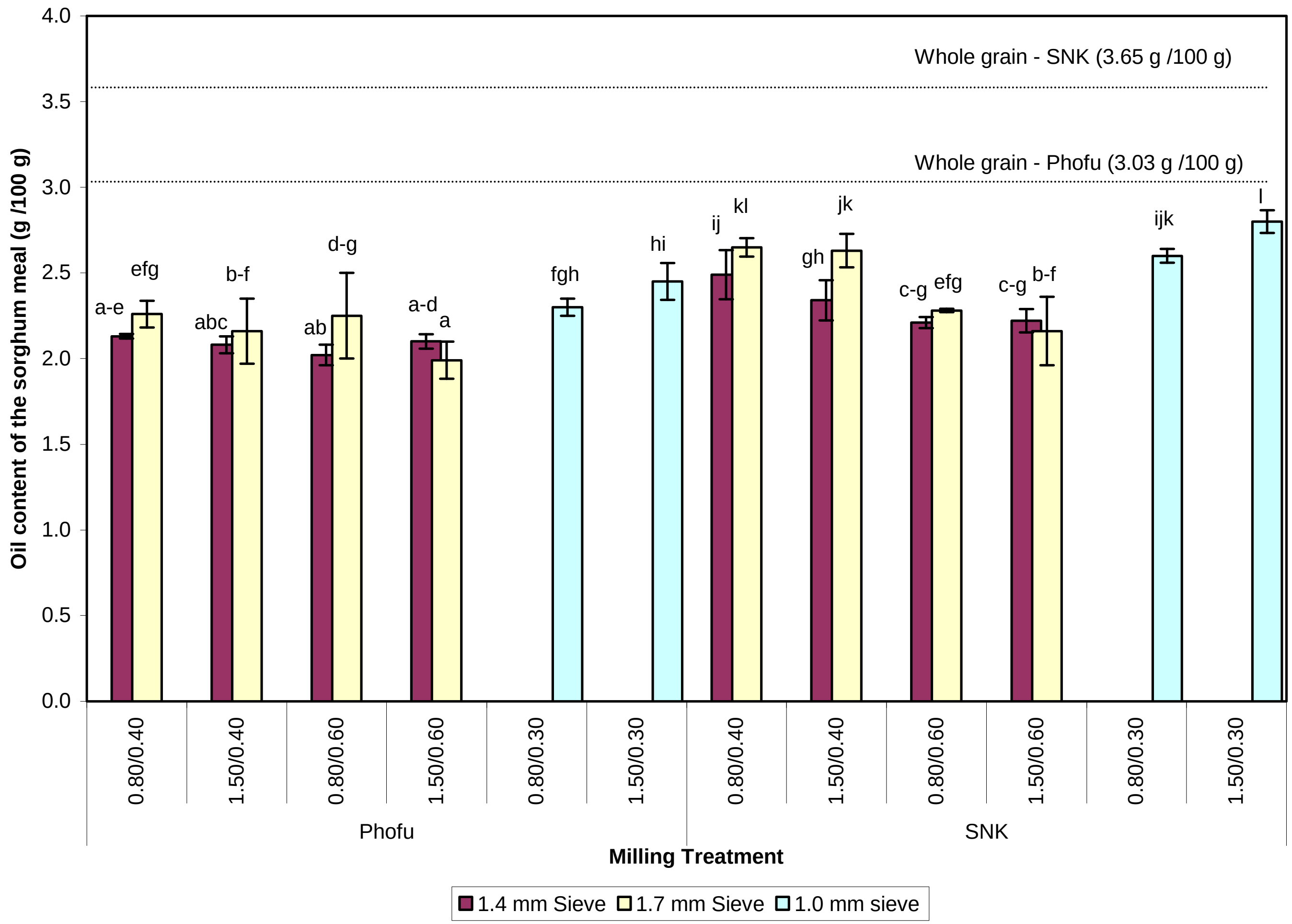

Fig. 3.1.9. **Effect of roll gap size (first number top gap, second number bottom gap) and sieve opening on the oil content of meals produced from corneous (Phofu) and intermediate (SNK) endosperm sorghum types milled using a two-stage roller mill (Data bars with different letter notations are significantly different at p<0.05 and the error bars are standard deviations).**

Oil content of the meal generally increased with the decreasing bottom roll gap (Fig. 3.1.9). For example, mean oil content for SNK increased from 2.05 g/100 g to 2.54 g/100 g when the bottom roll gap was reduced from 0.60 mm to 0.30 mm. This trend probably suggests that milling with the narrow gap caused crushing of the germ, such that small germ fragments escaped sieving and contaminated the meal. The meal oil content generally increased with the increasing sieve opening, especially for the bottom roll gaps 0.40 mm and 0.60 mm.

Fig. 3.1.10 shows that increasing the bottom roll gap from 0.30 mm to 0.60 mm increased the size of the meal particles, and substantially reduced the proportion of very fine (<500 µm) particles. The meals produced were compared with hand pounded and abrasively decorticated-hammer milled meals, and it was observed that the 0.30 mm roll gap produced meals that closely matched particle sizes of meals of these milling processes in the range below 500 µm (Fig. 3.1.10), but differed in that all the roller milled particles were smaller than 1180 µm. In comparison, approximately 35% and 22% of the hand pounded and hammer milled meal particles, respectively, were in the size range 1180 µm to 1700 µm.

Based on the above findings, a roller milling process which entailed conditioning grain to 16% moisture for 15 min, followed by milling with top and bottom gap settings of 0.80 mm and 0.30 mm, respectively, and sieving with a 1.0 mm sieve opening, was adopted for the subsequent milling trials.

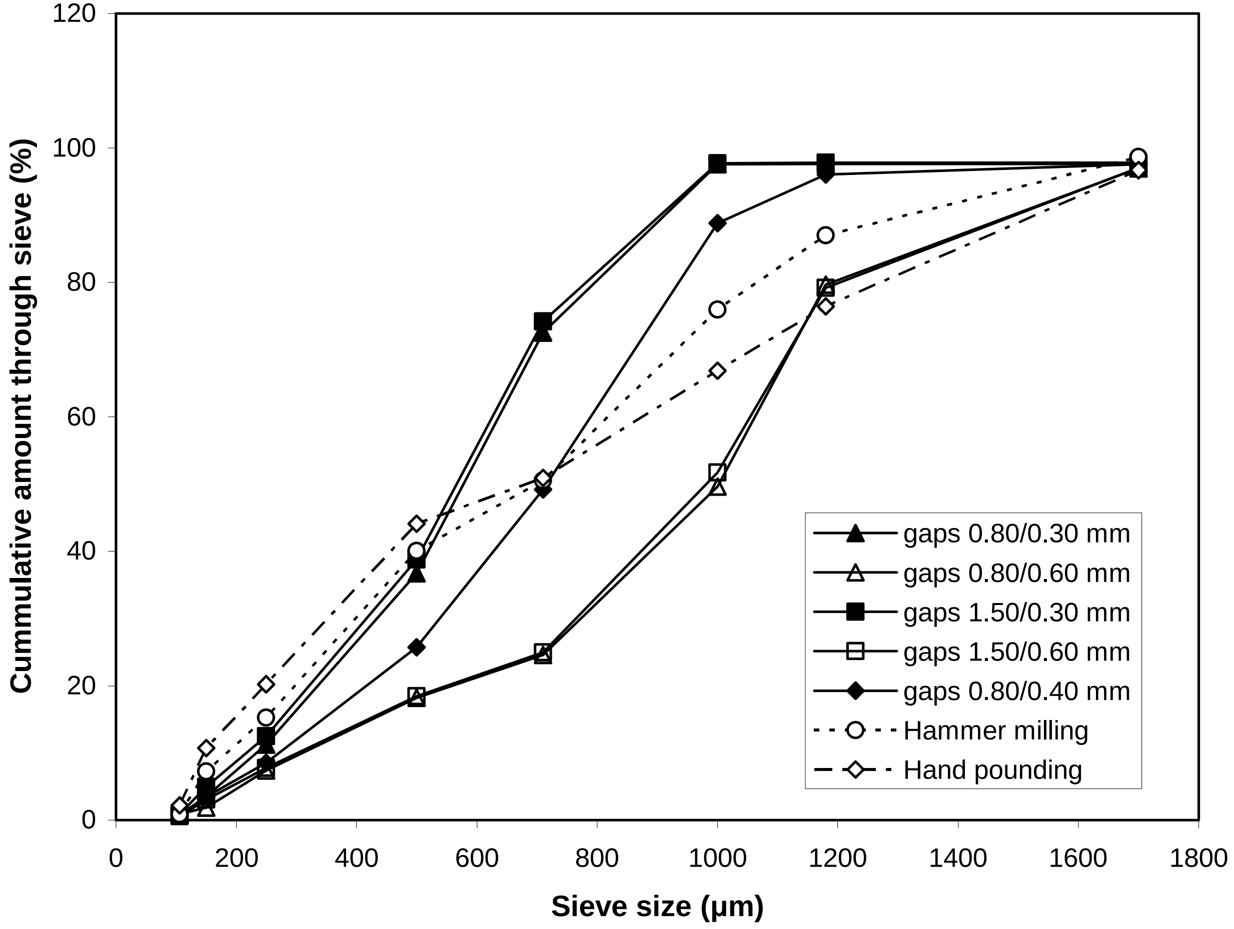

Fig. 3.1.10. **Effect of milling process on the particle size distribution of sorghum meals produced from corneous endosperm sorghum (Phofu) by hand pounding, hammer milling and roller milling, using different roll gap settings.**

3.1.3.3. Comparative evaluation of hand pounding (HP), abrasive decortication-hammer milling (ADHM), and roller milling (RM)

3.1.3.3.1. 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 milling process affected extraction rate. When all sorghum types were considered, HP and ADHM were not significantly different, giving mean extraction rates of 74.2 g/100 g and 75.7 g/100 g, respectively. RM performed substantially better, giving an 11% (7.8 g/100 g) yield advantage over ADHM. However, when the three weathered sorghum types were excluded from the data, ADHM performed significantly better than HP, but 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 AD.

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 (1996) 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 this present study did not include types that had completely floury endosperms. In contrast to RM, there were significant correlations (Table V) between AD 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 (1989) that for abrasive decortication and hand pounding, grains with harder endosperms give higher flour yields than those with softer endosperms.

Table IV

Effect of Sorghum Type and Milling Process on the Extraction Rate of Sorghum Meal

Sorghum type	**Meal extraction (g /100 g)**			**Main sorghum type effect**	**Main sorghum type effect (excluding weathered grain)**
	Hand Pounding	**Abrasive Decortication - Hammer milling**	**Roller Milling**		
BSH1	79.7f (1.6)	83.1cd (5.9)	81.6ab (1.6)	**81.5cd (3.2)**	**81.5efg (3.2)**
Kanye Standard[1]	77.2ef (1.3)	70.9ab (0.9)	85.6gh (1.1)	**77.9bc (6.7)**	**-**
LARSVYT	63.4a (0.6)	79.6bcd (5.2)	82.2bc (0.8)	**75.1ab (9.4)**	**75.1ab (9.4)**
Lekgeberwa	87.1g (3.4)	80.0bcd (5.2)	85.5gh (0.1)	**84.2d (4.4)**	**84.2g (4.4)**
Buster	73.4cd (1.2)	74.4abc (6.2)	84.3efg (0.4)	**77.4bc (6.1)**	**77.4cd (6.1)**
Marupantsi[a]	74.6de (1.1)	73.2abc (2.0)	83.9def (0.4)	**77.2bc (5.3)**	**-**
Mmabaitse[a]	71.1bc (1.7)	67.9a (7.4)	83.2cde (0.4)	**74.1ab (8.0)**	**-**
Phofu	72.8cd (1.3)	81.4cd (5.7)	80.7a (0.7)	**78.3bc (5.0)**	**78.3cde (5.0)**
Sefofu	79.2f (1.2)	77.2a-d (7.2)	84.8fg (0.3)	**80.4cd (4.8)**	**80.4def (4.8)**
Segaolane	80.0f (1.1)	84.8d (0.2)	86.8h (0.1)	**83.8d (3.2)**	**83.8fg (3.2)**
SNK	63.4a (1.1)	67.5a (0.9)	83.2cde (0.2)	**71.4a (9.4)**	**71.4a (9.4)**
Town	68.2b (1.0)	68.5a (0.7)	82.6bcd (0.4)	**73.1ab (7.4)**	**73.1ab (7.4)**
Main milling effect	**74.2a (7.0)**	**75.7a (6.9)**	**83.7b (1.8)**	**77.9**	
Main milling effect (excluding weathered grain)	**74.1a (8.1)**	**77.4b (6.9)**	**83.5c (2.0)**		**78.4**

Figures in brackets are standard deviations

Means in columns and the two bottom rows with different letter notations are significantly different at p<0.05

[1]Weathered grain

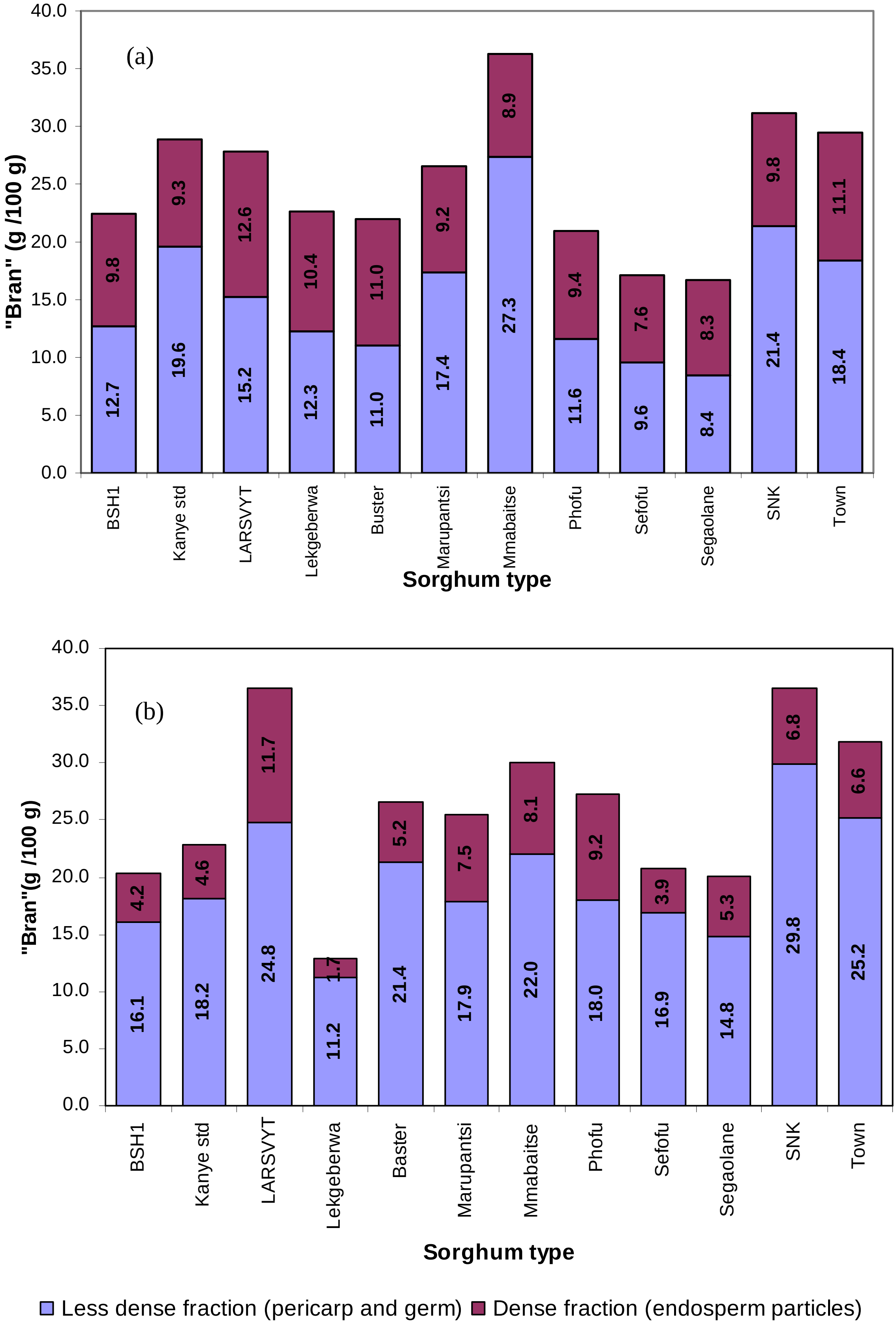

Fig. 3.1.11. **Effect of abrasive decortication (a) and hand pounding (b) on the composition of sorghum ‘‘bran’’ (mixture of bran and endosperm particles) produced.**

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

	[1]Milling process	Meal characteristic						
		Extraction rate	**Ash**	**Oil**	**Protein**	**L* Value (Lightness)**	**C^*_{ab} (Chroma)**	**H^*_{ab} (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}	HP					0.87****		
	ADHM					0.81****		
	RM					0.82****		
Whole grain h^*_{ab}	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}	HP							
	ADHM		0.83****	-0.72***		0.60**		
	RM		0.74***			0.59**		
Meal H^*_{ab}	HP		-0.54*			0.98****		
	ADHM	0.53*	0.66**			0.96****	0.75***	
	RM					0.97****	0.68**	

*p<0.10, **p<0.05, ***p<0.01, ****p<0.001
[1]HP = Hand pounding; ADHM = Abrasive decortication-hammer milling; RM = Roller milling

Table VI
Effect of Sorghum Type and Milling Process on the Colour Properties (L*, C^*_{ab} and H^*_{ab}) of Sorghum Meal[a]

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

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

Comparison of the amounts of endosperm particles in the bran revealed that ADHM and HP were more wasteful than RM. Fig. 3.1.11(a) shows that 25-50% portion (depending on sorghum type) of the bran obtained with ADHM was in actual fact endosperm particles. These particles ranged in size from complete spherical decorticated kernels to small particles bigger than 1000 µm. With HP (Fig. 3.1.11(b)), the endosperm particles accounted for 13-34% fraction of the bran. No endosperm particles could be separated from the bran obtained with RM, showing that RM was less wasteful under the given test conditions.

3.1.3.3.2. Colour of the meals

Light coloured sorghum products are usually preferred by consumers (Aboubacar et al 1999, Boling and Eisener 1982, Gomez 1993). Table VI shows that the milling process significantly ($p<0.05$) affected the colour of the meals, with ADHM producing the lightest coloured meals (as indicated by L*), followed by HP. RM produced slightly darker meals. However, in terms of hue, meals obtained with HP and RM were not significantly ($p<0.05$) different (Table VI). This may be because, unlike ADHM, the other two processes had a tempering stage which probably stained the grain endosperm by leaching dark coloured pigments from pericarps of the pigmented sorghum types. The colour intensity (chroma) of the meals was lowest with HP and highest with RM. This could be associated with the concentration of the dark coloured pigments in the meal, and therefore, the level of bran contamination of the meal. Excluding the weathered sorghum types improved the lightness colour (increased L* and h*) of the meals with all the milling processes, and maintained the same colour ranking order obtained for all twelve sorghum types, indicating that weathered grains affect meal colour in the same manner for all milling processes.

Sorghum type also caused significant variations in the colour properties of the meals (Table VI). Light coloured sorghum types, such as BSH1, LARSVYT and Phofu produced light coloured 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 discoloured the meals. Meal lightness (L*) correlated positively with the colour characteristics (L*, C^*_{ab}, and h^*_{ab}) of the whole grain (Table V), indicating that the colour properties of the final meal depends on the colour of the whole grain. Unlike the light coloured types, pigmented sorghum types produced meals with higher chroma values, reflecting higher colour intensity contributed by the coloured pigments (Table V). 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 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 colour problems of weathered and pigmented grains.

3.1.3.3.3. Ash content of the meals

Ash content is an indicator of the level of bran contamination in milled products (Kent and Evers 1994). The meal ash content obtained with all 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 (Serna-Saldivar and Rooney 1995)) were removed as expected. The lowest meal ash contents were obtained with HP, and 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 with 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 with HP. Pericarp thickness also correlated significantly with ash content with ADHM ($r=-0.59$, $p<0.05$) and RM ($r=-0.57$, $p<0.10$).

Table VII
Effects of Sorghum Type and Milling Process on the Ash Content of Sorghum Meal

Sorghum type	**Ash content of the meal (g /100 g)**			**Main sorghum type effect**	**Main sorghum type effect (excluding weathered grain)**
	Hand Pounding	**Abrasive Decortication - Hammer milling**	**Roller Milling**		
BSH1	1.01ef (0.03) [49.2]	1.38f (0.02) [70.1]	1.49f (0.04) [74.3]	**1.29e (0.22) [64.2]**	**1.29d (0.22)**
Kanye Standard	0.91cd (0.02) [61.7]	1.00a (0.04) [62.2]	1.04a (0.03) [78.2]	**0.98a (0.06) [67.0]**	**-**
LARSVYT	0.82a (0.03) [36.3]	1.31e (0.03) [72.8]	1.42e (0.01) [81.5]	**1.19cd (0.27) [62.4]**	**1.19c (0.27)**
Lekgeberwa	0.88bc (0.02) [56.2]	1.11b (0.03) [64.4]	1.25b (0.02) [77.5]	**1.08b (0.16) [66.0]**	**1.08a (0.16)**
Buster	0.84ab (0.02) [43.3]	1.23d (0.01) [64.3]	1.33cd (0.07) [78.8]	**1.13bc (0.23) [61.4]**	**1.13b (0.23)**
Marupantsi	0.90cd (0.02) [57.9]	1.01a (0.02) [63.8]	1.04a (0.02) [75.3]	**0.99a (0.07) [66.0]**	**-**
Mmabaitse	1.29g (0.04) [57.0]	1.10b (0.01) [45.5]	1.33cd (0.04) [69.9]	**1.24de (0.11) [58.0]**	**-**
Phofu	1.04f (0.02) [55.5]	1.21d (0.03) [72.1]	1.27bc (0.05) [75.1]	**1.18cd (0.11) [67.7]**	**1.18c (0.11)**
Sefofu	0.90cd (0.02) [47.4]	1.24d (0.02) [62.7]	1.38de (0.06) [77.8]	**1.17cd (0.21) [62.6]**	**1.17c (0.21)**
Segaolane	0.92d (0.04) [56.0]	1.22d (0.02) [78.7]	1.28bc (0.05) [84.5]	**1.14bc (0.17) [72.7]**	**1.14b (0.17)**
SNK	0.92cd (0.02) [40.8]	1.12b (0.02) [52.9]	1.23b (0.03) [71.7]	**1.09b (0.14) [54.5]**	**1.09a (0.14)**
Town	0.98de (0.06) [43.2]	1.16c (0.04) [51.4]	1.41e (0.04) [75.2]	**1.18cd (0.19) [55.8]**	**1.18c (0.19)**
Main milling effect	**0.95a (0.12) [50.4]**	**1.18b (0.11) [63.4]**	**1.29c (0.14) [76.6]**	**1.14 [63.2]**	
Main milling effect (excluding weathered grain)	**0.92a (0.08)**	**1.22b (0.08)**	**1.34c (0.09)**		**1.16**

Figures in parenthesis are standard deviations
Figures in square brackets are amounts (%) of whole grain ash retained in the meal
Means in columns with different letter notations are significantly different at $p<0.05$

Table VIII
Effects of Sorghum Type and Milling Process on the Oil Content of Sorghum Meal

Sorghum type	Oil content of the meal (g /100 g)			Main sorghum type effect	Main sorghum type effect (excluding weathered grain)
	Hand Pounding	Abrasive Decortication - Hammer milling	Roller Milling		
BSH1	1.68b (0.12) [36.9]	2.53g (0.14) [57.9]	2.56d (0.05) [57.5]	**2.26cd (0.44) [50.7]**	**2.26cd (0.44)**
Kanye Standard	1.90d (0.09) [43.9]	2.14cd (0.01) [45.4]	2.22b (0.02) [56.9]	**2.09abc(0.15) [48.7]**	
LARSVYT	2.40g (0.02) [46.0]	2.04bc (0.09) [49.0]	2.31bc (0.04) [57.4]	**2.25cd (0.17) [51.0]**	**2.25cd (0.17)**
Lekgeberwa	2.46g (0.05) [45.9]	3.44i (0.01) [58.9]	3.62h (0.11) [66.3]	**3.17f (0.54) [57.2]**	**3.17fg (0.54)**
Buster	1.55a (0.07) [32.8]	2.36f (0.04) [50.6]	2.68e (0.08) [65.1]	**2.20bcd(0.50) [49.1]**	**2.20bc (0.50)**
Marupantsi	1.95de(0.05) [43.0]	2.28ef (0.04) [49.4]	2.38c (0.07) [59.1]	**2.20bcd (0.20) [50.3]**	
Mmabaitse	2.02e (0.04) [50.1]	1.67a (0.08) [38.8]	2.06a (0.03) [60.7]	**1.91a (0.19) [50.2]**	
Phofu	1.80c (0.02) [43.2]	1.99b (0.08) [53.5]	2.37c (0.13) [63.1]	**2.05ab (0.26) [53.0]**	**2.05a (0.26)**
Sefofu	2.26f (0.08) [42.6]	3.17h (0.12) [57.4]	3.40g (0.05) [68.6]	**2.95e (0.52) [56.5]**	**2.95f (0.52)**
Segaolane	2.22f (0.05) [45.9]	3.19h (0.06) [69.9]	3.03f (0.05) [67.9]	**2.81e (0.45) [60.9]**	**2.81e (0.45)**
SNK	1.72bc(0.03) [30.0]	2.56g (0.03) [47.4]	2.57d (0.05) [58.6]	**2.29d (0.42) [44.8]**	**2.29d (0.42)**
Town	1.80c (0.05) [32.4]	2.18de (0.12) [39.4]	2.53d (0.06) [55.1]	**2.17bcd (0.32) [41.9]**	**2.17b (0.32)**
Main milling effect	**1.98a (0.29) [41.1]**	**2.46b (0.53) [51.5]**	**2.64c (0.46) [61.4]**	**2.36 [51.2]**	
Main milling effect (excluding weathered grain)	**1.99a (0.33)**	**2.61b (0.52)**	**2.79c (0.45)**		**2.46**

Figures in parenthesis are standard deviations
Figures in square brackets are amounts (%) of whole grain oil retained in the meal
Means in columns and the two bottom rows with different letter notations are significantly different at p<0.05

The fact that the ash content of meals produced with HP did not correlate significantly with whole grain ash and pericarp thickness (unlike with 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 with ADHM ($r= -0.55$, $p<0.10$), and with grain abrasive hardness with HP ($r= -0.62$, $p<0.05$), indicating that the softer the grain, the more contaminated with bran the meal would be.

3.1.3.3.4. 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 (Serna-Saldivar and Rooney 1995) (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 (Serna-Saldivar and Rooney 1995), 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 weathered grains data 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 content was obtained with Mmabaitse and Phofu, whereas Lekgeberwa and Sefofu gave the highest oil in the meals. 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 content 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 the germ would be removed.

Table IX
Effects of Sorghum Type and Milling Process on the Protein Content of Sorghum Meal

Sorghum type	**Protein content of the meal (g /100 g)**			**Main sorghum type effect**	**Main sorghum type effect (excluding weathered grain)**
	Hand Pounding	**Abrasive Decortication - Hammer milling**	**Roller Milling**		
BSH1	14.76e (0.10) [90.8]	13.32d (0.13) [85.5]	14.58d (0.04) [91.9]	**14.22e (0.68) [89.4]**	**14.22d (0.68) [89.4]**
Kanye Standard	13.27c (0.12) [89.9]	12.65bc (0.06) [78.7]	12.59b (0.11) [94.6]	**12.83bc (0.33) [87.7]**	**-**
LARSVYT	14.79e (0.02) [87.9]	12.21b (0.04) [91.0]	12.07a (0.07) [92.9]	**13.02c (1.33)[91.5]**	**13.02c (1.33)[91.5]**
Lekgeberwa	14.36d (0.21) [95.2]	14.85f (0.32) [90.4]	14.89de (0.16) [96.9]	**14.70f (0.33) [94.2]**	**14.70e (0.33) [94.2]**
Buster	11.62a (0.07) [81.5]	11.42a (0.14) [81.1]	11.77a (0.12)[94.8]	**11.60a (0.18) [85.7]**	**11.60a (0.18) [85.7]**
Marupantsi	13.40c (0.02) [79.2]	13.99e (0.06) [81.1]	14.05c (0.10) [93.4]	**13.81d (0.31) [84.5]**	**-**
Mmabaitse	16.34g (0.07) [79.8]	15.88g (0.11) [72.6]	16.28f (0.09) [94.5]	**16.17h (0.23) [83.6]**	**-**
Phofu	12.71b (0.07) [84.0]	12.70c (0.15) [93.8]	12.75b (0.18) [93.4]	**12.72b (0.12) [90.4]**	**12.72b (0.12) [90.4]**
Sefofu	17.30h (0.02) [88.1]	16.59h (0.17) [81.0]	17.30g (0.14) [94.2]	**17.06i (0.37) [88.1]**	**17.06g (0.37) [88.1]**
Segaolane	15.96f (0.24) [93.3]	14.70f (0.18) [91.2]	15.03e (0.15) [95.3]	**15.23g (0.59) [93.3]**	**15.23f (0.59) [93.3]**
SNK	14.45de (0.10) [70.7]	13.78de (0.10) [71.8]	14.59d (0.03) [93.7]	**14.27e (0.38) [78.6]**	**14.27d (0.38) [78.6]**
Town	14.28d (0.11) [74.7]	14.00e (0.12) [73.6]	14.06c (0.02) [89.0]	**14.11e (0.15) [79.1]**	**14.11d (0.15) [79.1]**
Main milling effect	**14.44c (1.55) [84.6]**	**13.84a (1.47) [82.6]**	**14.16b (1.62) [93.7]**	**14.15 [87.2]**	
Main milling effect (excluding weathered grain)	**14.47c (1.59)**	**13.73a (1.50)**	**14.12b (1.65)**		

Figures in parenthesis are standard deviations
Figures in square brackets are amounts (%) of whole grain protein retained in the meal
Means in columns and the two bottom rows with different letter notations are significantly different at p<0.001

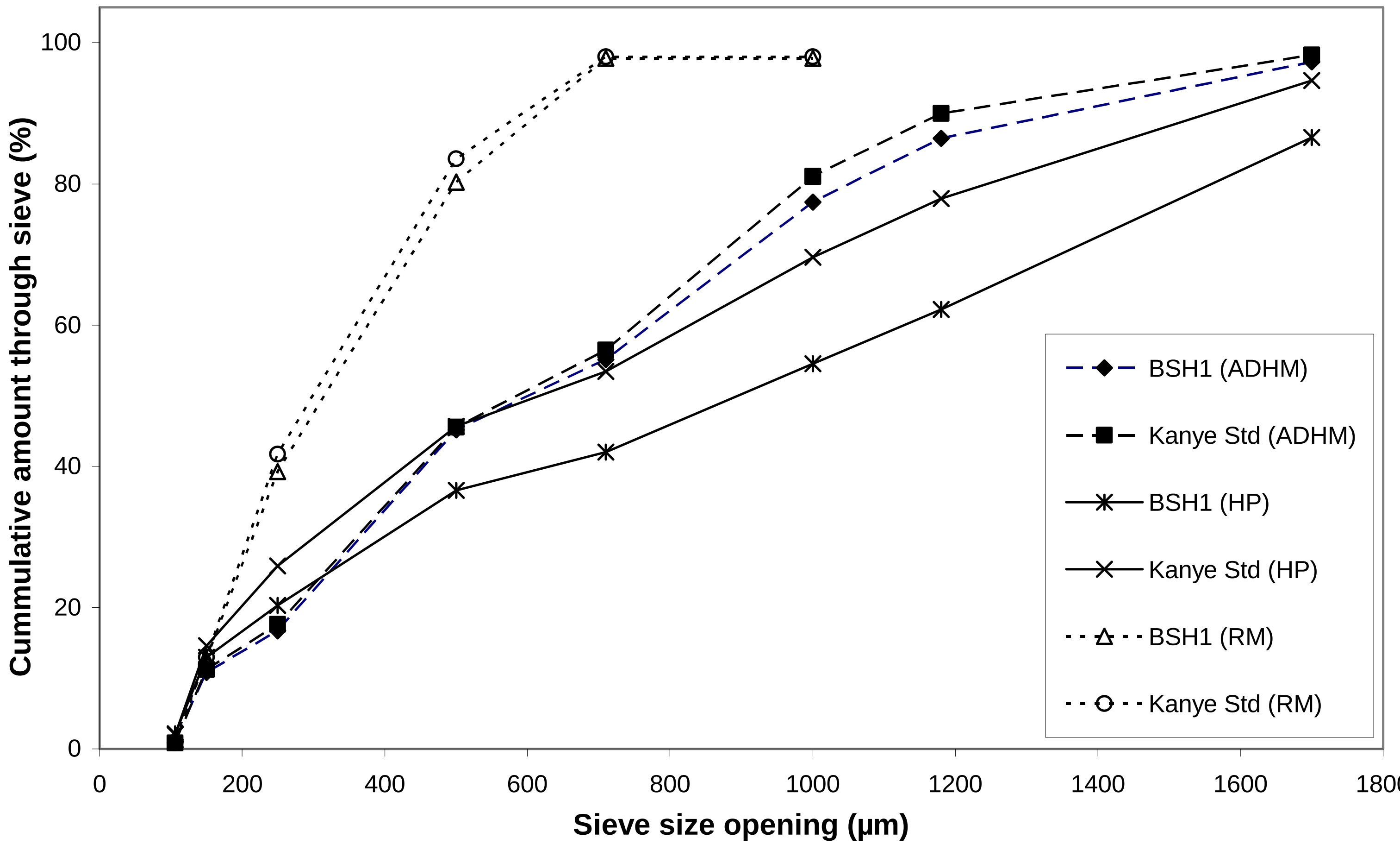

Fig. 3.1.12. **Effect of milling process on the particle size distribution of sorghum meals produced from corneous (BSH1) and intermediate (Kanye Std) endosperm grains by hand pounding (HP), abrasive decortication-hammer milling (ADHM) and roller milling (RM).**

3.1.3.3.5. Protein content of the meals

Unlike with 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), showing that the grain pericarp, which is relatively poor in protein, was removed. This was consistent with earlier findings by Taylor and Schüssler (1986) that approximately 80%, 16% and 3% of the 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. The protein content in sorghum has been shown to correlate with grain hardness (Chandrashekar and Mazhar 1999). 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.

3.1.3.3.6. Particle size distribution of the meals

Fig. 3.1.12 shows that RM produced finer meals, with all the particles passing through a 710 µm sieve size opening. In comparison, HP produced much coarser meals with approximately 50% of the particles falling in the size range 1180 µm to 1700 µm. Meals obtained with ADHM were slightly finer than those produced with HP, but coarser than meals obtained with RM. Grain type affected particle size distribution slightly with RM, but more with ADHM and 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 same milling conditions (Chandrashekar and Mazhar 1999).

3.1.4. CONCLUSIONS

This study confirms that the physico-chemical 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 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 gives lighter coloured meals. RM produces meals with slightly darker colour 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. RM holds great potential as a milling process for sorghum.

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3.2 Effects of Sorghum Type and Milling Process on the Sensory Characteristics of Sorghum Porridge

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ABSTRACT

Improvement in the technology of sorghum grain milling for food use requires an in-depth understanding of how grain type and milling process affect the sensory characteristics of the food product. In Africa and parts of India the product is generally porridge. Porridges prepared from meals produced by milling 12 sorghum types using hand pounding, roller milling, and abrasive decortication followed by hammer milling were subjected to descriptive sensory analysis and the data were analyzed by principal component analysis. Milling process had more effect on porridge sensory characteristics than sorghum type. Porridges from roller milled sorghum were generally darker, with more specks, more astringent and had enhanced branny aroma. Porridges from hand pounded meals were more stiff and coarse, but had rancid off flavour and humus odour. Porridges obtained with abrasive decortication and hammer milling were lighter in colour, had enhanced cereal aroma and were moderately intense in most other attributes. Sorghums with pigmented pericarps and soft endosperms generally produced dark, specky and astringent porridges with branny aroma, whilst light coloured hard grains produced light coloured porridges with enhanced cereal flavour and aroma. For high quality sorghum porridge, abrasive decortication-hammer milling was the best milling process in combination with light coloured hard grain.

3.2.1 INTRODUCTION

Porridge from sorghum is a staple food in most parts of Africa (Taylor and Dewar 2000) and some parts of India (Murty and Kumar 1995). The porridge making process varies depending on the type of porridge prepared and consumer preferences in a particular locality. The usual preparation process involves cooking sorghum meal with boiling water, either directly or after lactic acid fermentation (Taylor et al 1997). Generally, the texture of the porridge is directly influenced by the meal quality (Fliedel 1995). However, information on how meal quality affects the overall sensory qualities of the porridge is limited. It was established that sorghum meal quality is strongly affected by characteristics of the grain and the type of milling process used (Chapter 3.1). Comparison of the milling processes of hand pounding, roller milling and abrasive decortication, followed by hammer milling, revealed that hand pounding produced coarser meals with lower ash and oil contents than the other two milling processes. Roller milling gave finer meals with slightly more ash and oil. Roller milling also produced the darkest meals but it had the great advantage of giving the highest extraction rate. An in-depth understanding of how sorghum meal quality attributes affect the porridge sensory characteristics will assist in selecting the right sorghum grain type and milling process for achievement of predictable sorghum porridge quality. Therefore in this study the effects of sorghum grain type and milling process on porridge sensory characteristics was investigated.

3.2.2 MATERIALS AND METHODS

3.2.2.1 Sorghum Meal Samples

A total of 36 meal samples were produced by milling 12 sorghum grain types grown in Botswana (BSH1, Kanye standard, LARSVYT, Lekgeberwa, Buster, Marupantsi, Mmabaitse, Phofu, Sefofu, Segaolane, SNK and Town), using three milling processes (hand pounding (HP), roller milling (RM) and abrasive decortication followed by hammer milling (ADHM)) as described in Chapter 3.1. The milled samples were vacuum packed in batches of 1 kg in plastic pouches (5-layer polyethylene/nylon co-extruded film with oxygen and moisture barrier properties) and stored at 7°C until used.

3.2.2.2 Porridge Preparation

A typical Botswana porridge making process was used to prepare semi-stiff sorghum porridges. Each porridge sample was made to contain 20% solids. The cooking process entailed first mixing 300 mL warm deionized water with the meal to make a slurry. The slurry was then gradually added, while stirring to avoid lump formation, to 850 mL boiling water in a small (2 L) stainless steel saucepan. The porridge was simmered at low heat (on hot plate) for 30 min, stirring every 5 min. For each tasting session, porridge samples were cooked in a batch of four, allowing 5 min interval between cooking cycles (i.e. between samples). Once ready, the porridge was held at 50°C in a food warmer, in the saucepans, and was served to the sensory panel within 15 min. Two batches of the porridges (i.e. eight porridges) were prepared and evaluated each day.

3.2.2.3 Descriptive Sensory Analysis

Descriptive sensory profiling of the porridges was performed following the generic descriptive method described by Einstein (1991). A trained panel comprising six males and five females aged between 19 and 36 years analyzed the porridges.

TABLE X
Descriptive Sensory Attributes and their Definitions Used in the Descriptive Analysis of Sorghum Porridges

Attribute / Descriptor	Definitions	Reference to Clarify and Rate Perceived Sensation	Rating scale
Appearance			
Colour	Perceived colour intensity of the porridge, from white (light) to dark brown/purple (dark)	Maize meal porridge (rated 1) and Mmabaitse porridge made from HP meal (rated 8)	Light = 1 Dark = 9
Specks	Quantity of dark coloured specks visible on porridge	None	Few = 1 Many = 9
Texture			
Cohesiveness	Degree to which the chewed porridge held together	LARSVYT porridge (20% solids) made from HP meal (rated 6)	Not cohesive = 1 Very cohesive = 9
Stiffness	Force required to compress a spoonful of porridge between the tongue and palate	Marupantsi porridge with 10% solids (rated 2) and Segaolane porridge (20% solids) made from ADHM meal (rated 6)	Not stiff = 1 Very stiff = 9
Stickiness	Force required to remove material adhering to teeth and palate during normal eating.	Segaolane porridge (20% solids) made from HP meal (rated 4)	Not sticky = 1 Very sticky = 9
Coarseness	Extent to which grittiness or graininess of the porridge caused by small particles could be perceived	None	Not coarse = 1 Very coarse = 9
Aroma			
Cereal	Intensity of aroma associated with cooked cereals	Segaolane porridge (20% solids) made from HP meal (rated 5)	Not intense = 1 Very intense = 9
Branny	Intensity of aroma associated with bran	Marupantsi porridge made from ADHM meal with 5% fine bran added (rated 6)	Not intense = 1 Very intense = 9
Cabbage (humus)	Intensity of odour typical of cooked cabbage	Lekgeberwa porridge (20% solids) made from ADHM meal (rated 5)	Not intense = 1 Very intense = 9
Taste			
Bitterness	Fundamental taste of which caffeine is typical	Marupantsi porridge (20% solids) made from ADHM meal (rated 3)	Not intense = 1 Very intense = 9
Astringent	Chemical sensation associated with puckering of the tongue caused by substances such as tannins	Marupantsi porridge (20% solids) made from ADHM meal (rated 3)	Not intense = 1 Very intense = 9
Cereal (starchy) flavour	Intensity of flavour associated with starchy products	Segaolane porridge (20% solids) made from HP meal (rated 6)	Not intense = 1 Very intense = 9
Painty (rancid) off-flavour	Paint like off-flavour, typical of rancid oil	Segaolane porridge made from HP meal with 2% added rancid sunflower oil (rated 7)	Not intense = 1 Very intense = 9

All the panelists were students at the University of Pretoria, with at least 32 hr previous experience with descriptive sensory analysis of other sorghum-based products. The panelists signed a consent form which informed them about the nature of the sorghum samples they would evaluate, before participating in the sensory exercise.

Before evaluating the porridges, the panelists participated in eight training sessions of 1 hr each day during which they were familiarized with the product, generated descriptors, and agreed on attribute definitions and assessment criteria. Consensus was reached for 13 descriptors which described and differentiated between the porridge samples. These described the appearance, texture, aroma and taste of the porridges (Table X).

Evaluation of the porridges was carried out over nine sessions of 1 hr each (one session per day). During each session, eight meal samples were randomly selected, cooked and served in two sets of four per session, with a 15 min break between servings. Samples (approx. 30 mL) were served warm (±45ºC) in clear glass bowls covered with aluminium foil. The samples were blind labeled with random 3-digit codes, and were presented in random order. Each panelist was provided with four stainless steel spoons, one for each sample, and a polystyrene spittoon cup. In addition, slices of carrots and deionized water were supplied to cleanse the palate. Panelists sat in individual booths and assessed samples under white light. Responses were entered directly into a computer system using Compusense software (Compusense® Five release 4.6, Compusense, Guelph, Ontario, Canada). Each porridge was evaluated twice, with fresh porridge cooked for each evaluation session.

3.2.2.4 Statistical analyses

The following general linear model (GLM) was fitted to the sensory data to relate the profiled sensory attributes of the porridge (13 dependent variables) to four predictor factors (session, panelist, sorghum type and milling process), and their respective first order interactions. Residuals for individual sensory attributes were subjected to normality checks using Shapiro-Wilks test, normality plots, and box and whisker plots.

$$y_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_k + \delta_l + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + e_{ijkl}$$

Where y_{ijkl} = observed value, μ = a general mean of y-value, α_i = effect of the i^{th} panelist on the y-value, β_j = effect of the j^{th} sorghum type on the y-value, γ_k = effect of the k^{th} milling process on the y-value, δ_l = effect of the l^{th} session on the y-value, $(\alpha\beta)_{ij}$ = interaction effect of i^{th} panelist and j^{th} sorghum type on the y-value, $(\alpha\gamma)_{ik}$ = interaction effect of the i^{th} panelist and the k^{th} milling process on the y-value, $(\beta\gamma)_{jk}$ = interaction effect of the j^{th} sorghum type and the k^{th} milling process on the y-value and e_{ijkl} = total random error.

Panel mean scores of the attributes were subjected to Principal Component Analysis (PCA), using the correlation matrix as described by Borgognone et al (2001). The grain physico-chemical characteristics previously found to vary significantly among the sorghum types (Chapter 3.1) were included as supplementary variables in PCA, such that they could be related to the sensory attributes. The GLM was performed using SAS® software, version 8.2 (SAS Institute, Cary, NC), while PCA and ANOVA were performed using STATISTICA software, version 7.1 (StatSoft, Tulsa, Oklahoma).

3.2.3 RESULTS AND DISCUSSION

3.2.3.1 Differences Between the Attributes

Table XI shows that all flavour attributes of the porridges, with the exception of cereal (starchy) flavour, were generally scored low (mean scores less than 4.0), suggesting that these attributes contributed relatively little to the overall sensory perception of the porridges. Other attributes (appearance, texture and taste) received mean scores in the mid range of the scale, that is 4.1 (residue in mouth) to 4.9 (cohesiveness).

Coefficients of variation were high for all the attributes, showing that the perception of the sensory attributes of the porridges varied considerably. Also, one-way ANOVA F-values were significant for all the attributes, indicating that the panelists were able to differentiate between the porridges using all the descriptive terms selected. Although statistically most of the attributes varied significantly among the porridge samples, in general the differences were small.

3.2.3.2 Panelist and Session Effects

As anticipated, there were significant panelist and session effects for most of the attributes evaluated (Table XII). Panelist effect has been reported in several sensory studies (Chabanet 2000, Lapveteläinen and Rannikko 2000, Ruiz Pérez-Cacho et al 2006). This is commonly attributed to differences in the use of the rating scale by the panelists (Bower 1998, Santa Cruz et al 2002) and natural differences in the physiological and psychological behaviours of the panelists (Wolters and Allchurch 1994, Fischer et al 1994). The session effect was probably indicative of the panelists' sensory adaptation (partial loss of absolute sensitivity to stimuli), as explained by Kroeze (1990). This is supported by the fact that attributes that were scored significantly different between sessions were all scored slightly lower in the duplicate session (data not shown). Since the effects of panelists and sessions were anticipated to contribute some variability in the data, the two factors were included in the GLM as fixed variables to remove their distorting influence on the effects of sorghum type and milling process.

TABLE XI
Mean Scores (over 11 Panelists) of Sensory Attributes of Porridges Prepared from Abrasively Decorticated - Hammer Milled (ADHM), Roller Milled (RM) and Hand Pounded (HP) Sorghum Meals

Sorghum type	Milling process	Sample code	Cereal aroma	Branny aroma	Cabbage (humus) odour	Cereal (starchy) flavour	Bitterness	Astringency	Rancidity
BSH1	ADHM	1A	5.5 (1.6)[1]	3.0 (1.8)	3.0 (2.0)	5.8 (1.2)	2.5 (1.2)	2.3 (1.3)	1.6 (1.0)
BSH1	RM	1R	5.1 (1.2)	3.7 (1.9)	3.1 (1.5)	5.1 (1.3)	2.5 (1.3)	2.4 (1.4)	2.2 (1.6)
BSH1	HP	1H	5.0 (2.3)	3.5 (2.2)	4.5 (2.3)	5.0 (2.1)	4.1 (2.0)	2.9 (1.8)	3.8 (2.6)
Kanye Std	ADHM	2H	4.4 (1.7)	2.8 (2.0)	3.0 (1.7)	4.7 (1.4)	2.0 (1.4)	4.7 (1.4)	2.1 (1.0)
Kanye Std	RM	2A	4.1 (1.7)	3.6 (2.0)	2.3 (1.5)	4.9 (1.8)	1.9 (1.0)	4.9 (1.8)	2.5 (1.2)
Kanye Std	HP	2R	4.0 (2.0)	4.0 (2.3)	3.2 (2.2)	4.2 (1.6)	2.8 (1.5)	4.2 (1.6)	2.1 (1.2)
LARSVYT	ADHM	3H	5.6 (1.9)	3.4 (2.0)	3.0 (2.0)	5.4 (1.2)	2.5 (1.4)	3.0 (1.5)	3.3 (2.3)
LARSVYT	RM	3A	5.5 (1.4)	3.4 (1.7)	2.8 (1.6)	4.8 (1.9)	3.1 (1.3)	2.4 (1.2)	3.4 (2.0)
LARSVYT	HP	3R	4.8 (2.1)	3.3 (2.4)	4.3 (2.3)	5.1 (1.6)	2.3 (1.1)	2.0 (1.1)	3.5 (2.2)
Lekgeberwa	ADHM	4H	5.2 (2.2)	2.0 (1.5)	3.8 (2.7)	5.4 (1.6)	1.8 (1.1)	2.1 (1.6)	1.9 (1.5)
Lekgeberwa	RM	4A	5.2 (1.9)	2.6 (1.6)	3.6 (2.6)	5.1 (1.3)	2.3 (1.5)	2.1 (1.8)	2.1 (2.1)
Lekgeberwa	HP	4R	5.0 (2.0)	2.3 (1.4)	3.3 (1.8)	5.1 (1.6)	1.9 (1.1)	1.7 (1.0)	2.5 (1.5)
Buster	ADHM	5H	5.6 (2.0)	3.1 (1.7)	2.8 (2.2)	5.6 (1.7)	1.7 (1.0)	2.1 (1.5)	1.3 (0.6)
Buster	RM	5A	4.5 (1.7)	4.9 (2.1)	2.5 (1.8)	4.5 (1.5)	2.5 (1.6)	2.4 (1.5)	1.5 (1.0)
Buster	HP	5R	4.0 (1.6)	2.5 (1.7)	4.6 (2.1)	4.7 (1.4)	1.8 (1.1)	2.0 (1.4)	3.2 (2.4)
Marupantsi	ADHM	6H	5.4 (1.6)	3.3 (1.6)	3.3 (2.5)	5.6 (1.3)	2.1 (1.0)	2.8 (1.9)	1.9 (1.8)
Marupantsi	RM	6A	4.0 (2.1)	3.9 (2.2)	2.5 (2.0)	4.9 (1.8)	2.6 (1.3)	2.3 (1.5)	1.5 (0.9)
Marupantsi	HP	6R	4.5 (2.0)	3.9 (2.0)	2.9 (2.1)	4.8 (1.7)	2.0 (1.0)	2.6 (1.8)	3.0 (2.0)
Mmabaitse	ADHM	7H	3.8 (1.9)	3.3 (2.0)	3.5 (1.8)	4.8 (1.6)	2.2 (1.1)	2.8 (1.6)	2.0 (1.7)
Mmabaitse	RM	7A	4.3 (1.8)	4.2 (1.8)	2.2 (1.7)	4.5 (1.7)	3.0 (1.4)	3.1 (1.3)	2.0 (1.4)
Mmabaitse	HP	7R	4.3 (2.3)	4.1 (2.3)	3.4 (2.0)	4.5 (1.7)	3.3 (1.8)	3.3 (1.6)	3.5 (2.2)
Phofu	ADHM	8H	5.4 (1.7)	3.0 (1.4)	3.0 (2.0)	5.5 (1.3)	2.2 (1.2)	2.3 (1.2)	2.4 (1.4)
Phofu	RM	8A	5.0 (1.7)	3.4 (2.1)	3.1 (1.9)	4.8 (1.4)	2.3 (1.2)	2.6 (1.7)	2.4 (1.8)
Phofu	HP	8R	4.7 (2.4)	3.6 (2.1)	4.2 (2.1)	5.1 (2.0)	2.0 (1.0)	2.4 (1.4)	3.3 (1.9)
Sefofu	ADHM	9H	5.8 (2.2)	2.7 (1.6)	3.2 (2.7)	5.9 (1.6)	2.2 (1.3)	2.2 (1.3)	1.8 (1.3)
Sefofu	RM	9A	5.5 (2.3)	2.9 (1.8)	3.5 (2.9)	5.6 (1.5)	1.9 (1.2)	1.9 (1.3)	1.7 (1.3)
Sefofu	HP	9R	4.9 (1.9)	2.7 (1.6)	4.4 (2.3)	5.6 (1.5)	1.9 (1.4)	2.5 (1.7)	2.1 (1.3)
Segaolane	ADHM	10H	5.1 (1.9)	2.9 (1.7)	4.0 (2.7)	5.7 (1.4)	1.9 (1.2)	2.0 (1.5)	1.6 (1.3)
Segaolane	RM	10A	5.2 (1.4)	3.7 (2.0)	2.6 (2.1)	5.4 (1.3)	1.8 (1.1)	2.1 (1.2)	1.6 (1.2)
Segaolane	HP	10R	4.6 (1.8)	2.7 (1.7)	3.5 (1.9)	5.3 (1.5)	1.7 (1.0)	2.2 (1.5)	2.8 (2.2)
SNK	ADHM	11H	4.5 (1.8)	4.2 (2.3)	3.5 (2.0)	4.5 (1.9)	2.0 (0.9)	2.4 (1.3)	2.5 (2.1)
SNK	RM	11A	4.4 (1.6)	4.5 (2.0)	2.4 (2.0)	4.1 (1.7)	2.9 (1.3)	3.0 (1.9)	3.1 (2.3)
SNK	HP	11R	4.0 (1.7)	4.2 (2.1)	3.8 (2.2)	4.3 (1.5)	2.3 (1.1)	2.1 (1.2)	3.3 (2.1)
Town	ADHM	12H	4.3 (1.7)	4.9 (1.9)	2.3 (1.7)	4.9 (1.4)	2.4 (1.1)	2.6 (1.7)	2.0 (1.4)
Town	RM	12A	4.6 (1.7)	4.8 (2.2)	2.5 (1.5)	4.9 (1.6)	2.9 (1.5)	2.8 (1.3)	2.1 (1.6)
Town	HP	12R	4.5 (1.8)	4.2 (2.3)	2.5 (1.5)	5.0 (1.4)	2.0 (1.1)	2.3 (1.2)	2.7 (1.8)
Mean			4.8 (1.9)	3.5 (2.0)	3.2 (2.1)	5.1 (1.6)	2.3 (1.3)	2.4 (1.5)	2.4(1.9)
Minimum mean			3.8	2.0	2.2	4.1	1.7	1.7	1.3
Maximum mean			5.8	4.9	4.6	5.9	4.1	4.9	3.8
LSD			1.1	1.1	1.2	0.9	0.7	0.6	0.9
Coefficient of Variation (%)			39.8	58.3	66.2	31.9	57.8	61.3	77.7
F-value			1.92***	3.26***	2.21***	1.95***	3.65***	1.49*	3.85***
Skewness			-0.28	0.51	0.47	-0.30	0.56	1.00	0.81
Kurtosis			-0.18	0.05	0.06	-0.07	0.15	0.98	0.90
Shapiro-Wilk			0.99***	0.98***	0.98***	0.99***	0.98***	0.93***	0.96***

[1]Figures in brackets are standard deviations
*p<0.05, **p<0.01, ***p<0.001

TABLE XI Continued

Sorghum type	Milling process	Sample code	Porridge stiffness	Coarseness	Porridge stickiness	Cohesiveness	Specks	Porridge colour
BSH1	ADHM	1H	5.4 (1.2)	5.4 (1.1)	5.0 (1.6)	5.3 (1.8)	2.9 (0.9)	2.2 (0.8)
BSH1	RM	1A	3.8 (1.4)	3.2 (1.7)	4.6 (2.0)	4.6 (1.7)	3.0 (1.0)	2.7 (1.0)
BSH1	HP	1R	4.8 (1.3)	7.0 (1.0)	4.9 (1.3)	5.2 (1.4)	2.4 (0.6)	2.1 (0.8)
Kanye Std	ADHM	2H	5.1 (1.0)	5.3 (1.1)	5.1 (1.8)	5.3 (1.4)	5.2 (1.4)	6.0 (1.1)
Kanye Std	RM	2A	4.2 (1.8)	2.4 (1.2)	4.0 (1.6)	4.6 (2.3)	6.7 (1.6)	7.5 (0.9)
Kanye Std	HP	2R	4.6 (1.6)	5.9 (1.3)	6.0 (1.5)	6.5 (1.5)	5.0 (1.6)	6.9 (1.2)
LARSVYT	ADHM	3H	4.7 (1.4)	4.9 (1.6)	4.6 (1.7)	4.9 (1.4)	3.2 (1.2)	2.7 (1.0)
LARSVYT	RM	3A	3.3 (1.4)	2.6 (1.4)	4.2 (1.6)	4.6 (2.0)	3.4 (1.2)	3.7 (1.2)
LARSVYT	HP	3R	5.8 (1.6)	6.3 (1.5)	5.2 (1.8)	5.7 (1.5)	2.8 (0.8)	3.1 (1.0)
Lekgeberwa	ADHM	4H	4.5 (1.3)	4.9 (1.5)	4.6 (1.4)	4.7 (1.7)	2.7 (1.0)	1.9 (0.8)
Lekgeberwa	RM	4A	3.8 (1.2)	2.9 (1.5)	4.9 (1.7)	4.8 (2.0)	2.9 (1.1)	2.5 (0.9)
Lekgeberwa	HP	4R	5.4 (1.5)	6.7 (1.4)	4.4 (1.6)	4.8 (1.9)	2.7 (0.9)	2.5 (0.9)
Buster	ADHM	5H	5.6 (1.6)	5.5 (1.3)	4.0 (1.9)	4.6 (1.8)	4.4 (1.5)	3.0 (1.2)
Buster	RM	5A	4.1 (1.7)	2.8 (1.6)	3.6 (1.6)	4.0 (2.0)	5.9 (1.9)	5.5 (1.0)
Buster	HP	5R	6.2 (1.1)	6.8 (1.3)	4.9 (1.7)	5.1 (2.2)	2.3 (0.6)	3.3 (0.8)
Marupantsi	ADHM	6H	5.0 (1.4)	5.4 (1.3)	4.7 (2.0)	5.0 (1.7)	5.4 (1.3)	6.0 (1.4)
Marupantsi	RM	6A	3.3 (1.3)	3.0 (1.4)	4.4 (1.9)	4.7 (2.0)	6.8 (1.3)	7.4 (1.1)
Marupantsi	HP	6R	6.2 (1.5)	6.3 (1.1)	5.6 (1.8)	5.7 (1.9)	5.0 (1.7)	6.8 (1.0)
Mmabaitse	ADHM	7H	4.9 (1.6)	5.2 (1.2)	4.7 (1.6)	4.7 (1.4)	6.0 (1.8)	8.3 (0.8)
Mmabaitse	RM	7A	4.0 (1.7)	3.3 (1.6)	4.4 (1.7)	4.8 (2.3)	6.9 (1.8)	8.5 (0.7)
Mmabaitse	HP	7R	5.8 (1.3)	6.5 (1.4)	5.3 (1.9)	5.3 (1.9)	4.5 (2.1)	8.6 (0.5)
Phofu	ADHM	8H	5.0 (1.8)	5.2 (1.3)	4.8 (2.0)	4.6 (1.9)	4.0 (1.4)	3.7 (1.4)
Phofu	RM	8A	3.3 (0.9)	2.7 (1.6)	4.4 (1.6)	4.6 (2.1)	3.1 (1.0)	3.5 (0.7)
Phofu	HP	8R	5.5 (1.6)	5.7 (1.6)	5.5 (2.2)	5.6 (2.2)	2.9 (0.9)	3.6 (1.1)
Sefofu	ADHM	9H	4.5 (1.3)	4.9 (1.4)	4.7 (1.5)	4.8 (1.6)	3.4 (1.1)	2.7 (1.0)
Sefofu	RM	9A	2.4 (1.2)	2.5 (1.6)	3.8 (2.0)	4.0 (2.2)	3.1 (1.0)	2.9 (1.3)
Sefofu	HP	9R	5.0 (1.4)	5.8 (1.3)	4.0 (1.4)	5.1 (1.5)	2.5 (0.8)	2.6 (0.8)
Segaolane	ADHM	10H	4.7 (1.4)	5.0 (1.3)	4.6 (1.7)	4.7 (1.4)	3.9 (1.4)	3.3 (1.2)
Segaolane	RM	10A	3.2 (1.4)	2.8 (1.9)	4.2 (2.4)	4.4 (2.3)	5.4 (1.3)	5.1 (1.2)
Segaolane	HP	10R	4.5 (1.5)	5.7 (1.2)	5.0 (1.8)	5.2 (1.7)	3.5 (1.3)	4.5 (1.4)
SNK	ADHM	11H	5.1 (1.7)	5.0 (1.2)	4.9 (1.8)	5.3 (1.2)	5.0 (1.5)	5.5 (1.1)
SNK	RM	11A	3.0 (1.0)	3.0 (1.6)	3.6 (1.6)	4.0 (2.1)	6.5 (1.4)	6.7 (1.0)
SNK	HP	11R	5.2 (1.8)	6.2 (1.3)	5.5 (2.0)	5.5 (1.9)	5.2 (1.2)	5.4 (1.4)
Town	ADHM	12H	4.0 (1.4)	5.1 (1.1)	3.8 (1.9)	4.3 (1.6)	4.7 (1.4)	5.3 (1.0)
Town	RM	12A	2.9 (1.6)	2.8 (1.8)	3.9 (1.8)	4.7 (2.4)	6.3 (1.4)	6.5 (0.9)
Town	HP	12R	3.8 (1.4)	7.0 (1.4)	5.1 (1.6)	4.5 (1.8)	4.6 (1.6)	6.0 (1.0)
Mean			4.5 (1.7)	4.8 (2.0)	4.6 (1.8)	4.9 (1.9)	4.3 (1.9)	4.7 (2.3)
Minimum mean			2.4	2.4	3.6	4.0	2.3	1.9
Maximum mean			6.2	7.0	6.0	6.5	6.9	8.6
LSD			0.8	0.8	1.0	1.0	0.8	0.6
Coefficient of variation (%)			37.8	42.6	39.1	38.4	44.6	48.2
F-Value			9.99***	25.4***	2.43***	1.71**	25.3***	84.8***
Skewness			-0.21	0.13	0.02	0.13	0.11	0.04
Kurtosis			-0.12	0.34	-0.32	-0.31	0.13	0.19
Shapiro-Wilk			0.99*	0.99ns	1.00ns	1.00ns	1.00*	1.00ns

[1]Figures in brackets are standard deviations
*p<0.05, **p<0.01, ***p<0.001, ns - not significant

Table XII
General Linear Model (GLM) Coefficients of Multiple Determination(R^2) and Sensory Attribute F-values for Sources of Variations and Interactions Obtained for 13 Sensory Attributes Rated for 36 Sorghum Porridge Samples Prepared from 12 Sorghum Types Milled by 3 Milling Processes

Attribute	Model F-Value	R^2	Session	Panelist	Sorghum type	Milling process	Panelist x Sorghum type Interaction	Panelist x Milling process Interaction	Sorghum type x Milling process Interaction
Cereal aroma	1.28*	0.27	2.74	4.09***	3.81***	5.37**	0.79	1.25	0.75
Branny aroma	1.68***	0.32	6.47*	2.51**	7.27***	6.62**	0.94	1.65*	1.14
Cabbage (humus) odour	1.46***	0.29	14.47***	4.07***	2.12*	14.45***	0.89	1.12	1.30
Stiffness	3.11***	0.47	1.02	3.38***	7.07***	119.85***	1.03	1.60*	2.28***
Coarseness	5.78***	0.62	0.40	1.46	2.04*	420.33***	0.74	1.89*	0.89
Stickiness	1.98***	0.36	22.63***	8.59***	2.12*	22.09***	1.12	0.96	1.37
Cohesiveness	1.62***	0.32	1.94	3.46***	1.51	16.05***	1.00	3.60***	0.78
Specks	6.54***	0.65	1.49	4.68***	62.92***	75.87***	1.07	1.60*	4.95***
Colour	18.47***	0.84	8.33**	3.62***	260.13***	63.80***	0.89	1.35	4.21***
Cereal (starchy) flavour	1.53***	0.30	0.00	6.74***	4.45***	7.20***	1.02	0.83	0.46
Bitterness	1.43***	0.29	2.79	1.92*	5.49***	4.80**	0.85	0.56	2.52***
Astringency	1.01	0.22	3.96*	2.07*	2.35**	0.10	0.76	0.95	1.13
Rancidity	1.85***	0.35	20.49***	3.29***	4.33***	34.16***	1.01	0.96	1.20

*p<0.05
**p<0.01
***p<0.001

3.2.3.3 Sorghum Type and Milling Process Effects

The effect of sorghum type was highly significant ($p<0.001$) for all the attributes except cabbage (humus) odour, coarseness, stickiness, cohesiveness and astringency (Table XII). In contrast, the milling process effect was highly significant ($p<0.001$) for all the attributes except cereal aroma, branny aroma, bitterness and astringency. Thus, it appears that porridge cereal and branny aroma were predominantly determined by the sorghum type, while humus odour, coarseness, stickiness and cohesiveness were primarily consequences of the milling process. Of interest are the combined effects (interactions) of sorghum type and milling process, which were highly significant ($p<0.001$) for porridge stiffness, quantity of specks, porridge colour and bitterness, indicating that these attributes were dependent on both the sorghum type and the milling process. The interactive effect of these variables on porridge stiffness is consistent with earlier findings that porridge stiffness is influenced, among others, by the particle size profile of the meal (Fliedel 1995). It was determined earlier that the particle size distribution of the meals was affected by the endosperm texture of the sorghum kernel with HP and ADHM, but not with roller milling (Chapter 3.1). Thus, the particle size distribution was dependent on both the sorghum type's grain physical properties and the milling process. Quantity of specks and porridge colour are associated with pigmented testa (if present) and the pericarp of the sorghum kernel, which varies in thickness and pigmentation colour depending on the sorghum type (Rooney and Miller 1982). During milling, the efficient separation of the pericarp from the starchy endosperm depends on the structural integrity of the pericarp and the milling process used (Chapter 3.1), thus explaining the observed significant interactive effect of the two variables on the quantity of specks. Drewnowski and Gomez-Carneros (2000) comprehensively reviewed possible causes of bitterness in foods and reported that bitterness is detected at extremely low thresholds, and may result from trace quantities of low molecular weight phenolic compounds (such as flavonoids), microbial metabolites, rancid oils and hydrolyzed proteins. The sorghum types with coloured pigments such as SNK and Town, which presumably had higher amounts of flavonoids, were perceived to be more bitter. This perception was enhanced in RM porridges, perhaps aggravated by additional increase in flavonoid levels, owing to higher extraction rates associated with RM. Also, the sorghum types Marupantsi and Mmabaitse, which were previously found to be slightly weathered (Chapter 3.1), were scored higher in bitterness.

3.2.3.4 Principal Component Analysis

PCA was used to better reveal relationships between the porridge sensory attributes, sorghum type characteristics, and the milling processes. Three PCs accounting for 73% of the total variation within the data were used to explain relationships between the variables (Figs. 3.2.1 and 3.2.2). PC1 separated porridges with darker colour, high quantity of specks, more intense bran aroma and higher astringency (e.g. 2R, 3R, 5R, 7R and 11R) to the right of the loading plot (Fig. 3.2.1) from those on the left of the plot that did not possess these qualities. Most of the porridges on the right were obtained with RM, indicating that this milling process produced porridges with these apparently undesirable qualities. As revealed in Fig. 3.2.1(a), these undesirable attributes were positively correlated with each other, and were also correlated positively with grain visual hardness score (i.e. grain softness). The perceived branny aroma indicates the presence of pericarp fragments (bran) in the porridges, and was consistent with earlier findings that sorghum meals obtained with RM were more contaminated with bran than meals obtained with HP and ADHM (Chapter 3.1). The bran fragments also contributed to the specks quantity and the darker colour of the porridges, thus explaining the positive correlation between these attributes. The dark colour may have resulted from staining of the porridges by phenolic pigments (anthocyanins) present in the pericarp (Hahn et al 1984). The astringency sensation in sorghum products has been associated with phenolic compounds, especially condensed tannins (Drewnoski and Gomez-Carneros 2000). However, none of the sorghums used in this study were tannin types, suggesting that other phenolic compounds present in the sorghum grains caused astringency. In sensory studies of bran infusions of sorghums with variable compositions of phenolic compounds, Kobue-Lekalake et al (2007) found that bran infusions from a tannin free sorghum were slightly bitter and astringent. The authors attributed these sensations to catechin and procyanidin B1, the common monomer and dimer, respectively, in sorghum.

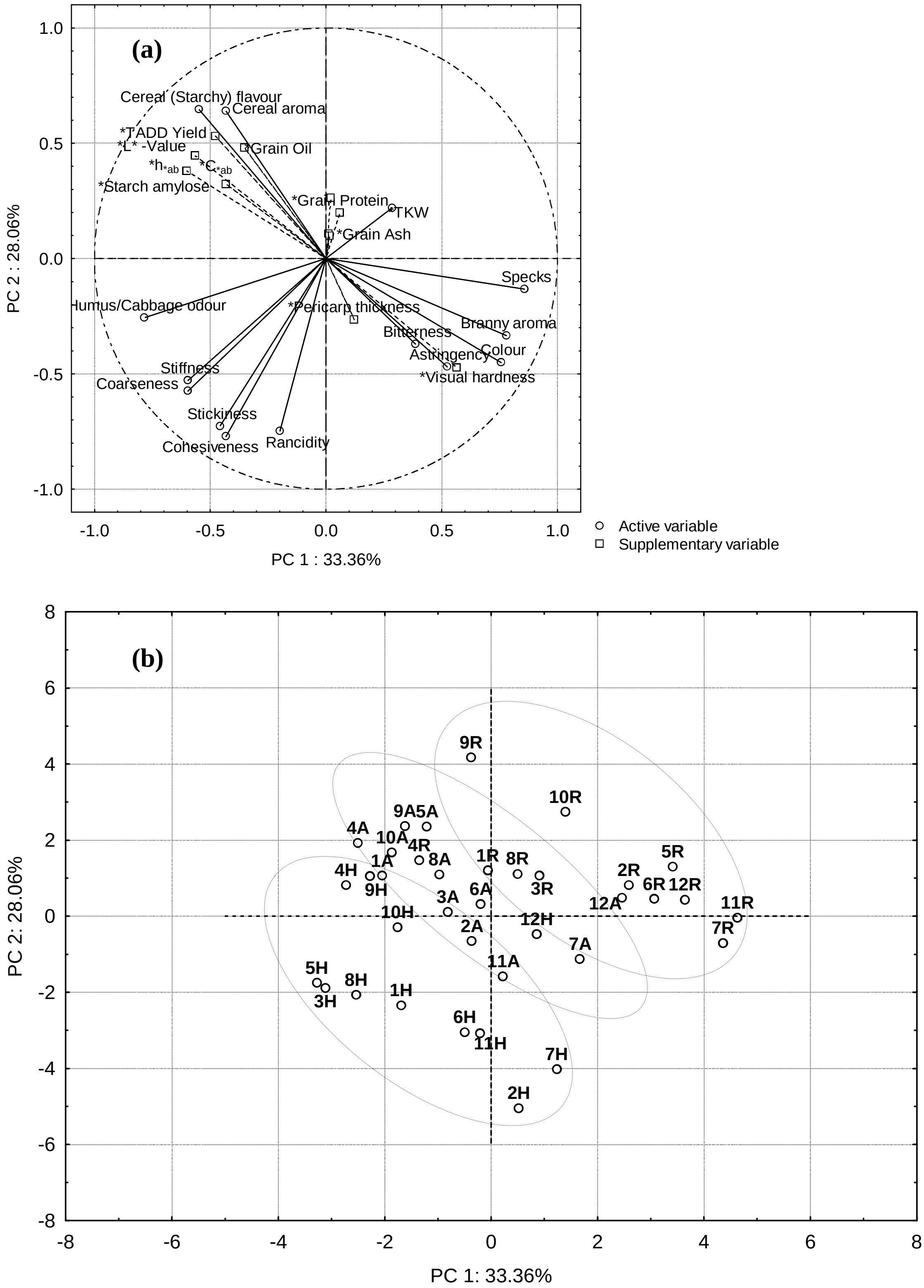
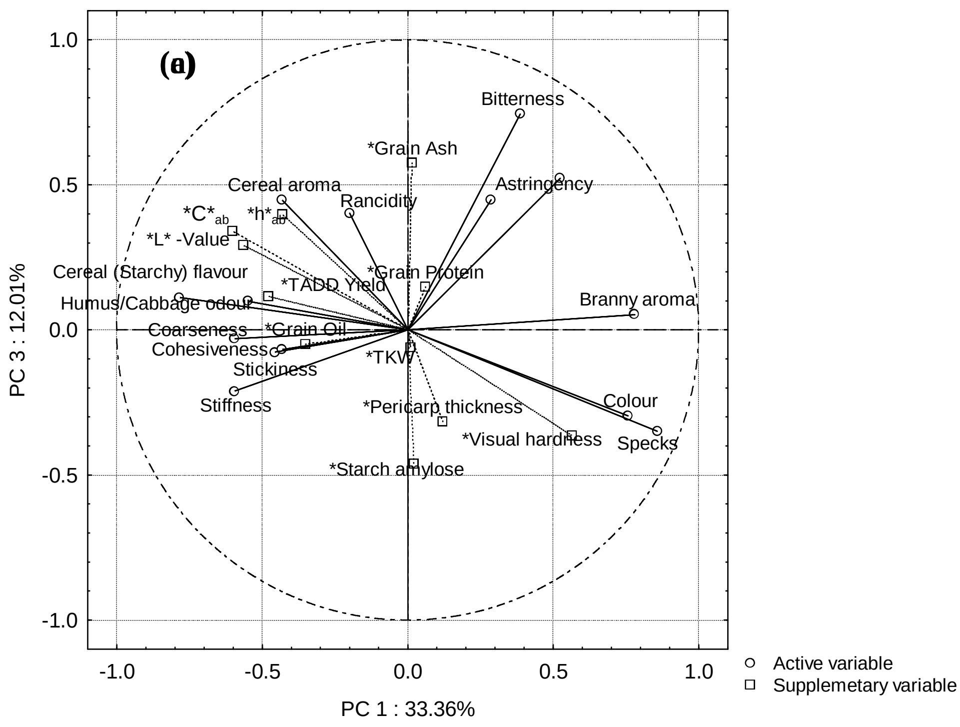


Fig. 3.2.1. PCA plots of 36 sorghum porridge samples prepared from 12 sorghum types milled by hand pounding (H), abrasive decortication–hammer milling (A), and roller milling (R). (a) loadings projections of sensory variables, (b) score plot of the porridges on PC1 and PC2. The numbers 1-12 represent the sorghum types BSH1-Town, respectively (Table XI). TKW abbreviates thousand kernel weight; TADD is tangential abrasive dehulling device.



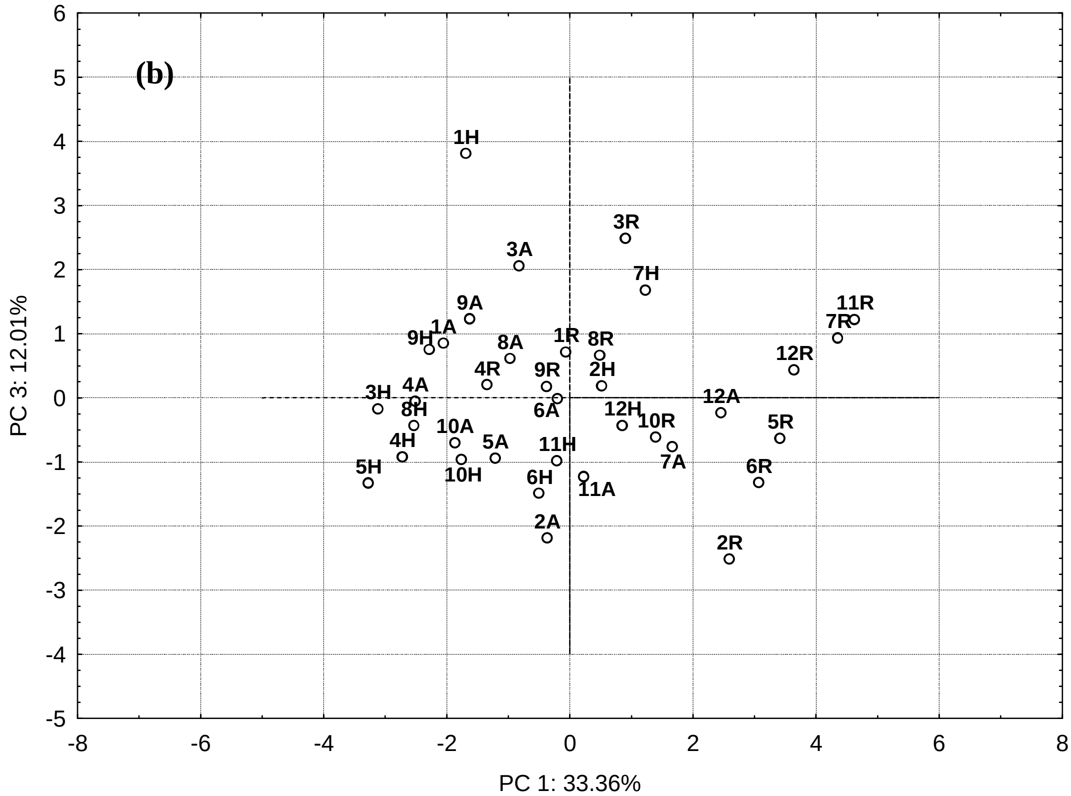


Fig. 3.2.2. **PCA plots of 36 sorghum porridges on PC1 and PC 3, prepared from 12 sorghum types milled by hand pounding (H), abrasive decortication–hammer milling (A), and roller milling (R). (a) loadings projections of sensory variables, (b) score plot of the porridges on PC1 and PC3. The numbers 1-12 represent the sorghum types BSH1-Town, respectively (Table XI). TKW abbreviates thousand kernel weight; TADD is tangential abrasive dehulling device.**

Porridges displayed on the left of the score plot (Fig. 3.2.1(b)) were associated with cabbage (humus) aroma, cereal (starchy) flavour, and were generally more stiff and coarse. These characteristics were mainly associated with porridges obtained with HP and ADHM. Cereal (starchy) flavour is associated with the endosperm components of the grain, and is particularly linked to the Maillard reaction products obtained when amino acids react with reducing sugars in the presence of lipids (Mottram and Whitfield 1995, Bredie et al 1997). Stiffness and coarseness of the porridges correlated positively with Tangential Abrasive Dehulling Device (TADD) dehulling yield (grain hardness) and negatively with visual hardness score (i.e. grain hardness) (Fig. 3.2.1(a)). It was established in Chapter 3.1 that vitreous grains produce meals with larger particle sizes, and that HP meals had a higher proportion of large particle sizes. This indicates that the generally desired stiff and coarse porridges are obtained with the coarse meals produced from vitreous sorghum types. According to Chandrashekar and Mazhar (1999), flours produced from soft sorghums show higher peak viscosity, lower gelatinization temperatures and lower setback viscosity, compared to flours obtained with hard grains. Consequently, the starch in porridge produced using hard grain meals may not swell completely and would be perceived to be gritty and thick. The cabbage (humus) odour associated with HP is probably a result of how meals produced with HP were dried (freshly pounded meals, containing 25-30% moisture, were dried in the open sun for 18-24 hr); the odour being caused by volatile compounds, possibly geosmin, 2-methylisoborneol and/or 2,6-dimethyl-3-methoxypyrazine which are produced by microbial activity (Whitfield 1998).

PC2 mainly separated porridges in terms of stickiness, cohesiveness and intensity of the rancid off-flavour. These sensory attributes were strongly perceived in porridges obtained with HP (Fig. 3.2.1(b)). Stickiness in cereal products has been related to the amount of water-soluble carbohydrates, especially the high molecular weight amylopectin fragments (Aboubacar and Hamaker 2000). Stickiness has also been linked to the amount of α-amylase degraded dextrin fractions (Every and Ross 1996), which may have resulted from the partial fermentation of meals obtained with HP during drying. Rancidity is often caused by the accumulation of secondary oxidative products, such as pentanal and hexanal (Malcolmson et al 1996), typically produced through the autoxidative and enzymatic oxidation of polyunsaturated fatty acids (Eskin and Przybylski 2001). These spoilage processes were highly likely in meals obtained with HP, given that sorghum oil contains unsaturated linoleic (49%), oleic (31%), and linolenic (2.7%) fatty acids (Serna-Saldivar and Rooney 1995). These reactions could have been favoured by the high water activity of the hand pounded meals, and exposure of the meals to atmospheric oxygen and direct sun light during drying, which are ideal conditions for the acceleration of lipid deterioration (Hamilton et al 1997, Eskin and Przybylski 2001). PC3 separated the porridges on the basis of bitterness (Fig. 3.2.2).

Figure 1b shows that the milling process had a profound effect on the sensory characteristics of the porridges. However, the relationships noted between the porridge attributes and the sorghum grain characteristics indicated that sorghum type had some effect too. This was demonstrated by the positions of the porridges of sorghum types Kanye standard (2), Mmabaitse (7), SNK (11), and Town (12), which were distributed almost entirely on the right of the plot. In contrast, BSH1 (1), Lekgeberwa (4) and Sefofu (9), had their porridges distributed entirely on the left. The former sorghum types had pigmented pericarps (Chapter 3.1), therefore producing darker, branny and specky porridges, while the latter were all white and were associated with lighter porridges (Fig. 3.2.1(a)). The effect of the sorghum type is further evident in Fig. 3.2.2(b) where porridges of BSH1 (1), LARSVYT (3) and Sefofu (9) were all distributed on the upper half of the score plot, showing that these sorghum types produced bitter and astringent porridges, irrespective of the milling process used. Porridge from hand pounded BSH1 (1H) was perceived to be the most bitter and astringent of all the porridges, possibly because it contained higher amounts of microbial metabolites, produced during drying of the meal. Likewise, Buster (5), Marupantsi (6) and Segaolane (10) (all on bottom half of the plot) produced porridges which were not bitter and astringent. Based on the PCA data, sorghum type Lekgeberwa (4) which was characterized by white grain colour, hard endosperm and thick pericarp, was the best for porridge making as it produced porridges with the least apparently undesirable sensory attributes and enhanced the desirable attributes, with all three milling processes.

3.2.4 CONCLUSIONS

Sorghum type and milling process used to produce the meal have great effects on the sensory characteristics of sorghum porridge. However, milling process has more effect than sorghum type. In terms of porridge quality, abrasive decortication and hammer milling is superior to the other milling processes as the porridges produced have enhanced positive sensory attributes such as light colour and cereal flavour. This is probably because the dry abrasive action effectively removes bran from the endosperm without tainting, resulting in production of "clean" dry meal. Similarly hard, light coloured grains give light coloured porridges with enhanced cereal flavour. Such grains withstand impact forces of the milling process without breaking much, thus allowing effective separation of bran.

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3.3 Influence of Sorghum Grain Characteristics and Milling Process on the Textural Properties of Sorghum Porridge

ABSTRACT

The effects of sorghum type and milling process on the functional properties of sorghum meal, and the pasting and instrumental textural properties of derived porridges were studied to understand their relationship with the sensory textural characteristics. Four different sorghums milled by hand pounding (HP), abrasive decortication-hammer milling (ADHM) and roller milling (RM) were used. RM produced finer meals, which had 20-25% higher water absorption (WAI) and 16-18% higher water solubility (WSI) than HP and ADHM meals. Also, RM meals gave the highest pasting viscosities (PV), but lowest hot paste (HPV) and cold paste (CPV) viscosities. The highest HPVs and CPVs were obtained with HP. Porridge instrumental firmness was correlated positively with HPV, CPV, and setback, and negatively with damaged starch, meal oil and ash content, particle size index, WAI and WSI of the meal. HPV of meal pastes could be used to predict porridge firmness levels acceptable by consumers. HP produced porridges that were firmer and coarser while RM porridges were softer and finer by both instrumental and sensory methods. Corneous sorghums produced coarser porridges. X-ray diffraction test gave B-type diffraction patterns, revealing that starch granules were gelatinised in all the porridges. Porridge instrumental stickiness was variable among the porridges and was negatively correlated with starch amylose content. Milling process had more effect than the sorghum type on all the parameters except stickiness, which was mainly affected by sorghum type. Porridge firmness was attributed to coarse meal particles, caused by less disrupted starch granules. Hence, consumer demands for acceptable porridge texture can be met by manipulating the proportion of coarse endosperm particles in the meal.

3.3.1 INTRODUCTION

In Chapter 3.2 it was established that texture, defined by the sensory panel in terms of stiffness, stickiness, cohesiveness and coarseness, varied considerably among porridge samples, showing that texture is an important quality factor for sorghum porridge. Various investigators (Boling and Eisener 1982, Fliedel 1995, Aboubacar et al 1999) have also reported the importance of porridge texture on the sensory acceptance of sorghum porridge by consumers. Thus, it is important to understand how sorghum type and different milling processes influence sorghum porridge characteristics. Such information could help in explaining the observed variations in the sensory data, and could assist processors in producing sorghum meal which makes porridge that fulfils sensory textural expectations of consumers.

According to Hoseney (1994), in general textural differences in cereal products are caused by variations in the functional properties of starch, which constitutes about 75% of kernel weight in sorghum (Serna-Saldivar and Rooney 1995). The functional characteristics of starch are determined by the concentration and physical properties of starch granules, interactions of leached amylose and amylopectin polymers, and interactions between starch elements and other components dispersed in the food matrix (Hansen et al 1991, Ciesielski et al 2003). Most studies on sorghum porridge texture have focused on the influence of sorghum cultivar (Fliedel 1995, Taylor et al 1997, Aboubacar et al 1999). Fliedel (1995) reported differences in the firmness and stickiness of *tô* prepared from different sorghum varieties, and attributed these differences to the amylose content of the starch. Variations in the pasting properties of sorghum starches prepared from different sorghum varieties have also been reported (Taylor et al 1997). Beta and Corke (2001) concluded that genetic and environmental factors influence sorghum starch functional properties. No reports on how the milling process affects sorghum porridge texture were found. Therefore, this work investigated the influence of both sorghum type and milling process on the functional properties of sorghum meal, and the pasting and instrumental textural properties of derived porridges, and how these affect the sensory textural perception of the porridge.

3.3.2 MATERIALS AND METHODS

3.3.2.1 Samples

Twelve sorghum meal samples obtained by milling four different sorghum grain types (Town, Kanye standard, Phofu and BSH1) with three different milling processes (hand pounding, roller milling, and abrasive decortication-hammer milling), as described in Chapter 3.1, were used in this study. The sorghum types selected had different physico-chemical characteristics given in Table XV, and had been shown, through descriptive sensory analysis (Chapter 3.2), to produce porridges with different textural properties.

3.3.2.2 Meal particle size index (PSI)

Meal particle sizes were determined as described in Chapter 3.1. The percentage of meal passing through a test sieve with 710 µm opening was designated as particle size index (PSI).

3.3.2.3 Water Absorption Index (WAI)

Determination of WAI was performed as described by Antila and Seiler (1984) by measuring the amount of water absorbed by the meal samples at ambient temperature. WAI was expressed as grams of water per gram of dry sample. Samples were analyzed six times.

3.3.2.4 Water Solubility Index (WSI)

The supernatant from the WAI determination was decanted into pre-weighed moisture dishes and evaporated at 103°C overnight. The dishes, containing dry residue, were cooled in a desiccator and weighed. The amount of the dry residue was determined and was recorded as WSI, expressed on dry matter basis as g solutes per g of the meal sample.

3.3.2.5 Damaged starch and amylose content

Damaged starch was determined using the Megazyme procedure (Megazyme International Ireland, www.megazyme.com). The process entails hydrolyzing damaged starch granules present in the meal to glucose, first using α-amylase then with amyloglucosidase. The glucose produced is reacted with oxidase/peroxidase reagent and the coloured complex formed is quantified spectrophotometrically at 510 nm. Samples were analyzed in triplicate.

Starch content of the meals was determined by complete enzymatic hydrolysis of starch solutions prepared from the meals to glucose (McCleary et al 1994). The amylose content of the starch was established by enzymatic hydrolysis of the starch solutions prepared from the meals after precipitation of amylopectin with concanavalin A. Both assays were carried out using the Megazyme method for amylose and amylopectin content (Gibson et al 1996). Each meal sample was analyzed in duplicate.

3.3.2.6 Pasting properties

Pasting properties of sorghum meal suspensions containing 12 g solids/100 g were studied using a Series 3 D Rapid Visco Analyser (RVA) (Newport Scientific, Warriewood, Australia). The RVA was programmed to rapidly stir each freshly mounted suspension at 900 rpm for 20 sec, then decrease and hold shear rate constant at 160 rpm for the remainder of the test period. Temperature profile entailed holding initially at 50ºC for 2 min, then increasing to 92ºC over 5 min and holding at 92ºC for 30 min before finally cooling to 50ºC over 5 min and holding constant for 3 min. Pasting peak viscosity (PV – peak viscosity at the start of the 92°C holding period), hot paste viscosity (HPV – viscosity at 37 min, i.e. at 92ºC just prior to cooling), cool paste viscosity (CPV – maximum viscosity obtained upon cooling the paste) and setback viscosity (SB – cool paste viscosity – hot paste viscosity) were determined for each meal suspension from the RVA plots obtained. Each sample was analyzed in triplicate.

3.3.2.7 Textural properties

The textural properties (firmness and stickiness) of the porridges were determined using the TA-XT2 Texture Analyser (Stable Micro Systems, Godalming, UK). The following instrument test parameters were used: mode was force in compression; option was return to start; pretest speed was 2.0 mm/sec; test speed was 2.0 mm/sec; post test speed was 10.0 mm/sec; sample penetration distance was 10.0 mm; trigger type was auto – 0.05 N; and a flat cylindrical perspex probe (20 mm diameter) was used. Porridge samples (containing 12 g solids/100 g) were prepared by gradually adding sorghum meal slurry (62 g of meal in 100 mL water) to 330 mL boiling water in a small stainless steel saucepan, stirring continuously to avoid lump formation. A bench-top electrical stove with twin hotplates set on low heat was used as a heat source. The porridge was simmered for 15 min (stirring every 5 min) and was immediately filled into three sample tubes (50 mL volume and 30 mm diameter). The tubes were then covered with aluminium foil and were held at 50ºC for 90 min. To determine texture of the sample, the aluminium cover was removed from the tube and the surface layer of the porridge was scraped off. The tube was then firmly secured centrally on the texture analyser stage. The test cycle was started immediately, and the force-time curve was recorded. Two parameters were derived from the curve: the porridge firmness, defined as the maximum force obtained as the probe penetrated the porridge; and porridge stickiness, determined as the maximum force recorded as the probe withdrew from the porridge. Duplicate porridge samples were prepared for each meal sample and each porridge sample was analyzed in triplicate (i.e. three tubes per porridge sample).

3.3.2.8 Scanning Electron Microscopy (SEM)

Portions (Approx 2 mL) of fresh porridge samples prepared as described for texture analysis were placed in small plastic cylinders (40 mm diameter and 5 mm height) and were immediately shock frozen in liquid nitrogen at -196°C (immersed for 20 min). The samples were then transferred (still submerged in liquid nitrogen) to a freeze drier and freeze dried. The freeze dried samples were gently fractured on the periphery by chopping with a sharp knife. Samples of the meals used to prepare the porridges, and fragments of the freeze-dried porridges obtained by fracturing, were mounted (separately) on an aluminium stub using adhesive carbon tape, and were sputter coated with gold. The coated samples were examined using JEOL-JSM 840 scanning electron microscope (JEOL, Tokyo, Japan) operated at an acceleration voltage of 5 kV.

3.3.2.9 Wide angle X-ray diffraction

X-ray diffraction was used to evaluate the extent of starch gelatinization (loss of starch crystallinity) in the cooked samples by comparing the meal and freeze-dried porridges obtained with the hard endosperm BSH1 sorghum type. The samples were mixed with liquid nitrogen and were ground to fine powder in a mortar. Diffractograms of the powdered samples were recorded with a Bruker AXS D8 Advance Theta X-ray diffractometer (XRD) (Siemens, Karlsruhe, Germany), using a CrKα radiation source (λ= 2.2897 Å) equipped for low-angle XRD analysis. Diffractograms were recorded between 5 and 50° (2Θ) at a rate of 1° (2Θ) per min and a step interval of 0.1° (2Θ).

3.3.2.10 Statistical analysis

Multifactor analysis of variance (ANOVA) was carried out using sorghum type and milling process, and their interactions, as main factors. Fisher's least significant differences (LSD) were used for comparison of means. Pearson correlation coefficients between data sets were also determined. Principal Component Analysis was performed, using STATISTICA software (StatSoft, Tulsa, Oklahoma), to reveal relationships between the determined characteristics.

3.3.3 RESULTS AND DISCUSSION

Table XIII
Effects of Sorghum Type and Milling Process on The Particle Size Index (%)[1] of Meals Produced from Four Selected Sorghum Types Milled By Hand Pounding, Abrasive Decortication and Hammer Milling, and Roller Milling

Sorghum type	Hand Pounding	Abrasive Decorticating - Hammer Milling	Roller Milling	Sorghum type effect
BSH1	42.0a (0.7)	55.1b (0.9)	97.8a (0.8)	65.0a (26.1)
Kanye Std	53.4c (0.2)	56.4b (0.1)	98.0a (0.9)	69.3c (22.3)
Phofu	50.9bc(0.2)	50.5a (0.3)	98.0a (0.7)	66.5ab(24.4)
Town	48.5b (0.8)	53.6ab(0.3)	98.2a (0.4)	66.8b (24.5)
Milling process effect	48.7a (4.5)	53.9b (2.4)	98.0c (1.0)	66.9

[1]amount of meal (db), expressed as percentage of total meal sample sieved through a 710 µm test sieve
Figures in columns and the bottom row with different letter notations are significantly different at p<0.01
Figures in brackets are standard deviations

Table XIV
Effects of Sorghum Type and Milling Process on The Level of Damaged Starch (%)[1] of Meals Produced By Milling Four Selected Sorghum Types using Hand Pounding, Abrasive Decortication and Hammer Milling, and Roller Milling

Sorghum type	Hand Pounding	Abrasive Decorticating - Hammer Milling	Roller Milling	Sorghum type effect
BSH1	2.0c (0.2)	1.7b (0.0)	2.0a (0.2)	1.9c (0.2)
Kanye Std	1.0a (0.1)	1.6ab (0.1)	1.7a (0.1)	1.5a (0.4)
Phofu	1.7bc (0.2)	1.4a (0.2)	1.8a (0.1)	1.6b (0.2)
Town	1.4b (0.0)	1.4a (0.1)	1.7a (0.2)	1.5ab(0.2)
Milling process effect	**1.5a (0.4)**	**1.5a (0.2)**	**1.8b (0.2)**	**1.6**

[1]amount of damaged starch (db) expressed as percentage of total amount of meal sample
Figures in columns and the bottom row with different letter notations are significantly different at p<0.01
Figures in brackets are standard deviations

3.3.3.1 Damaged starch

Table XIII shows that roller milling (RM) produced finer meals than hand pounding (HP) and abrasive decortication and hammer milling (ADHM), indicating that RM imposed more severe forces on the grains than HP and ADHM. Consequently, RM produced slightly more damaged starch than the other two milling processes (Table

XIV). This is in agreement with the findings reported by Morrison and Tester (1994) that the amount of damaged starch increases with the severity of the forces that the grains are exposed to during milling. With the exception of the sorghum type Phofu, grain endosperm texture appeared to influence the amount of damaged starch. For example, sorghum type BSH1, which had a corneous type endosperm with an average visual hardness score of 1.7 (Table XV), produced more damaged starch (1.9%) than the relatively softer Kanye standard (hardness score of 3.7) and Town (2.7), which all gave damaged starch levels of 1.5% (Table XIV). Sorghum grain visual hardness (endosperm corneous texture) correlated ($p<0.05$) with damaged starch (Table XVI), indicating that hard grains required more effort to mill, and were therefore, exposed to more severe milling forces. Starch amylose content also correlated negatively with starch damage ($p<0.05$). For example, BSH1 which had the lowest amount of starch amylose (Table XV), had more damaged starch than Kanye standard and Phofu, both of which had the highest starch amylose content. Han et al. (2002) reported similar findings in maize. Perhaps the most probable explanation for this is that given by Han et al. (2002) that amylose, unlike amylopectin, is not susceptible to damage by the physical forces of the mill. As demonstrated by Morrison and Tester (1994), a higher proportion of amylose may strengthen the starch granule, thus minimizing the extent of damage inflicted on the starch granules.

Table XV
Starch Amylose Content, Protein Content, Oil Content, and Endosperm Texture of Four Selected Botswana Sorghum Grain Types Used for Pasting, Textural and Microstructural Studies

Sorghum type	Starch Amylose Content (g/100 g)	Protein content[1] (g/100 g, db)	Oil content[1] (g/ 100 g, db)	Visual hardness[1,2]
BSH1	24.4a (0.4)	12.9c (0.3)	3.63c (0.06)	1.7a (0.7)
Kanye Std	28.8b (1.1)	11.4b (0.2)	3.34b (0.04)	3.7d (0.7)
Phofu	28.9b (0.6)	11.0a (0.2)	3.03a (0.09)	2.3b (0.4)
Town	30.0c (0.7)	13.0c (0.1)	3.79d (0.03)	2.7c (0.4)

Figures in columns with different letter notations are significantly different at $p<0.05$
Figures in brackets are standard deviations
[1]Obtained from Chapter 3.1
[2]Scale 1-5, with 1 denoting corneous (hard) and 5 representing floury (soft) endosperm

Table XVI
Pearson Correlation Coefficients Between the Pasting Properties of Sorghum Meals Produced from Four Sorghum Grain Types Milled using Hand Pounding, Roller Milling and Abrasive Decortication Followed by Hammer Milling, and the Meal Composition and Whole Sorghum Grain Characteristics

	PV	HPV	CPV	SB	WAI	WSI	DS	TA-XT2 Firmness	TA-XT2 Stickiness
HPV	-0.44								
CPV	-0.24	**0.93*** **							
SB	-0.05	**0.77****	**0.95*****						
WAI	**0.75****	-0.44	-0.31	-0.17					
WSI	0.29	-0.36	-0.34	-0.29	**0.65***				
DS	0.19	-0.31	-0.38	-0.41	0.32	0.36			
TA-XT2 Firmness	-0.27	**0.73****	**0.67***	0.55	-0.34	-0.30	-0.17		
TA-XT2 Stickiness	0.34	-0.17	-0.24	-0.27	0.11	0.22	0.52	0.31	
PSI	**0.88*****	**-0.70***	-0.56	-0.38	**0.89*****	0.53	0.41	-0.53	0.24
Meal Extraction	0.41	-0.39	-0.45	-0.45	**0.65***	0.43	0.40	-0.10	0.45
Meal Oil	**0.62***	**-0.79****	**-0.66***	-0.49	0.56	**0.62***	0.33	-0.40	0.53
Meal Ash	0.30	**-0.67***	**-0.64***	-0.55	0.54	**0.83*****	0.49	-0.35	0.44
Meal Protein	-0.29	-0.28	-0.38	-0.42	-0.10	-0.09	0.28	-0.02	-0.004
TADD Deh. Yield	-0.42	-0.13	-0.24	-0.31	0.08	0.57	0.46	-0.02	0.05
TKW	0.23	-0.17	-0.17	-0.15	-0.19	**-0.58***	0.009	0.21	0.48
Pericarp thickness	0.38	0.32	0.31	0.26	0.51	-0.34	-0.09	0.30	0.41
Visual hardness	0.35	0.03	0.20	0.32	-0.08	-0.54	**-0.60***	-0.16	-0.36
Starch amylose	0.09	0.01	0.20	0.33	0.03	-0.09	**-0.60***	-0.40	**-0.80****
Whole grain protein	-0.26	-0.48	-0.50	-0.47	-0.15	-0.04	0.25	-0.07	0.12
Whole grain fat	-0.17	-0.51	-0.48	-0.41	-0.19	-0.22	0.08	-0.13	0.02
Whole grain ash	-0.39	-0.30	-0.41	-0.45	-0.03	0.34	0.47	0.001	0.18
Sensory Cohesiveness	-0.10	**0.62***	**0.65***	**0.60***	-0.27	-0.46	-0.37	**0.71****	0.09
Sensory Stickiness	-0.26	**0.85*****	**0.78****	**0.64***	-0.41	-0.35	-0.37	**0.87*****	0.11
Sensory Coarseness	**-0.84*****	**0.70***	0.54	0.35	**-0.86*****	-0.56	-0.34	**0.62***	-0.18
Sensory Stiffness	-0.46	**0.71****	**0.63***	0.49	**-0.58***	-0.35	-0.17	**0.63***	0.23

PV-Pasting viscosity, HPV-Hot paste viscosity, CPV-Cold paste viscosity, SB-Setback, WAI-Water absorption index, WSI-Water solubility index, DS-Damaged starch, PSI-Particle size index, TKW-Thousand kernel weight

* p<0.05

**P<0.01

***P<0.001

3.3.3.2 Water absorption index (WAI)

Table XVII
Effects of Sorghum Grain Type and Milling Process on the Water Absorption Index (g water/ g, db) of the Sorghum Meal Produced by Milling Four Selected Sorghum Types using Hand Pounding, Abrasive Decortication and Hammer Milling, and Roller Milling

Sorghum grain type	Hand Pounding	Abrasive Decorticating - Hammer Milling	Roller Milling	Sorghum type effect
BSH1	1.20a (0.04)	1.28b (0.05)	1.58a (0.03)	1.35a (0.17)
Kanye Std	1.34b (0.07)	1.12a (0.06)	1.57a (0.03)	1.34a (0.20)
Phofu	1.39b (0.04)	1.35c (0.02)	1.55a (0.04)	1.43b (0.09)
Town	1.23a (0.07)	1.25b (0.03)	1.55a (0.02)	1.34a (0.17)
Milling process effect	**1.29b (0.09)**	**1.25a (0.10)**	**1.56c (0.03)**	**1.37**

Figures in columns and the bottom row with different letter notations are significantly different at $p<0.05$
Figures in brackets are standard deviations

RM meals absorbed 20-25% more water than HP and ADHM meals (Table XVII). WAI was found to correlate positively and significantly with PSI ($p<0.001$) (Table XVI), showing that fine meal particles absorbed more water than the coarse particles, probably owing to the increased surface area associated with the small particles.

3.3.3.3 Water solubility Index

Table XVIII
Effects of Sorghum Variety and Milling Process on the Water Solubility Index (g solutes / g, db) of the Sorghum Meal Produced by Milling Four Selected Sorghum Types using Hand Pounding, Abrasive Decortication and Hammer Milling, and Roller Milling

Sorghum type effect	Hand Pounding	Abrasive Decorticating - Hammer Milling	Roller Milling	Sorghum type effect
BSH1	0.030a (0.001)	0.038c (0.002)	0.042c (0.002)	0.037b (0.006)
Kanye Std	0.030a (0.002)	0.031a (0.002)	0.034a (0.001)	0.032a (0.002)
Phofu	0.037c (0.003)	0.041d (0.001)	0.041c (0.002)	0.040c (0.003)
Town	0.034b (0.003)	0.034b (0.001)	0.039b (0.000)	0.036b (0.003)
Milling process effect	**0.033a (0.004)**	**0.036b (0.004)**	**0.039c (0.004)**	**0.036**

Figures in columns and the bottom row with different letter notations are significantly different at $p<0.05$
Figures in brackets are standard deviations

The RM meals, which had the highest level of damaged starch and the highest WAI, correspondingly gave 16-18 % higher WSI than HP and ADHM meals (Table XVIII).

This is in agreement with findings by Morrison and Tester (1994) that damaged starch leaches out more soluble material than undamaged starch granules. These authors found that the soluble fractions of maize and wheat starch obtained from suspensions containing damaged starch consisted largely of low molecular weight amylopectin fragments and small amounts of lipid free amylose.

3.3.3.4 Effects of milling method and sorghum type on pasting properties of sorghum meals

Fig. 3.3.1 shows the effects of the milling processes on the pasting profiles of porridges from meals produced from sorghum grain type Town. Pasting profiles of the other 3 sorghum types (not shown) displayed the same general pattern. Pasting is a process which follows gelatinization, involving swelling of starch granules, leaching and alignment of granule components and disruption of starch granule remnants (Newport Scientific 1998). From the findings on WAI and WSI it seems possible that starch granules of RM meals absorbed more water and swelled more, thus giving the comparatively higher peak viscosities (PV) than HP and ADHM meals (Table XIX). PV marks the equilibrium point between granule swelling and rupturing (Bao and Bergman 2005), and is often correlated with final product quality parameters (Newport Scientific 1998). In this study, PV was found to correlate significantly ($p<0.05$) and positively with PSI and negatively with porridge sensory coarseness (Table XVI). As shown in Fig. 3.3.2(G-I), the RM meals were more uniform in particle size distribution and appeared to span a narrow particle size range below 1 mm, giving higher PSI values. As a consequence of this particle size profile, the particles presumably swelled uniformly within a narrow temperature range, causing the high PV values observed for RM meals. In comparison, the HP meals had particles spanning the entire size range from very fine (FP) to very large (LP) (Fig. 3.3.2A-C), thus giving relatively lower PSI and correspondingly lower PV values. The ADHM meals (Fig. 3.3.2D-F) were intermediate between RM and HP meals in these properties.

The sorghum type BSH1, which had relatively more corneous endosperm (Table XV) gave lower PV values (Table XIX), while Kanye standard, which had a relatively softer endosperm, gave higher PV values. This difference was perhaps due to the fact that starch granules, which are loosely packed in the soft endosperm (as described by Rooney and Miller (1982) and shown in Fig. 3.3.3A) were easily accessible to water, and presumably provided large surface area for more water absorption, hence swelling excessively. In comparison, in the corneous endosperm starch granules are compactly bound with protein bodies (Chandrashekar and Kirleis 1988). This structural arrangement is shown in Fig. 3.3.3B. According to these authors, the arrangement of protein bodies around the starch granules may inhibit starch gelatinisation, hence producing the low PVs observed for meals obtained with corneous sorghums. McDonough et al (1997) stated that cell walls can also inhibit swelling, hence restricting gelatinisation. Therefore, the differences in the swelling rates of the starch granules in porridges obtained with the different meals could also be explained by differences in the cell walls of the sorghum types, which were presumably still intact in the endosperm particles of the meals.

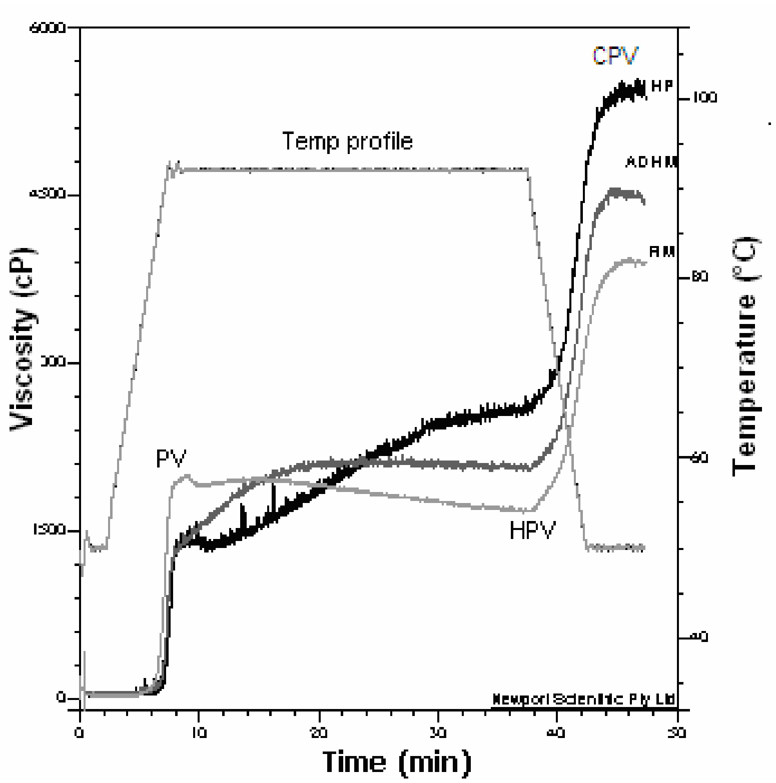

Fig. 3.3. 1. Effects of hand pounding (HP), abrasive decortication-hammer milling (ADHM) and roller milling (RM) on the pasting profiles of sorghum meal samples obtained with Town sorghum type. PV – peak viscosity, HPV – hot paste viscosity, and CPV – cool paste viscosity

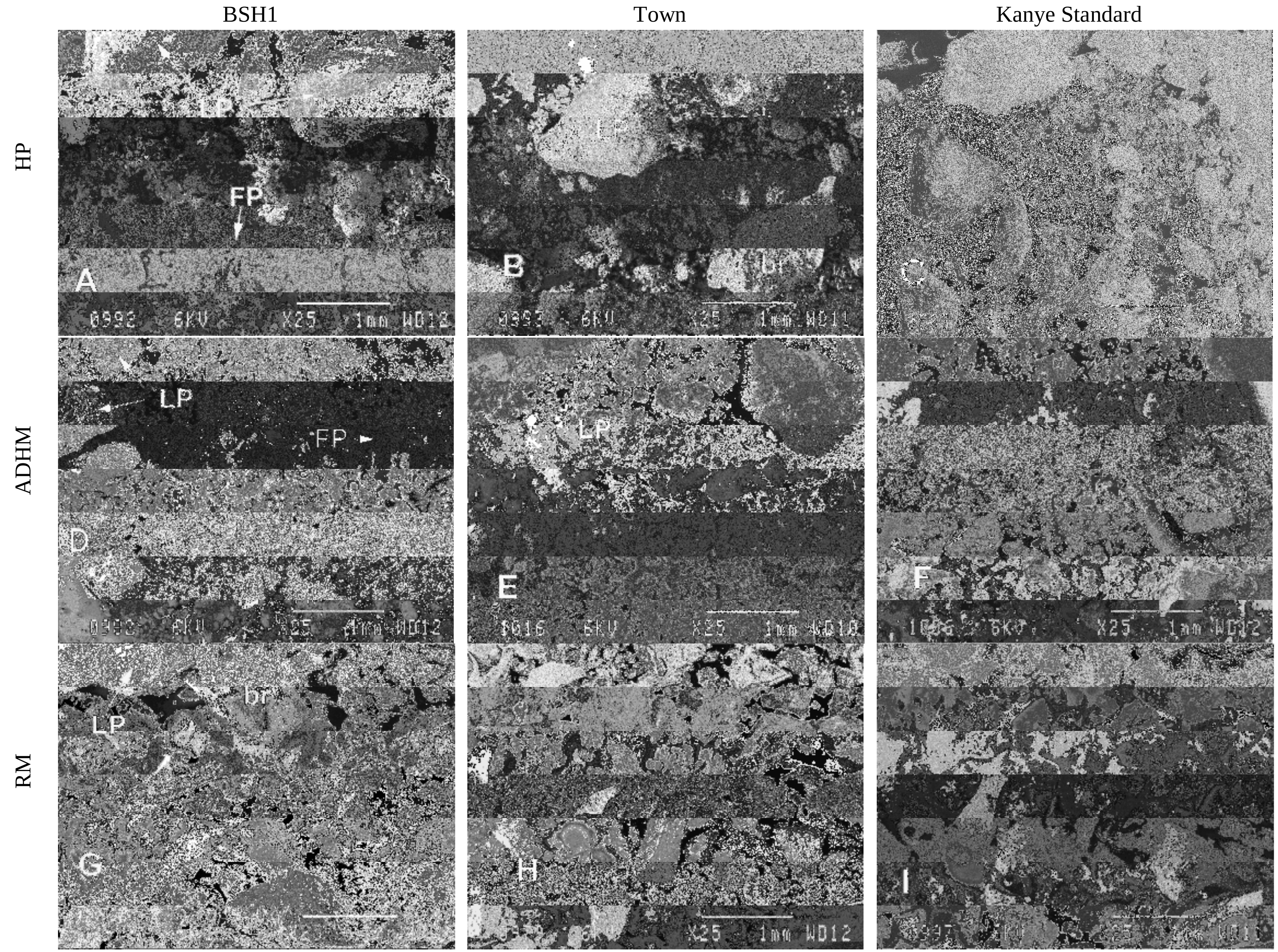

Fig.3.3. 2. Scanning electron micrographs of meals obtained by milling three sorghum types (BSH1 - ADG, Town – BEH, and Kanye Standard - CFI) by hand pounding (HP), roller milling (RM) and abrasive decortication followed by hammer milling (ADHM). LP – large endosperm particle, FP – fine endosperm particle, and br – bran particle.

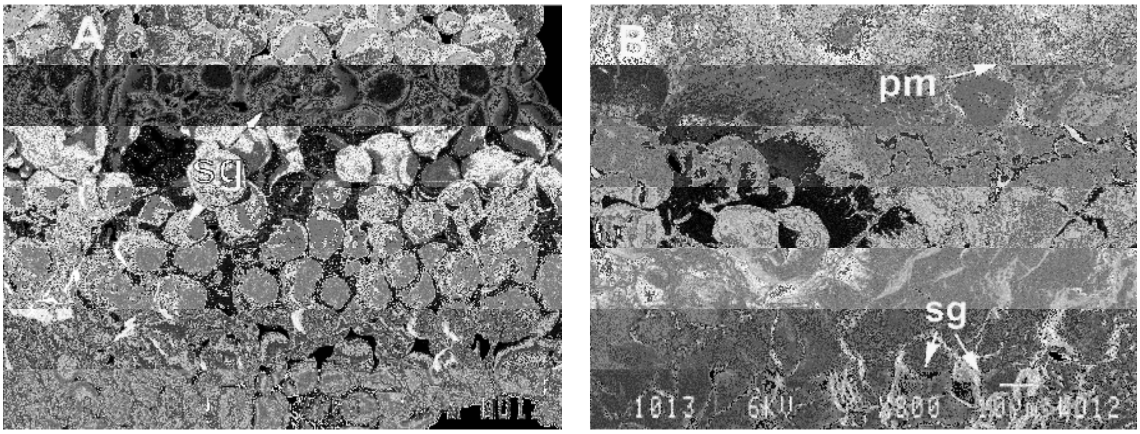

Fig. 3.3.3. Scanning electron micrographs of sorghum meals produced from sorghum type Phofu using abrasive decortication - hammer milling (A) free starch granules (sg) in a soft endosperm meal particle, and (B) starch granules (sg) compactly bound with protein matrix (pm) in a hard endosperm meal particle

HP meals gave the highest mean hot paste viscosity (HPV), while ADHM and RM meals produced pastes with 16% and 28% lower HPVs, respectively (Table XIX). In general RM pastes shear thinned slightly, while HP and ADHM did not shear thin (Fig. 3.3.1). This possibly indicates that unlike in HP and ADHM pastes, the swollen starch granules in RM pastes ruptured, leaching out amylose and amylopectin polymers into solution, thereby causing shear thinning of the paste. HPV correlated negatively ($p<0.01$) with meal oil (Table XVI), probably suggesting that lipid-amylose complexes were formed, thus restricting swelling and solubilisation of starch, as in rice (Bao and Bergman 2005). In this current study, it has been observed that HPV could represent the quality parameter by which the consumer evaluates the adequacy of porridge firmness. In practical porridge making, more sorghum meal would be added at this stage to improve porridge stiffness. The highest HPVs were obtained with the sorghum type Phofu and the lowest with Town. Since the meals of Phofu and Town differed only slightly in particle size index and amylose content (Tables XIII and XV), the variations in HPV may probably be explained by differences in the proportions and molecular structures of the leached starch polymers of the different sorghum types. As explained by Jane and Chen (1992), the viscosity of the starch paste not only depends on the extent of swollen starch granules but also on the structural formation and molecular weight of amylose and amylopectin components.

Table XIX
Peak Viscosity (PV) and Hot Paste Viscosity (HPV) of Sorghum Meals Obtained from Four Sorghum Types Milled by Hand Pounding, Abrasive Decortication-Hammer Milling and Roller Milling[1]

Sorghum type	PV (cP)				HPV (cP)			
	Hand pounding	Abrasive decortication - hammer milling	Roller milling	Sorghum type effect	Hand pounding	Abrasive decortication - hammer milling	Roller milling	Sorghum type effect
BSH1	1077a (26)	1507b (55)	2180ab(100)	1588a (485)	2552a (34)	2248b (44)	2029b (37)	2276b (230)
Kanye Std	1810d (74)	1800c (31)	2280b (29)	1963b (241)	2777a (18)	2424c (28)	2075b (51)	2425c (306)
Phofu	1558c (47)	1230a (67)	2143ab (56)	1644a (404)	3140b (82)	2516c (36)	2181b (22)	2612d (424)
Town	1364b (4)	1391ab (17)	1911a (89)	1555a (271)	2541a (84)	2038a (11)	1670a (66)	2083a (382)
Milling process effect	**1452a (283)**	**1482a (221)**	**2129b (154)**	**1688**	**2753c (259)**	**2306b (193)**	**1989a (205)**	**2349**

[1] Means in columns and the bottom row with different letter notations are significantly different at $p<0.01$
Figures in brackets are standard deviations

Table XX

Cool Paste Viscosity (CPV) and Setback Viscosity (SB) of Sorghum Meals Obtained from Four Sorghum Types Milled by Hand Pounding, Abrasive Decortication-Hammer Milling and Roller Milling[1]

Sorghum type	CPV (cP)				SB (cP)			
	Hand pounding	**Abrasive decortication - hammer milling**	**Roller milling**	**Sorghum type effect**	**Hand pounding**	**Abrasive decortication - hammer milling**	**Roller milling**	**Sorghum type effect**
BSH1	4743a (143)	4691a (152)	4250ab (15)	4562a (257)	2191a (128)	2444a (117)	2221a (52)	2285a (150)
Kanye Std	5968b (308)	5158b (49)	4608b (216)	5244b (622)	3191bc (318)	2734b (21)	2533a (186)	2819b (345)
Phofu	6982c (259)	4856ab (150)	4500ab (146)	5446b (474)	3842b (179)	2340a (125)	2319a (131)	2833b (767)
Town	5229ab (197)	4544a (45)	3921a (130)	4564a (579)	2688ab (169)	2506ab (48)	2251a (66)	2482a (212)
Milling process effect	**5730c (904)**	**4812b (257)**	**4320a (303)**	**4954**	**2978b (663)**	**2506a (169)**	**2331a (164)**	**2605**

[1] Means in columns and the bottom row with different letter notations are significantly different at p<0.01
Figures in brackets are standard deviations

As expected, a sharp increase in viscosity was observed upon cooling the pastes (Fig. 3.3.1), with RM pastes giving the lowest mean cool paste viscosity of 4320 cP, which was 25% lower than the highest (5730 cP) achieved with HP meals (Table XX). Cool paste viscosity (CPV) is caused by retrogradation of starch, a process involving re-association of starch molecules (initially amylose), which form a firm gel with imbedded swollen starch granule remnants (Bao and Bergman 2004). Therefore, CPV indicates the ability of the material to form a viscous paste after cooking and cooling, and is commonly used to assess the textural quality of products (Newport Scientific 1998). Overall, Phofu gave significantly ($p<0.01$) higher CPVs and Town gave the lowest, probably for the same reasons as for HPV.

The difference between CPV and HPV is defined as setback (SB) (Newport Scientific, 1998). HP meals gave the highest mean SB (2978 cP), which was 19 and 28% higher than mean values for ADHM and RM pastes, respectively. Mean SB values for ADHM and RM meals were not significantly different (Table XX). Sorghum type Kanye standard gave pastes with the highest SB values, while BSH1 consistently produced the lowest values. Kanye standard had a softer endosperm and higher proportion of amylose in the starch than BSH1 (Table XV). Therefore the higher SB associated with Kanye standard could indicate that more amylose was released into solution, which retrograded and formed a firmer gel on cooling, than in BSH1.

3.3.3.5 Effects of milling method and sorghum type on porridge texture (firmness and stickiness)

Fig 3.3.4 illustrates variations in the TA-XT2 Texture Analyser force-time curves obtained with porridges prepared from meals of Kanye standard, obtained with the three different milling processes.

Point A represents the point at which a 0.05 N trigger on the surface of the porridge was attained. The probe then penetrated the porridge to a depth of 10 mm, during which compression force was exerted on the porridge. From point A to B the porridge was packed tightly in the cylinder by the descending probe. From point B the porridge was displaced until the probe reversed direction at point C. Point C represents the maximum force attained under the conditions of the test, and was used as an index of the porridge firmness. As the direction of the probe reversed (point C to E), a negative resistance force was recorded, caused by the porridge adhering to the probe. The maximum negative force (point D) was used as an indicator of porridge stickiness (adhesiveness). Adhesion between the porridge and the probe was probably caused by hydrogen bonding between the hydrogen and oxygen atoms (Morrison and Boyd 1983) of polymethyl methacrylate (Perspex probe) and the hydroxyl groups of the starch molecules (and their hydrolysis derivatives) in the porridge.

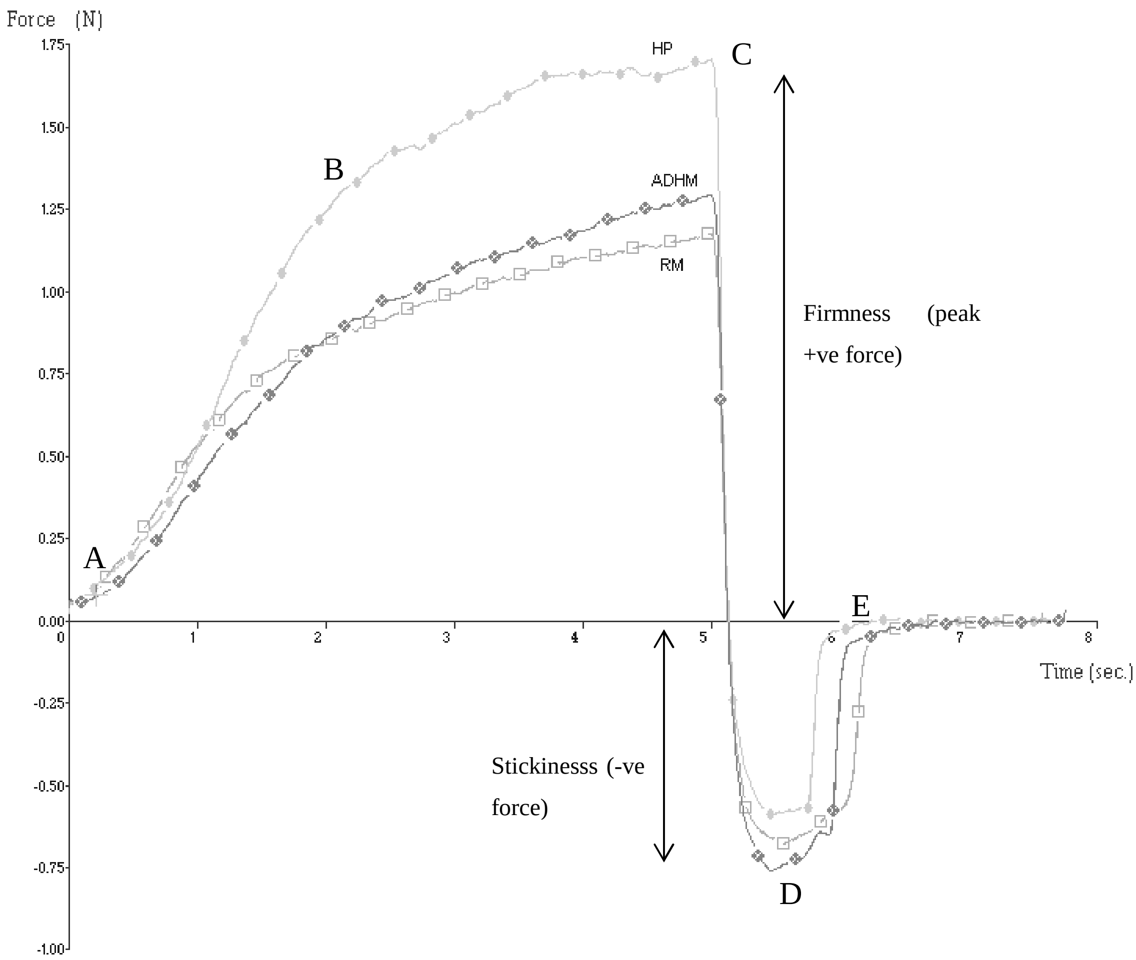

Fig. 3.3. 4. Effect of milling process (hand pounding (HP), abrasive decortication-hammer milling (ADHM) and roller milling (RM)) on the textural properties of sorghum meal obtained with sorghum type Kanye std. Each curve is an average of six plots

Firmness

Milling process had highly significant ($p<0.001$) effect on porridge firmness (Table XVI), with HP producing porridges that required 27% and 45% more force to displace than porridges obtained with ADHM and RM, respectively. Sorghum type also had a highly significant effect ($p<0.001$) on porridge firmness. Of most importance was that the interactive effect of both sorghum type and milling process was also highly significant, showing that sorghum firmness depended on both factors. For example, BSH1 (having hard endosperm) produced the firmest porridges with ADHM (1.87 N) and RM (1.35 N), but gave the softest porridge with HP (1.58 N). By comparison, Town (intermediate endosperm texture) produced softer porridges with all the milling processes. Overall, BSH1 produced porridges which were 33% firmer than porridges obtained with Town. The differences in the firmness of the porridges may be explained with the aid of the structural model for pure starch pastes described by Morris (1990), and also through the microstructures observed using SEM (Figs. 3.3.5 and 3.3.7). According to this model, the textural properties of the starch paste are influenced by the formation of the continuous phase of the leached starch molecules, the rigidity of the starch granule remnants, the interactions between the leached starch polymers and the granule remnants, and the concentration of the remnants. In Fig 3.3.5A, starch granule remnants in the porridge obtained with Phofu, which gave firmer porridge than Town (Table XX), appeared to be more intact than those from Town (Fig. 3.3.5B). These starch granule remnants were only evident in some areas, possibly from the hard endosperm, of the freeze-dried specimen obtaind with porridges prepared from HP (not shown) and ADHM (Fig 3.3.5) meals, showing that these porridges were not homogeneous in composition, unlike those obtained with RM.

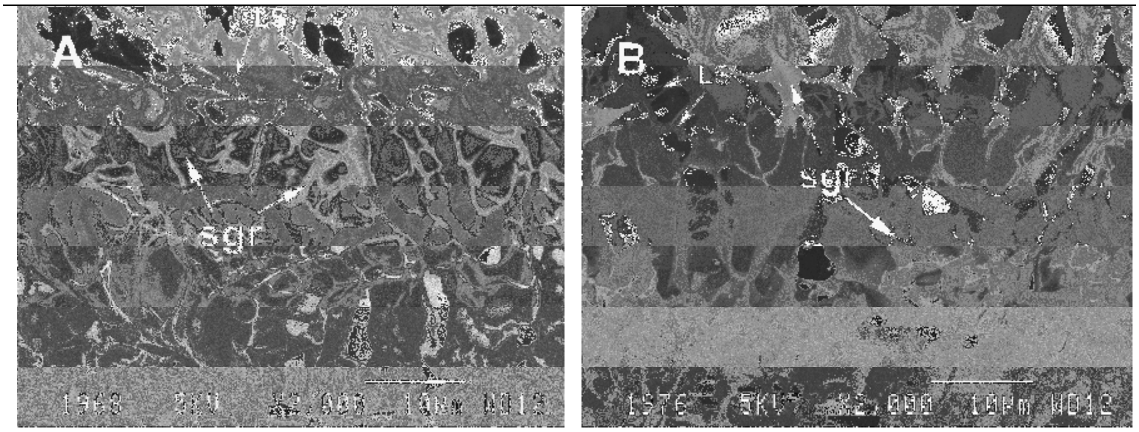

Fig. 3.3. 5. **Scanning electron micrographs of cryofrozen and freeze-dried sorghum porridges showing starch granule remnants (sgr) in porridges prepared from abrasively decorticated and hammer milled (A) Phofu and (B) Town sorghum types.**

Fig. 3.3.6 shows that upon cooking (demonstrated with the hard-endosperm BSH1 sorghum), the sorghum starch X-ray diffraction pattern transformed from the A type in raw meals to the B type (Hoseney 1994) in freeze-dried porridges. The different X-ray diffraction patterns observed are caused by differences in the degree of molecular ordering and crystallinity in the crystal structures of the different starch specimens. According to Imberty et al (1991), the polymer chains in starch are made of double helices, and the symmetry of these helices in A type starch differ from those in the B type in that the repeated unit in A type is maltotriosyl unit, while that in the B type is a maltosyl unit. Again, the B type starch has a large void in the crystal lattice that may accommodate large quantities of water molecules while the A type starch has no void. The transformation from A to B type was indicated by the reduction of the number of major peaks from three in the diffractograms of raw samples (peaks 22.4, 27.3 and 35.2 Å) to one in the cooked samples (30.8 Å). The change in the X-ray pattern was identical for the differently milled samples, showing that starch gelatinization and retrogradation occurred in all the porridges derived therefrom. This was consistent with the fact that raw cereal starches give the A type X-ray pattern, while retrograded starch gives the B pattern (Hoseney 1994). The other sorghum types used, which were relatively softer than BSH1, were presumably transformed in the same manner.

Fig. 3.3.7 illustrates other differences observed in the microstructure of the different porridges. Unlike in Fig 3.3.5, which illustrated microscopic views of structures of less disrupted starch granules, which presumably originated from the hard endosperm particles, Fig 3.3.7 seem to show structures of continuous retrograded starchy phase, which was presumably a mix of soluble starch exuded from the ruptured granules, the protein bodies, and other components of the melted grain. The pores probably represent pockets previously occupied by the removed water. Clearly, the starch granules of the different porridges appeared to have ruptured to different extents. The fine porous structure observed for the porridges from RM meals probably indicates that almost complete leaching of amylose and amylopectin molecules, and complete starch granule disruption, occurred in these porridges (G-I). Possibly, water was uniformly dispersed within the RM porridges, accounting for the homogeneous structure. In comparison, porridges from HP (A-C) and ADHM (D-F) meals had structures which were relatively non-uniform and had large pores (p).

Table XXI

Effects of Milling Process (Hand Pounding, Roller Milling, Abrasive Decortication – Hammer Milling) and Sorghum Type on Sorghum Porridge Firmness and Stickiness[1]

Sorghum type	Firmness (N)				Stickiness (N)			
	Hand pounding	Abrasive decortication - hammer milling	Roller milling	Sorghum type effect	Hand pounding	Abrasive decortication - hammer milling	Roller milling	Sorghum type effect
BSH1	1.58a (0.09)	1.87d (0.11)	1.35d (0.07)	1.60c (0.24)	-0.70b (0.08)	-0.91c (0.06)	-0.86c (0.04)	-0.82d (0.11)
Kanye Std	1.88b (0.13)	1.32c (0.02)	1.18b (0.03)	1.46b (0.32)	-0.64ab (0.07)	-0.75b (0.03)	-0.71b (0.04)	-0.70c (0.06)
Phofu	1.79b (0.07)	1.21b (0.03)	1.26c (0.04)	1.42b (0.27)	-0.62ab (0.04)	-0.60a (0.03)	-0.73b (0.04)	-0.65b (0.07)
Town	1.61a (0.07)	1.01a (0.05)	0.99a (0.03)	1.20a (0.30)	-0.59a (0.03)	-0.57a (0.04)	-0.58a (0.02)	-0.58a (0.03)
Milling process effect	**1.72c (0.16)**	**1.35b (0.33)**	**1.19a (0.14)**	**1.42**	**-0.64a (0.07)**	**-0.71b (0.14)**	**-0.72b (0.11)**	**-0.69**

[1]Where the means for have different letters for a given parameter (e.g. firmness, they are significantly different from each other (p<0.001)

Means in columns with different letter notations are significantly different at p<0.001

Figures in brackets are standard deviations

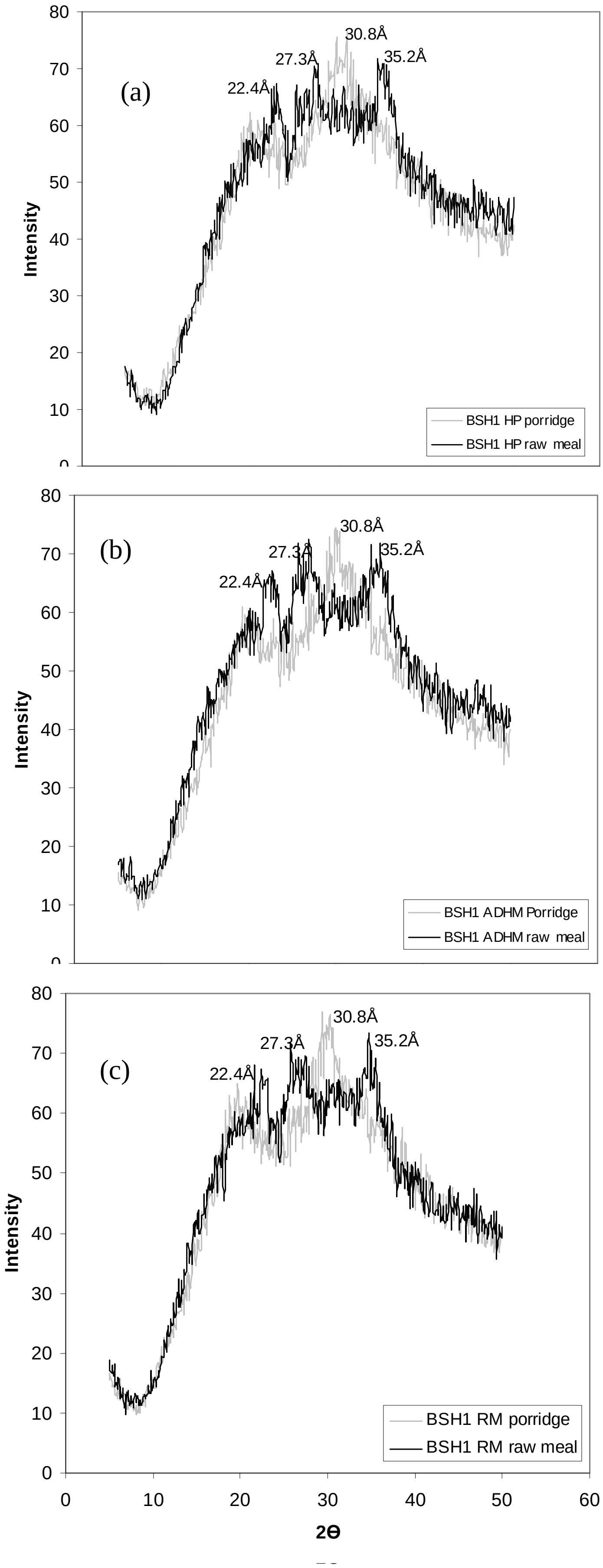

Fig. 3.3.6. X-ray diffractograms of raw sorghum meals, and freeze-dried porridges prepared therefrom, obtained with BSH1 sorghum type milled by (a) hand pounding (HP), (b) abrasive decortication-hammer milling (ADHM) and (c) roller milling (RM). Solid black line depicts A type X-ray diffraction pattern and the light grey line shows the B type diffraction pattern.

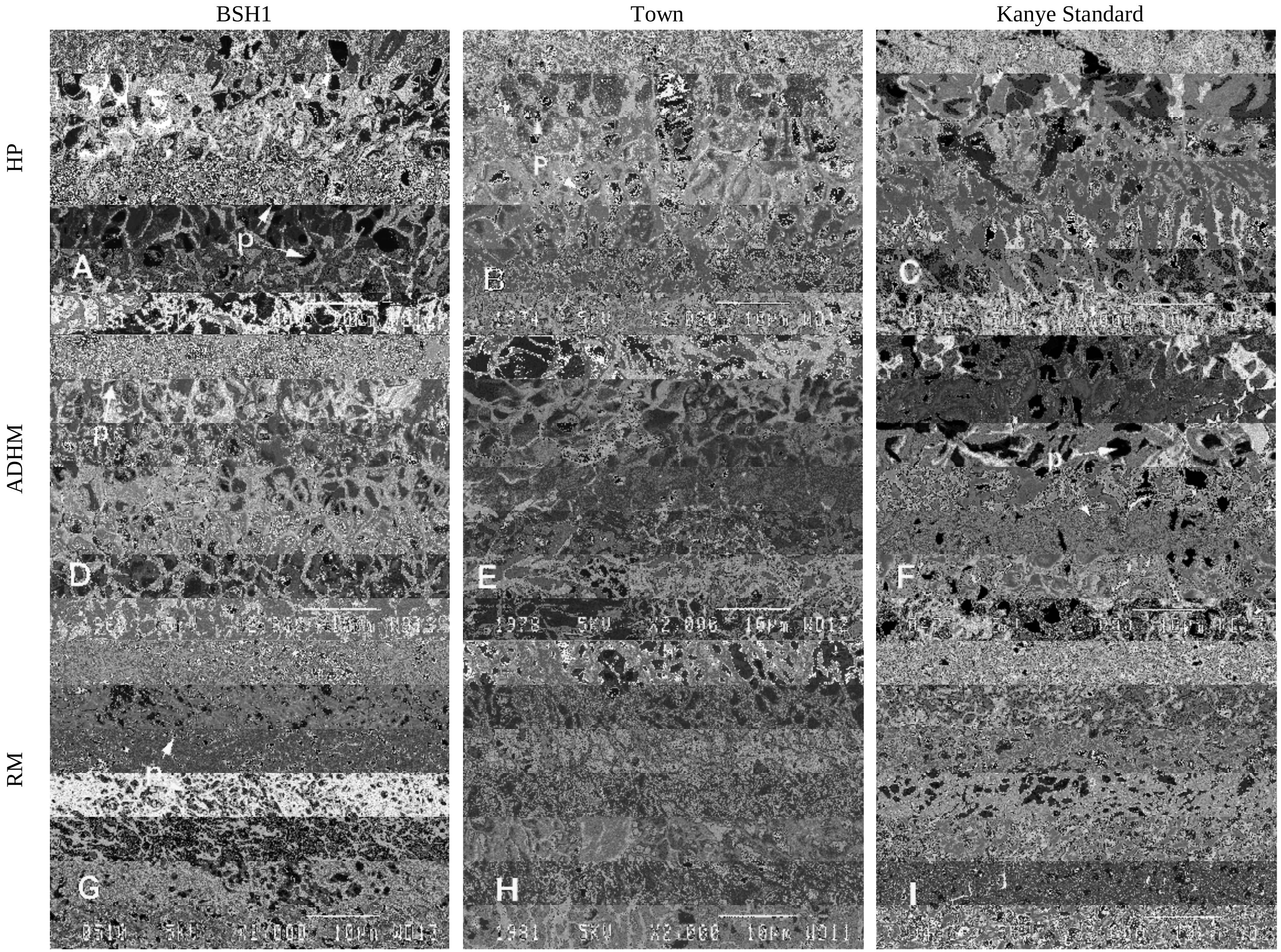

Fig. 3.3.7. Scanning electron micrographs of cryofrozen and freeze-dried components of sorghum porridges prepared from meals obtained by milling three sorghum types (BSH1 - ADG, Town – BEH, and Kanye Standard - CFI) by hand pounding (HP), roller milling (RM) and abrasive decortication followed by hammer milling (ADHM). These show variations in the porous (p) structure.

These differences are probably attributable to differences in the particle size distributions of the meals, thus causing differences in the textural properties of the porridges. As explained, the firming of starch gels is a consequence of starch retrogradation, associated primarily with amylose in the early stages of starch gel formation (Bao and Bergman 2004). However, in this study no significant correlation between amylose content and porridge firmness was noted, suggesting that other factors of the porridge matrix (such as protein) also influenced porridge firming significantly.

Stickiness

Milling process and sorghum type, together with their interaction effects, were also highly significant ($p<0.001$) for sorghum porridge stickiness (Table XXI). Porridges made from RM and ADHM meals were more sticky. Less sticky porridges were obtained with the sorghum type Town (having intermediate endosperm texture), which had 30% starch amylose content, while BSH1, which had 24% starch amylose content, gave the stickiest porridges. Thus, porridge stickiness was negatively correlated with starch amylose content (Table XVI). This relationship suggests that large amounts of leached amylose inhibited porridge stickiness, and is perhaps in agreement with the existing knowledge of the pasting properties of amylose and amylopectin, that in mixtures of amylose and branched starch molecules (presumably amylopectin molecules), the branched molecules seem to interact with amylose inhibiting it from forming long double helices, thus limiting the development of stable aggregates (Klucinec and Thompson 1999). In addition, the findings of the present work agree with observations made in other processed cereal products. For example, Aboubacar and Hamaker (2000) found that sorghum couscous stickiness correlated positively with high molecular weight fragments of amylopectin soluble in aqueous extracts of couscous, suggesting that high proportions of amylopectin dispersed in the starch gel promoted stickiness. In another study, Iturriaga et al. (2006) observed that rice cultivars with proportionally high amylopectin content were stickier than those with proportionally higher amylose. Consequently, these authors attributed rice stickiness to amylopectin. In this current study, stickiness did not correlate with any of the sensory textural properties, perhaps showing that this test did not emulate sensory stickiness.

3.3.3.6 Principal Component Analysis (PCA)

PCA was performed to better understand relationships between the meal functional properties, the pasting and textural parameters of the porridges, and the physicochemical properties of the whole grains and meals (Chapter 3.1). The first three principal components (PCs) explained 74% of the variation observed among the samples. PC1 separated the more firm, cohesive and sticky porridge samples (all porridges obtained with Phofu and Kanye Std using HP and ADHM meals), from those on the right (all the porridges made from RM meals, and porridges made from BSH1 and Town meals obtained with ADHM) (Fig. 3.3.8B). The latter were characterized by higher PSI (i.e. large amounts of small meal particles), higher amounts of damaged starch, higher WAI and WSI, and higher meal oil and ash contents (Fig. 3.3.8A). Porridge firmness, both instrumental and sensory, was positively correlated with the pasting properties (HPV, CPV and SB) and was negatively correlated with damaged starch, meal oil and ash content, PSI, WAI and WSI of the meal. Three distinct groups of porridge samples (marked ‘M’) associated with the different milling processes were revealed (Fig. 3.3.8B). HP produced porridges which mainly displayed desirable textural characteristics (such as firmness, coarseness and cohesiveness), while RM gave porridges which lacked these properties. ADHM generally gave porridges which were intermediate in the textural characteristics.

PC2 separated coarser porridges to top of the score plot (Fig. 3.3.8B). These meals were obtained with sorghum types that had more corneous endosperms, mainly BSH1 and Town, and were associated largely with HP and ADHM milling processes. PC3 separated porridges on the basis of instrumental stickiness and starch amylose content. Porridges obtained with BSH1, which were characterised by increased stickiness, presumably because of the low amounts of starch amylose, were separated to the top of the score plot (Fig. 3.3.9B), while porridges prepared fromTown, which by contrast were less sticky and had high amounts of starch amylose, were distributed on the bottom of the plot. Because all the porridges obtained with each of the sorghum types were distributed close to each other on the same area of the plot (Fig. 3.3.9B), it could be deduced that stickiness of the porridge was primarily determined by the sorghum type.

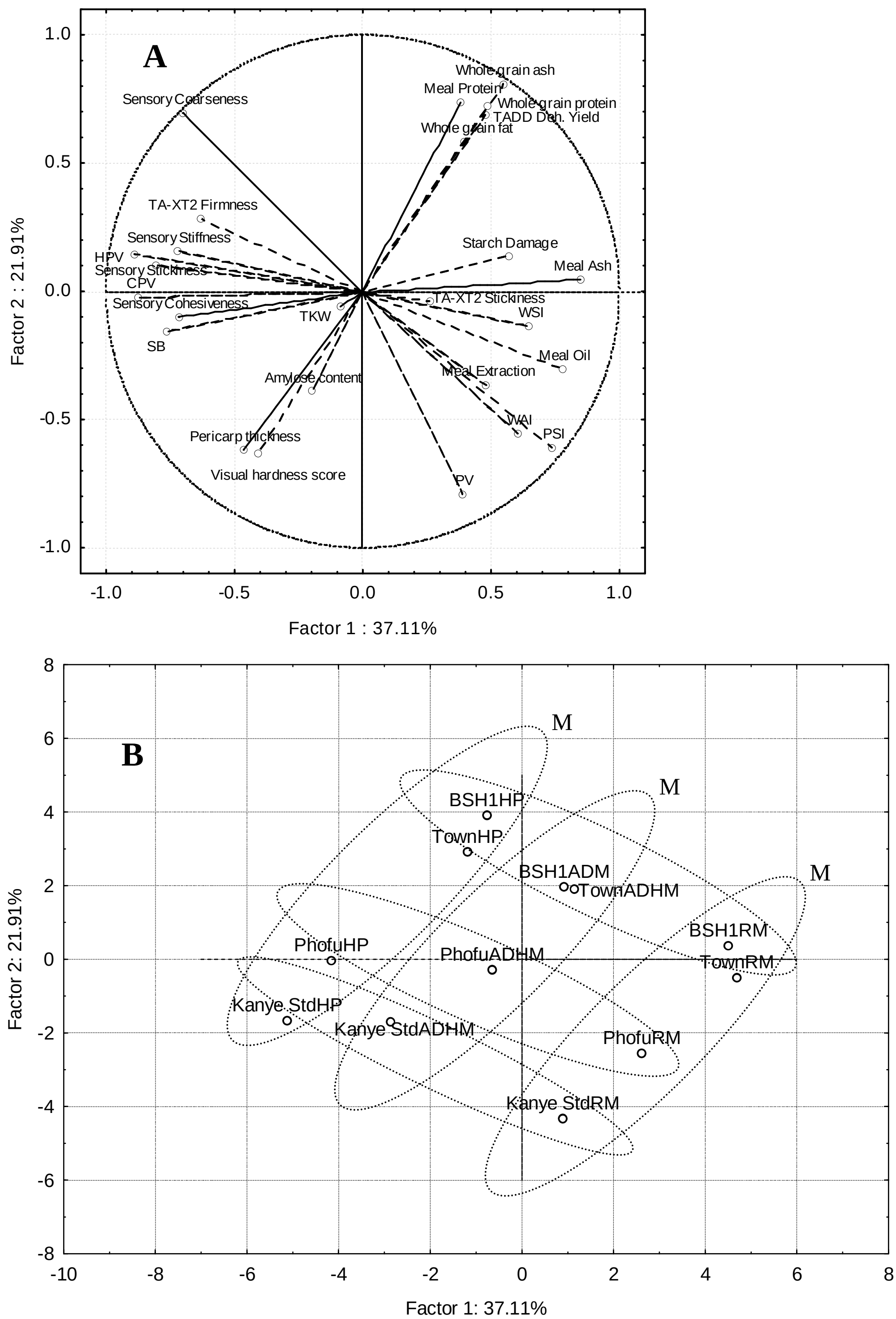

Fig. 3.3. 8. Principal component analysis (PCA) plots of sorghum porridge samples prepared from four sorghum types (BSH1, Phofu, Kanye Std and Town) milled by hand pounding (HP), abrasive decortication – hammer milling (ADHM), and roller milling (RM). (A) loadings projections of determined variables and (B) score plot of the porridges on PC1 (Factor 1) and PC2 (Factor 2)

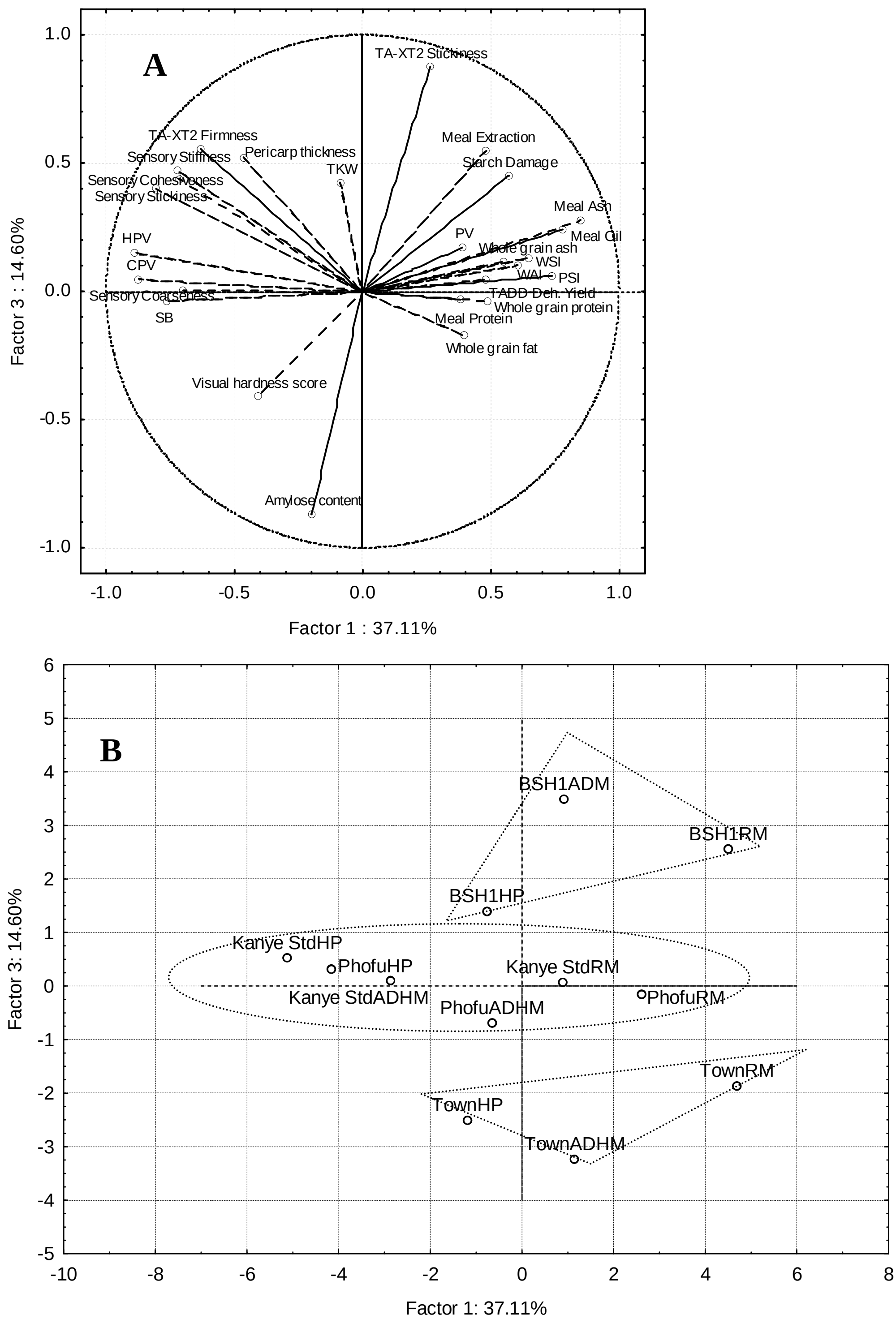

Fig. 3.3. 9. Principal component analysis (PCA) plots of sorghum porridge samples prepared from four sorghum types (BSH1, Phofu, Kanye Std and Town) milled by hand pounding (HP), abrasive decortication – hammer milling (ADHM), and roller milling (RM). (A) loadings projections of determined variables and (B) score plot of the porridges on PC1 (Factor 1) and PC3 (Factor 3)

The influence of sorghum type appears to be important not only for sorghum porridge but for other sorghum products as well. For example, Yetneberk et al (2004) also used PCA to relate sorghum cultivars that had variable endosperm texture, to sensory characteristics of injera (fermented flat bread) and established that sorghum cultivar affected injera making and keeping qualities.

3.3.4 CONCLUSIONS

Sorghum meal functional properties (water absorption and water solubility), pasting characteristics and porridge textural properties (firmness and stickiness) are affected by sorghum type and the milling process, but milling process has more effect than sorghum type on all of the properties except stickiness. Differences in meal particle size cause variations in porridge firmness, where the increase in the proportion of coarse endosperm particles causes an increase in porridge firmness, primarily because the coarse particles absorb water slowly, thus restricting swelling of the starch granules, such that there is a high proportion of non-ruptured gelatinised starch granules that reinforce the porridge matrix. Corneous sorghum types with high amounts of protein produce firmer porridges, owing to presence of the hard and less water-permeable protein-starch matrix in the endosperm meal particles. On the basis of this information, a meal quality grading scheme that takes into account the particle size profile and protein levels that would give porridge with quality characteristics that meet consumer sensory textural expectations can be devised.

Sorghum types which have more corneous endosperm and high amounts of protein produce porridges that are coarser in texture, owing to the hard and impermeable protein-starch matrix associated with the distribution and high content of protein bodies in the corneous endosperm.

Hot paste viscosity (HPV) correlates highly with the instrumental and sensory porridge firmness and could be used to predict porridge firmness acceptable by consumers.

3.3.5 LITERATURE CITED

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