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Sorghum dry-milling processes and their influence on meal and porridge quality

By

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DECLARATION

I declare that the dissertation herewith submitted for the degree of PhD (Food Science) at the University of Pretoria, has not previously been submitted by me for a degree at any other university or institution of higher education.

Martin Mosinyi Kebakile

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ABSTRACT

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By

Martin Mosinyi Kebakile

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Sorghum bicolor (L.) Moench is an important staple cereal in Africa, where it ranks second after maize. Despite its importance, the sorghum food industry remains non vibrant, constrained in part by inadequate milling technology. Presently, Prairie Research Laboratory (PRL) type abrasive dehullers and hammer mills, which apparently produce meals of inconsistent quality and low output, are generally used for industrial milling of sorghum. Efforts to improve sorghum milling require an in-depth understanding of how milling process and grain type affect the sensory characteristics of the final food products. Such knowledge is currently lacking. Therefore, this study investigated the effects of milling process and sorghum type on the quality of sorghum meal and porridge.

Twelve sorghum types with diverse physico-chemical properties were milled by roller milling (RM), abrasive decortication-hammer milling (ADHM) and hand pounding (HP), and the effects on meal extraction and meal quality were evaluated. Porridges were prepared using standardised Botswana recipe, and their sensory profiles were characterised using Descriptive Sensory Analysis. Additionally, factors that affect the texture of sorghum porridge were investigated, and suggestions for improving the sorghum milling process are given.

Both the sorghum type and the milling process affected the quality of the meal and the sensory characteristics of the porridge, but the milling process was found to have more effects on these characteristics than the sorghum type, because of the diverse milling principles of the milling processes. RM gave far better extraction rate and had

substantially higher throughput than HP and ADHM. However, meals obtained with RM had slightly more ash and were a little darker, and gave porridges which were correspondingly darker in colour, had slightly more branny aroma, more astringency and bitter taste, than meals obtained with the other two milling processes, indicating higher bran contamination of the meals, presumably caused by fragmentation of the pericarp. Clearly, even with tempering the pericarp was still friable, and hence, requires indepth sorghum tempering studies. Grain hardness proved to be important for milling, as it correlated positively with extraction rate with ADHM and HP, but not with RM. Hard grains generally gave coarser and better refined meals, and produced porridges that were firmer, compared to soft grains. Weathered and pigmented pericarp sorghums produced dark and specky meals, and gave porridges with apparently undesirable sensory qualities, because of staining caused by the pericarp pigments, showing that these characteristics affect the quality of sorghum foods negatively. When used with hard and light coloured sorghums, ADHM gave more appealing meal and porridge qualities (light coloured, firm texture and enhanced cereal aroma), indicating that dry abrasive decortication is advantageous for production of sorghum products with superior sensory qualities.

Firmness varied considerably among the porridges, caused by differences in the meal particle sizes, which was predominantly a consequence of the milling process. An increased proportion of coarse endosperm particles, as was the case with HP meals, caused increased porridge firmness. The coarse particles absorbed water slowly, thus restricting swelling of the starch granules, such that a high proportion of non-ruptured gelatinised starch granules that reinforce the porridge matrix resulted. The sorghum type also influenced porridge firmness, whereby the corneous sorghum types with high protein content produced firmer porridges, owing to presence of the hard and less water-permeable protein-starch matrix in the endosperm meal particles.

Because abrasive decortication gave meals and porridges with superior sensory qualities, while roller milling prduced high throughputs, a roller milling system that is preceded by a dry abrasive decortication process is recommended as a versatile milling process for industrial processing of diverse sorghum products that have superior sensory qualities.

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1 INTRODUCTION

Sorghum bicolor (L.) Moench is the second most important cereal food, after maize, for millions of people living in the semi-arid and sub-tropical regions of Africa (Taylor 2003). Although globally sorghum is ranked fifth in importance (after wheat, maize, rice and barley), its critical role as a source of energy and dietary protein to the food insecure people of sub-Saharan Africa cannot be overemphasised (Dendy 1995, Taylor 2003).

In Southern Africa, sorghum is consumed popularly as staple porridge (Taylor 2003), which is commonly prepared from decorticated endosperm meal. Traditionally, the meal is produced by hand pounding, using wooden pestle and mortar, or by grinding with a stone (Murty and Kumar 1995). Presently, milling by mechanical means, commonly using abrasive decorticators and hammer mills, has become popular (Bassey and Schmidt 1989, Rohrbach 2003). Although the abrasive decorticators are credited for having stimulated the development of a sorghum milling industry, the types commonly used are limited in terms of production throughput and control of meal quality, and they are also associated with high milling losses (Gomez 1993, Taylor and Dewar 2001). Thus, there is still lack of suitable sorghum milling technology that could transform sorghum processing into a vibrant food industry, making sorghum competitive with other major cereals, such as maize and wheat. A recent development in Southern Africa has been the introduction of simplified roller mills with two to three pairs of rolls and vibrating sieving screens (Taylor and Dewar 2001). These types of roller mills have attracted scientific attention as potential alternatives to abrasive decorticators for sorghum milling (Gomez 1993). However, the performance of these roller mills with regard to production of meals that make porridge of good quality has not been investigated.

Consumers generally measure the quality of sorghum porridge in terms of overnight keeping quality (Fliedel 1995), texture (Aboubacar et al 1999, Boling and Eisener 1982, Taylor et al 1997), colour (Brannan et al 2001), taste and aroma (Aboubacar et al 1999). Early findings by the Botswana Ministry of Agriculture (1978) revealed that not all sorghum varieties make porridge that is acceptable by consumers. Recently, unpublished findings of consumer market studies conducted in Botswana by the National Food Technology Research Centre revealed that some newly developed varieties with superior agronomic performance to the traditional varieties were not well adopted by farmers, as they were claimed to make porridge with inferior sensory qualities. This perception has had negative impact on the national sorghum breeding programme in Botswana, and probably also in other countries.

It is generally accepted that the sensory attributes of sorghum products are influenced mainly by the physico-chemical properties of the grain (Serna-Saldivar and Rooney 1995) and the milling process used to produce the flour or meal (Gomez 1993, Munck et al 1982). It has also been established that sorghum varieties differ very substantially in their physical and chemical characteristics (Rooney and Miller 1982), and therefore, will produce products with varied qualities. However, information is very scanty on how these sorghum grain characteristics influence the quality of the sorghum meal, and subsequently, the quality of the sorghum porridge.

In summary, it appears the quality of the sorghum porridge is determined by the sorghum grain characteristics and the milling process used, but information is scarce on the relationships between these factors. Such information, if well established, could pave the way for an improved industrial sorghum milling process, and assist breeders and millers in producing products with specific sensory characteristics that are well acceptable by consumers. Therefore, in this project, the effects of the sorghum type (grain characteristics) and the milling process on the quality of the sorghum meal and porridge were investigated.

2 LITERATURE REVIEW

Comprehensive reviews of the structure, chemical composition and nutritional value of sorghum have been published (FAO 1995, Rooney and Serna-Saldivar 1993, Serna-Saldivar and Rooney 1995). These reviews make excellent references for detailed information on the physico-chemical properties of sorghum in general. In this review focus is put on the kernel characteristics of the non waxy sorghum (normal type) that relate to milling performance and quality attributes of the final sorghum products, the dry milling processes applied to sorghum, and the quality evaluation and standards for sorghum grain and end-use products.

2.1 Sorghum kernel structure and its relation to milling performance and porridge quality

Detailed structural descriptions of the sorghum kernel are documented by Rooney and Miller (1982). In their descriptions, the sorghum kernel is considered to be a naked caryopsis, which varies widely in size and shape among the sorghum types. The kernel is generally spherical in shape, measuring 4 mm long, 2 mm wide and 2.5 mm thick. The kernel weight, volumetric weight and density can range between 25 and 35 mg, 708 and 760 kg / m^3, and 1.26 and 1.38 g/cm^3, respectively. Kernels of some sorghum types retain glumes after threshing (Rooney and Serna-Saldivar 1993). These glumes may be red, purple or tan (Rooney and Miller 1982), and may also be sienna (Prof G. Peterson, sorghum breeder, University of Texas A&M, personal communication). When the grain is exposed to damp conditions while in the field, intensely coloured pigments leach from the glumes and stain the kernel (Serna-Saldivar and Rooney 1995). The stained kernels subsequently result in the discolouration of the final sorghum products.

Rooney and Miller (1982) also reviewed the structure of the sorghum caryopsis, which consists of three main parts, namely the pericarp, endosperm and germ (Fig. 2.1). The relative proportions of these components vary among sorghum types, influenced by genetic and environmental factors (Serna-Saldivar and Rooney 1995). However, on average these components constitute about 6%, 84% and 10% of the sorghum kernel, respectively (Rooney and Serna-Saldivar 1993).

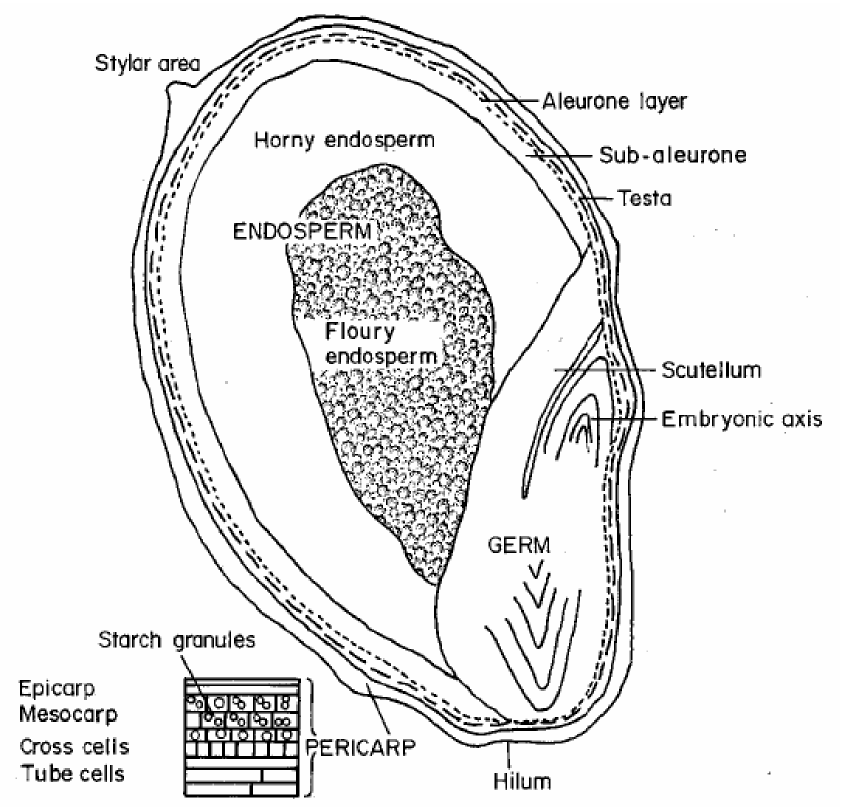


Fig. 2.1. **Section through a sorghum kernel (Rooney and Miller 1982)**

2.1.1 Pericarp

The sorghum pericarp (which originates from the ovary wall) is the outer covering adhering strongly to the endosperm, and is characterized by three distinctive layers: the epicarp, mesocarp and endocarp (Earp et al 2004). The epicarp is the outermost layer, and it is generally coated with wax and contains coloured pigments, which determine the colour of the grain (Serna-Saldivar and Rooney 1995). The mesocarp is the middle layer, which often contains starch granules, a characteristic unique to sorghum and pearl millet (Serna-Saldivar and Rooney 1995). According to Taylor and Dewar (2001) the presence of starch in the mesocarp could account for the high friability of the sorghum pericarp. A friable pericarp is disadvantageous for dry milling as it fragments into fine pieces and escape separation, thus contaminating the meal (Perten 1984). The thickness of the mesocarp determines the overall thickness of the pericarp. This is controlled by the Z-gene, where the dominant Z gene produces a thin pericarp and the recessive gene combination (zz) codes for a thick mesocarp (Rooney and Miller 1982). Thin pericarps tend to adhere tightly to the kernel, while thick pericarps attach loosely (Bassey and Schmidt 1989). Consequently, the thickness of the pericarp is an important grain property because sorghum types with thick pericarps decorticate easily by hand pounding than sorghums with thin pericarps, and the latter types perform better under mechanical decortication (Maxson et al 1971, Scheuring et al 1983). Pericarp thickness is also important in that sorghum types with thick pericarps are prone to weathering (Serna-Saldivar and Rooney 1995). These types of sorghums were shown to consistently contain higher amounts of phenolic compounds (Beta et al 1999), which if incorporated into derived food products could cause astringent taste (Drewnoski and Gomez-Carneros 2000). The mesocarp forms a mechanically weak area, which permits the pericarp to peel off in large flakes during milling (Shepherd 1981). The endocarp is the innermost layer of the pericarp, which consists of cross and tube cells (Earp et al 2004). According to Evers and Miller (2002), empty cells exist between the outer pericarp layers and the inner layers (presumably the cross and tube cells) which rapidly absorb water (about 4-5% of grain weight) when soaked, thus toughening the pericarp and facilitating its separation from the endosperm. This water absorption process is exploited in hand pounding of sorghum by "conditioning" (or tempering) the grain before milling.

Because in sorghum the pericarp always contaminates the meal due to its friability (Perten 1984), pericarp colour is important as it affects the colour of the meal and the appearance of products derived from. Pericarp colour is determined by R and Y genes, where red (R Y), yellow (rrY) and white (R-yy or rryy) are typical phenotypes (Earp et al 2004). Hahn et al (1984) stated that the phenolic anthocyanin, anthocyanidin and flavonoid compounds were pigmented compounds responsible for the pericarp colour. Located below the endocarp is the testa tissue (seed coat), which may be pigmented in some sorghum types (Earp et al 2004). Pigmentation of the testa layer is genetically controlled, produced by the B_1-B_2 genes, and is indicative of the presence of condensed tannins, also called proanthocyanins (Earp et al 2004). Condensed tannins confer agronomic advantages to the grain in the field by reducing fungal infection and improving resistance to pests (Serna-Saldivar and Rooney 1995). However, tannins may not be desirable in sorghum products because they have the disadvantage of binding with proteins (Scalbert et al 2000), thus reducing the nutritional value of sorghum products (Duodu et al 2002). They may also impart bitter and astringent taste to the food (Drewnoski and Gomez-Carneros 2000, Kobue-Lekalake et al 2007), and discolour sorghum products (Akingbala et al 1981, Rooney and Serna-Saldivar 1993). Recent research has however, shown that tannins have powerful antioxidant activity (Dykes et al 2005, Gu et al 2004), and therefore, could impart health benefits to humans (Dykes and Rooney 2007, Hagerman et al 1998). However, the concentration and the antioxidant activity of the tannins in processed sorghum products are influenced by the sorghum type and the processing methods used (Dlamini et al 2007).

Another pericarp component associated with the quality of milled products is the hilum, which is located at the ventral side of the kernel (Fig 2.1). The hilum is a modification of the seed coat and contains black pigments that can make milled products appear "specky" if the degree of milling is not adequate (Rooney 1973).

2.1.2 Endosperm

The endosperm is the starch-rich tissue of the kernel, consisting predominantly of the corneous (outer) and floury (central) starchy endosperm portions (Fig. 2.1). It is separated from the pericarp (and the testa, if present) by a single layer of rectangular cells called the aleurone layer, which is also an endosperm tissue. The aleurone layer contains protein bodies, enzymes, ash (phytic acid bodies) and oil (Rooney and Serna-Saldivar 1993). The corneous endosperm, which is also called the hard endosperm, contains a protein matrix which exists in continuous interface with starch granules. The protein matrix has embedded protein bodies (Serna-Saldivar and Rooney 1995). This structural arrangement is compact and gives the corneous endosperm a translucent appearance (Rooney and Serna-Saldivar 1993). The floury endosperm (sometimes called the soft endosperm) also contains protein matrix and starch granules, but has a comparatively loosely packed structure with air voids. The air voids gives the endosperm an opaque or chalky appearance (Serna-Saldivar and Rooney 1995). Starch and protein gradients exist from the periphery to the centre of the endosperm, whereby starch concentrations increase towards the centre while protein amounts decrease (Rooney and Miller 1982). The starch granules are spherical in the floury endosperm, but are smaller and polygonal in the corneous endosperm (Rooney and Miller 1982). The relative proportions of the corneous and floury endosperm vary among sorghum types, influenced by genetic and environmental factors (Serna-Saldivar and Rooney 1995). These proportions determine the texture of the kernel, where kernels with more corneous than floury endosperm are classified as hard or corneous (Rooney and Miller 1982). A comprehensive review of work focusing on causes of grain hardness in sorghum and maize is given by Chandrashekar and Mazhar (1999). In this review, it is concluded that grain hardness (strength) results from a combination of factors, which include cell wall structure and the types and concentrations of prolamins present in the endosperm. Thus, in hard grains the cell wall polymers are more rigid, and there are more and evenly distributed protein bodies, most of which contain more γ-prolamins which seem to be cross-linked by disulphide bonds, than in soft grains. The amounts of α- and γ-prolamins appear to be essential for corneous texture, where these prolamins are usually higher in hard grains than in soft grains (Chandrashekar and Mazhar 1999, Shull et al 1990).

Implications of endosperm texture on milling performance and food processing

Sorghum endosperm texture has been shown to be the main characteristic that determines milling performance, where corneous endosperm sorghums give more full endosperms and fewer broken particles than floury endosperm grains when decorticated (Awika et al 2002, Desikachar 1982, Kirleis and Crosby 1982, Maxson et al 1971, Reichert et al 1982). Maxson et al (1971) found that endosperm texture (when graded on scale of 1 to 5, where 1 represents complete corneousness and 5 complete flouriness) correlated negatively (r = -0.98) with grain hardness. These authors reported that when 50 g sorghum grain portions were milled in a Strong Scott laboratory barley pearler for 2 min, sorghums with high proportion of corneous endosperm (hard kernels) resisted the forces of abrasive milling. These hard grains gave endosperm grit yields ranging from 45.7 to 71.6%, and the grits contained approximately 0.4% ash and 0.23 to 0.68% lipid. In contrast, sorghums with floury endosperms shattered, yielding only 0.1 to 1.1% endosperm fragments. These contained approximately 4% ash and 0.85 to 1.40% lipid, respectively. Using the Vicker's hardness test, Munck et al (1982) established that sorghum hardness (corneousness) was negatively correlated with crude fibre (r = -0.75, $p<0.001$), fat (r = -0.62, $p<0.05$), and ash (r = -0.69, $p<0.01$) contents of grits obtained with hard endosperm sorghum when decorticated to yield 75% endosperm material. Conversely, endosperm softness correlated positively with fibre (r = 0.70), fat (0.86), and ash (0.73) contents of grits produced from soft endosperm sorghums, indicating that separation of bran and germ was better achieved with hard grains. Shepherd (1982) used a modified UDY Cyclone Mill to evaluate the milling performance of 25 International Food Quality Trials (IFQT) sorghums, where 10 g grain samples were decorticated for 60 sec. The author reported that abraded material ranging in amounts from 0.98 to 4.78 g was removed for all the 25 sorghums, with the highest amount removed from the soft endosperm sorghum, and the least from the hard endosperm grain. In another study where the tangential abrasive dehulling device (TADD) was used to determine abrasive hardness index (AHI – defined as time in sec required to abrade off 1% by weight of the kernel), Reichert et al (1982) found that AHI for 31 sorghums ranged from 5.0 to 12.8%, with the lowest AHI given by the softest grain, and the highest by the hardest grain. Parallel results trends were observed for extraction rate (the percent by weight of the kernel removed as acceptable flour), where values ranging from 69 (for the softest endosperm grains) to 98% (for the hardest sorghum grains) were determined. Similar findings were reported by Desikachar (1982) for 16 sorghum varieties decorticated with a McGill laboratory rice mill. In this study, decortication yields ranged from 64.7 to 83.5%, and amounts of broken endosperm fragments ranged from 3.0 to 22.5%. Higher decortication yields and lower broken endosperm fragments were obtained with hard kernels. Hard endosperm sorghum grains were also shown to produce flours with improved light colour (Aboubacar et al 1999, Awika et al 2002) and large particle sizes than soft grains with abrasive decortication-hammer milling (De Francisco et al 1982, Jambunathan et al 1992).

Sorghum endosperm texture also determines the food making properties of sorghum (Murty and Kumar 1995). Using a Precision Penetrometer to compare firmness of sorghum *tô* (a West African porridge), Bello et al (1990) and Da et al (1982) found that *tô* porridges prepared from hard endosperm grains were firmer than those obtained with soft grains, indicating that hard grains are desirable for production of thick porridges. However, Fliedel (1995) did not find any correlation between *tô* firmness and endosperm texture using an Instron texture analyzer. Similar findings were reported for *tuwo* (sorghum porridge consumed in Niger) by Aboubacar et al (1999). Cagampang and Kirleis (1985) found that gelatinisation temperatures of starches of corneous endosperms were 1 to 2ºC higher than those of the softer endosperms. These temperatures ranged from 64.2 to 69.0ºC and 59.5 to 66.5ºC for corneous and soft endosperm starches, respectively. Other findings reviewed by Chandrashekar and Mazhar (1999) were that flours produced from soft grains had higher pasting peak viscosities and lower setback than hard grain flours. These flours also gave pastes with higher breakdown, showing that the pastes were more susceptible to shear than those obtained with hard grains (Cagampang and Kirleis 1984). In addition to affecting porridge firmness, endosperm texture was also found to influence porridge stickiness, where grain hardness correlated negatively with stickiness (determined with an Instron instrument) of sorghum flour pastes (Cagampang et al 1982). Other than for porridge making, hard grains are also good for making dumplings (Bello et al 1990), tortillas (Suhendro et al 1998) and popped sorghum (Chandrashekar and Mazhar 1999). Hard endosperm texture is, however, not good for making soft injera (Yetneberk et al 2004), kisra and roti (Rooney et al 1988).

2.1.3 Germ

The germ, which consists of the embryonic axis (radicle and plumule) and the scutellum, is firmly embedded in the kernel, secured by strong cementing layer and interlinking glands between the scutellum and the endosperm (Rooney 1973). The germ is rich in lipids, protein and minerals, with most of the lipids contained in the scutellum (Rooney and Serna-Saldivar 1993). The size of the germ varies among sorghum types, but in all sorghums, it is proportionally large relative to the size of the endosperm (FAO 1995), making the sorghum kernel one of the highest in oil content among the cereals (Kent and Evers 1994). It is difficult to de-germ sorghum (FAO 1995), and the degree of difficulty varies among sorghum types (Rooney 1973). As a result sorghum meals inevitably become contaminated with oil (Gomez 1993), which often cause rancidity problems in sorghum products (Hoseney 1994).

2.2 Sorghum chemical composition as related to milling and product quality

2.2.1 Starch

Starch accounts for the largest proportion of the sorghum kernel weight, constituting about 75-79 % of the grain (Serna-Saldivar and Rooney 1995). Starch is the main nutrient sought after in sorghum, specifically for providing energy. Like in other cereals, sorghum starch has two types of molecules that are closely packed in discrete granules (Donald 2005). These are amylose, which is an essentially linear polymer, and amylopectin, a highly branched polymer (Fig. 2.2) (Bao and Bergman 2004). These molecules make up approximately 23-30% and 70% of the total starch in normal (non waxy) sorghum, respectively (Serna-Saldivar and Rooney 1995). Waxy sorghums contain little (approximately 5%) or no starch amylose (Rooney and Serna-Saldivar 1993).

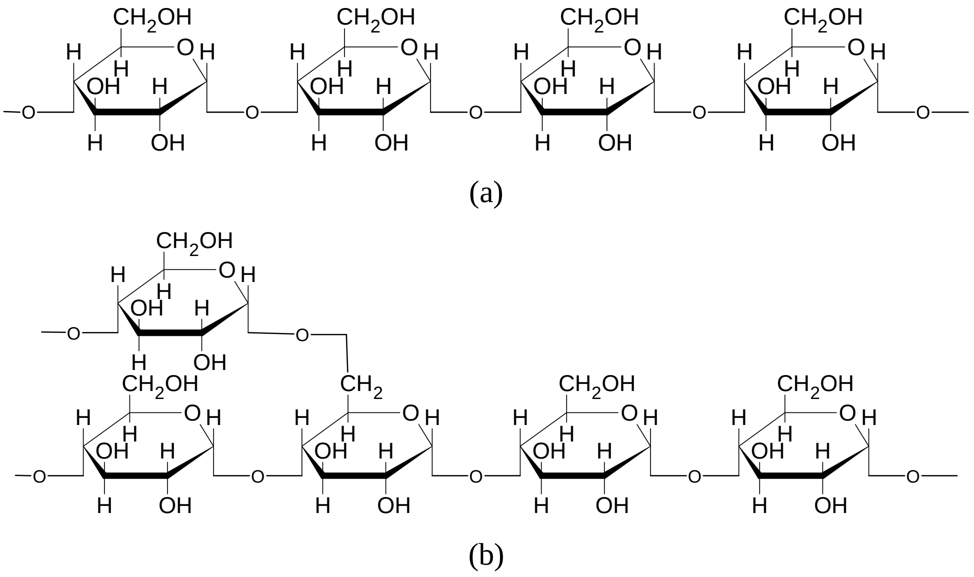


Fig. 2.2. Haworth representation of (a) amylose, a linear molecule composed of 1,4-α-linked D-glucose, and (b) amylopectin, a 1,4-α linked polymer with 1,6-α branch points. Only parts of the macromolecules are shown to illustrate fundamental differences in the molecular structure (after Cornell 2005).

Typically, starch amylose has a helical structure made of glucose residues linked by 1,4-α glycosidic linkages, whereas amylopectin consists of short linear chains branched by 1,6-α glycosidic linkages on longer chains with 1,4-α linkages, all of glucose (Bao and Bergam 2004). The functional properties of starch, and the characteristics of the derived food products, appear to be greatly influenced by the proportions and the structural forms of the starch amylose molecules. When starch granules are heated in water, amylose molecules are released into solution, and upon cooling they re-associated rapidly by cross-linking with each other through hydrogen bonding to form a gel, thus determining the textural changes of the starch paste (Morris 1990). In pastes with high lipid content, starch amylose molecules form helical inclusion lipid-amylose complexes, which cause high pasting temperatures and low paste viscosities (Mishra and Rai 2006). This could potentially take place in porridges prepared from sorghum flours in which the lipid-rich germs have not been removed. Such porridges could, as a result, be soft (less firm). Fliedel (1995) and Aboubacar et al (1999) found that sorghums with high starch amylose content produced firmer sorghum porridges than those with lower contents. Beta et al (2001) and Cagampang and Kirleis (1984) established that sorghum starch amylose content correlated positively with hard endosperm texture, this being consistent with the findings that hard textured sorghums produce firmer porridges (Bello et al 1990, Da et al 1982).

2.2.2 Protein

Protein is the second major component of sorghum, making up approximately 12% of the whole grain weight (Serna-Saldivar and Rooney 1995). Taylor and Schüssler (1986) determined that about 80, 16, and 3% of the total sorghum protein is contained in the endosperm, germ, and pericarp, respectively. As such, the decortication process, which primarily removes the pericarp, also removes some of the germ and part of the outer endosperm, which contain some amounts of protein. Thus, in essence, decortication reduces the amount of protein available in the grain (Serna-Saldivar and Rooney 1995).

Four fractions of protein have been identified in sorghum, namely the aqueous alcohol-soluble prolamin (deposited mainly in endosperm protein bodies), the alkali-soluble glutelin (in endosperm protein matrix), water soluble albumin and globulin (in the germ) (FAO 1995). Prolamin makes up approximately 50% of the total grain protein, followed by glutelin (Rooney and Serna-Saldivar 1993). According to Naik, quoted in FAO

(1995), the relative proportions of these protein fractions vary among sorghum varieties, influenced by genetic and environmental factors. Soil fertility factors also contribute greatly to fluctuations in sorghum protein content (Serna-Saldivar and Rooney 1995). Sorghum is limited as a dietary protein source because it is deficient in lysine (Serna-Saldivar and Rooney 1995), and also because the protein digestibility is reduced on wet cooking (Axtell et al 1981, Duodu et al 2002, Hamaker et al 1986), such as in porridge making. The reduction in digestibility is due to formation of enzymate-resistant protein polymers resulting from disulphide cross-linking of kafirins (Oria et al 1995, Rom et al 1992). Duodu et al (2002) carried out in vitro digestibility studies of sorghum protein and found that protein digestibility increased as the amount of pericarp and germ (bran) were reduced. This suggests that effective decortication and degerming of sorghum during milling could potentially improve bioavailability of protein in sorghum products.

2.2.3 Oil

The sorghum kernel contains oil in the range of 2.1-5.0% (Hoseney 1994), where about 76%, 13% and 11% of the total oil is contained in the germ (scutellum), endosperm and pericarp, respectively (Serna-Saldivar and Rooney 1995). Consequently, some amount of oil is removed with the bran (pericarp and germ) upon decortication (FAO 1995), but certainly not all (Rooney 1973, Gomez 1993). Like other cereals, sorghum contains polar, non-polar and non-saponifiable lipids (Osagie 1987). Non-polar lipids (also called neutral lipids) are the most abundant, accounting for approximately 93% of the total lipid content (Serna-Saldivar and Rooney 1995). The fatty acid composition is dominated by the unsaturated linoleic, oleic, and palmitic acids (Osman et al 2000), which make up approximately 49%, 31% and 14%, respectively, of the total free fatty acid content (Rooney and Serna-Saldivar 1993). Because of their unsaturated molecular structure, these fatty acids are prone to hydrolytic and oxidation spoilage (Eskin and Przybylski 2001), and hence cause rancid off flavours in the meals (Hoseney 1994).

2.2.4 Dietary fibre

Sorghum fibre is contained mainly in the pericarp and the endosperm cell walls, and consists mainly of cellulose (FAO 1995) and glucuronoarabinoxylans (Verbruggen 1993), and some amounts of β-glucans (Earp et al 1983), lignin, pectins and gums (Hoseney, 1994). These components account for 6.7 to 7.9% insoluble and 1.1 to 1.23% soluble fibre of the grain (Serna-Saldivar and Rooney 1995). Much of the insoluble fibre, which is resistant to the digestive enzymes in the human stomach, is located in the pericarp (Serna-Saldivar and Rooney 1995), and therefore decortication is primarily applied to remove the bulk of this type of fibre, thus making the derived sorghum products palatable and digestible. The cell walls of the endosperm mainly consist of water insoluble glucuronoarabinoxylans (Verbruggen et al 1993), as in maize (Huisman et al 2000). These sorghum arabinoxylans do not hold water, in contrast to oats and rye arabinoxylans, and therefore do not form slimy substrates (Hoseney 1994). Sorghum also contains some β-D-glucans in the endosperm, aleurone and pericarp (Earp et al 1983). β-D-glucans often form very viscous and sticky solutions (Wood 1984), and hence, could potentially affect the rheological and textural properties of sorghum products.

2.2.5 Minerals

The mineral content of sorghum is highly variable, influenced mainly by the environment than by genetics (FAO 1995). The minerals are concentrated in the pericarp, germ and the aleurone layer, and therefore their presence in the meal (determined as ash content) is indicative of the degree of bran contamination (and removal). Ash mainly contains salts of phosphorus and potassium (Serna-Saldivar and Rooney 1995). According to Pedersen and Eggum (1983), minerals such as iron, zinc, copper and phosphorus, decreased with extraction rates in sorghum flours. Phytic acid, a compound contained in the germ and the aleurone layer (Serna-Saldivar and Rooney 1995), binds with divalent dietary minerals, making them biologically unavailable (Rhou and Erdman 1995), if the bran is not adequately removed from the meal.

2.3 Dry milling processes for sorghum grain

In any sorghum dry-milling operation, the primary objectives are to (i) remove the outer less palatable and oil-rich tissues of the grain (pericarp and germ), thus retaining maximum yields of the starchy endosperm; and (ii) to reduce the endosperm into a meal (Munck et al 1982). Since the pericarp and the germ account for about 10-15% of the total kernel weight, an ideal milling process should yield from 85 to 90% of refined endosperm particles (Rao 1982), with minimal amounts of the pericarp and the germ. However, in practice this ideal endosperm yield is seldom achieved, even at the optimum conditions of the milling process, because of the intrinsic inefficiencies of the milling processes.

Conventionally, milling of cereal grains is achieved by two popular processes. In the first process the pericarp (bran) and the germ are first removed by degerming or decorticating processes, then the endosperm is reduced to grits or flour. This process is used commercially for maize milling and is describe in detail by Duensing et al (2003). Degerming sorghum with a conventional Beall-type degerminator results in breakage of the endosperm, and subsequent contamination of the meal with bran, owing to the integral nature of the germ and the spherical shape of the sorghum kernel (Taylor and Dewar 2001). The second process involves first breaking open the kernel, then scraping the endosperm from the bran. This process employs a roller mill, where the grain is subjected to multiple grinding and separation steps until a product of sought particle size and purity is achieved (Posner and Hibbs 1997). The latter process is popularly applied in commercial milling of wheat. In both these processes, resolution of the milled stock is achieved by sifting, aspiration, gravity separation, or a combination of these processes, to separate the bran and the germ from the endosperm grits or flour (Kent and Evers 1994).

During the past four decades, several industrial milling technologies that utilised these two approaches evolved for sorghum (reviewed by Munck 1995). At the onset of this evolution attempts were made to adapt the wheat roller milling technology for sorghum, but very little progress was made as the process gave uneconomical low yields and products of inferior quality (Perten 1983). Following this failure, other milling processes such as the German Schule, the Swiss Decomatic, the Danish United Milling System, and later the PRL (Prairie Research Laboratory) dehuller were developed (Gomez 1993). Out of these trials, dry abrasive milling technology, utilising a PRL type dehuller and a hammer mill, was found to be viable, and was widely adopted for service and semi-commercial milling in Africa (Eastman 1980, Dendy 1993). However, the PRL dehuller has been shown to be inadequate for production of meals with minimum bran contamination (Gomez 1993, Hammond 1996) and it only functions optimally with grains that possess specific suitable physical characteristics (Maxson et al 1971, Lawton and Faubion 1989, Mwasaru et al 1988). Although the PRL dehulling technology has become popular, traditional milling processes continue to exist in many rural areas of Africa as processes of choice for production of traditional sorghum products. These processes utilise either saddle stones or wooden pestle and mortars (Munck 1995).

Lately, there is growing interest to make novel and non-traditional sorghum-based products (Taylor et al 2006). To maintain production and good quality of such products at large scale production, more efficient milling technologies would be required. Recently, small roller mills with two or three roll pairs, which are designed specifically for coarse grains, have become popular in Africa (Taylor 2003).

2.3.1 Traditional hand pounding

Very few scientific studies have been reported on traditional sorghum milling practices and the quality of products obtained through these processes. Perhaps the best documented study in this respect is that conducted in Tanzania (Munck et al 1982, Eggum et al 1982). Typical African wooden mortar, pestle, and winnowing basket (Fig. 2.3) were used in the study. The technical dimensions for equipment used and the detailed descriptions of the milling and separation processes employed are documented by Eggum et al (1982). Points worth highlighting about the process and other findings reported elsewhere are as follows;

Up to 20% water was added to temper the grain (Munck et al 1982), presumably applied to toughen the pericarp and soften the endosperm, hence easing the separation of these tissues (Kent and Evers 1994). The high amount of moisture used to temper the grain renders hand pounding a semi-wet milling process, hence necessitating drying of the final meal to shelf stable moisture content (to less than 14%) before storage. Detachment of the pericarp from the endosperm is effected by the stamping force of the pestle, which cause rebound and shearing effects on the grain pericarp, making it peel off as large flakes. The pericarp flakes are then winnowed off (with a traditional winnowing basket) before reducing the endosperm to a meal.

Hand pounding was found to be very laborious, requiring about 1 hour to process 2-3 kg of sorghum grain by an experienced adult Tanzanian lady (Eggum et al 1982). Eastman (1980) estimated that at least 2 hours would be required each day to pound enough flour (meal) for a household in Botswana. Such flour has a shelf life of only 3 days, because of the development of rancid off-flavour, which results from oxidative and enzymatic spoilage during drying of the flour. Considering that consumer lifestyles are becoming inclined towards convenient products, this process may become completely unsustainable with time. Lulu D, an improved white sorghum with soft endosperm gave flour yields as low as 50%, while yields ranging from 73 to 86% were achieved with local sorghum types which had relatively hard endosperms. According to Eastman (1980), in Botswana a number of unpublished studies established that traditional pounding gave extraction rates averaging 70% with local sorghums. Other studies by Scheuring et al (1983) revealed that sorghum types with thick pericarps and hard endosperm are desirable for hand pounding. The chemical composition in terms of ash, protein, oil and starch of the hand pounded meal was very similar to composition of hand dissected endosperm (Munck et al 1982), suggesting that degermination and decortication (also referred to as pearling or dehulling in the milling industry) were effectively achieved with hand pounding, thus producing a highly purified product. Although the term “dehulling” is widely used to describe removal of sorghum pericarp, it is a misnomer, because sorghum grain does not possess a hull. The term “decortication” is rather more appropriate.

Fig. 2.3. **Typical traditional African wooden mortar and pestle (foreground) used for decortication, and a winnowing basket (background) used for separation of bran after hand pounding. Picture photographed in 2006 in Kanye, Botswana, by M. Kebakile.**

2.3.2 Dry Abrasive decortication

A comprehensive review of the development and use of abrasive decorticators in Africa has been made by Bassey and Schmidt (1989). Many of the decorticators developed are variants of a prototype developed by the Prairie Research Laboratory (PRL) in Canada. The PRL dehuller underwent various modifications to suit local conditions. One of the variants developed from the PRL dehuller was the Palyi-Hanson BR 001-2, which had a production capacity of 3 tonnes per hr. This prototype was later modified into a smaller decorticator, the PRL/RIIC dehuller, by the Rural Industries Innovations Centre (RIIC). Although these machines are called “dehullers”, they are applied to sorghum to remove mainly the outer pericarp layers, since as stated sorghum does not have a hull. Dry abrasive decortication, as the name implies, does not involve pre-conditioning of the grain. In fact, according to Perten (1983), tempering the grain for decortication with abrasive discs decreases throughput, increases broken grains, and increases fat and ash content of the flour.

Today, the PRL/RIIC dehuller, is perhaps the most popular decorticator for service- and semi-commercial production of sorghum meal in Africa (FAO 1995, Rorhbach 2003). In this machine, a 5-25 kg batch of grain is fed through a hopper into a cylindrical box, which contains a set of 13 evenly spaced circular carborundum stones (250 mm diameter, 21 mm wide) that rotate on a horizontal shaft at 2000 rpm (Fig. 2.4) (Bassey and Schmidt 1989). The grains are decorticated by rubbing against the abrasive surfaces of the stones, against each other, and against the walls of the dehuller barrel, where the pericarp and germ (and tannin-rich testa, if present) are progressively abraded off, and is subsequently siphoned by a cyclone fan. The barrel may be lined with rubber to hold grain from slipping, and hence, facilitate greater abrasion. Unlike for hand pounding, bran is abraded as fine particles, which are siphoned out by a fan positioned above the cylindrical box. The grain is discharged when considered sufficiently decorticated, with the timing depending entirely on the operator’s milling experience. Decortication may be done in batch (with one dehuller) or continuous mode, where several dehullers may be used in series (Mmapatsi and Maleke 1996). According to Eastman (1980) the PRL/RIIC dehuller gave meals of acceptable quality at extraction rates averaging 75% (with ranges of 75–85%), when tested in the field. The term “extraction rate” is used here to refer to the amount of grain material retained as meal of acceptable quality, as determined by the consumers. The author also claimed that the dehuller produced meals that contained 25% less fat, 10% less crude fibre and 15% less ash than manual hand pounding, and that the meals produced had shelf life of 3 months.

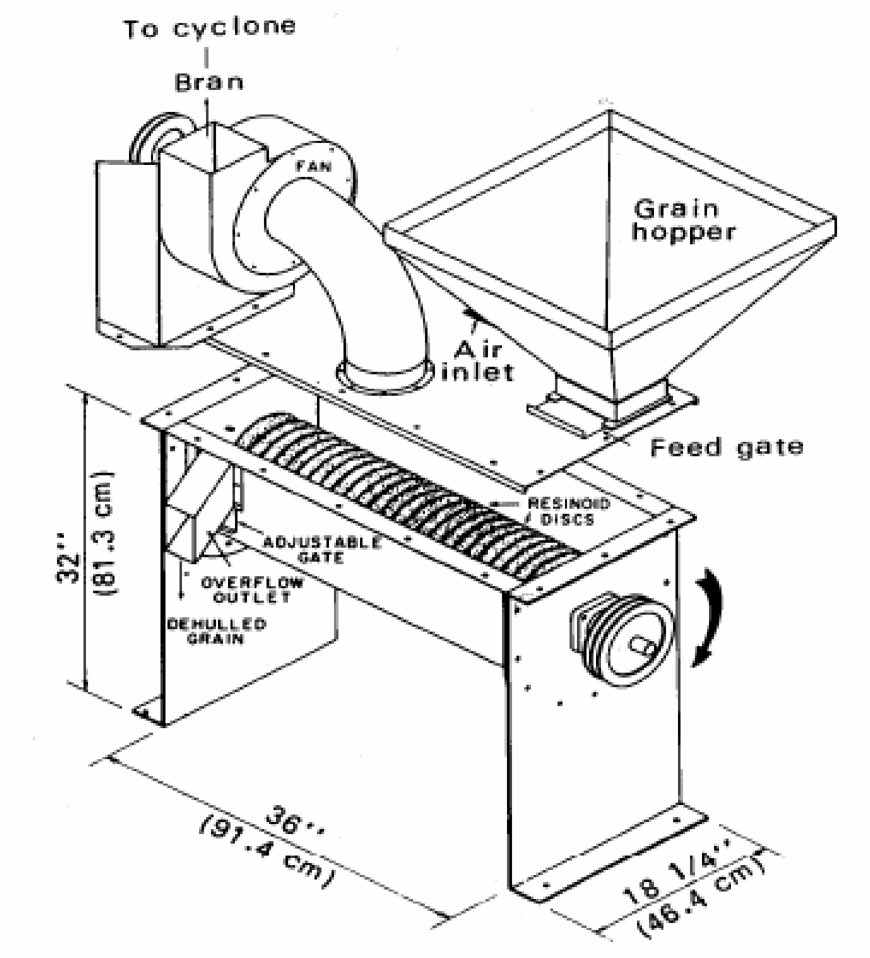
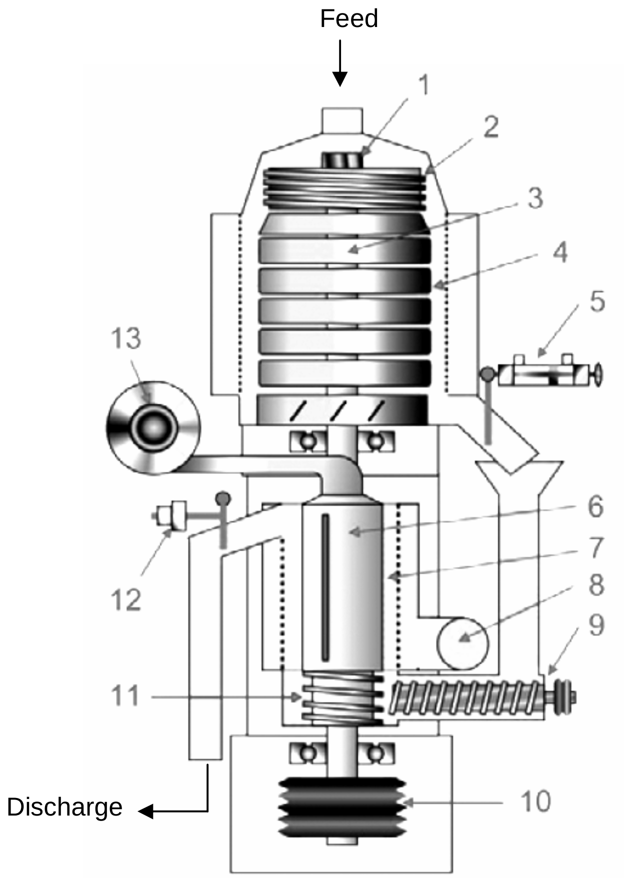


Fig. 2.4. **PRL type dehuller used to decorticate sorghum (Reichert 1982)**

Recently, Satake Corporation successfully tested a debranning process called PeriTec on sorghum (Satake 2004). This process utilises an abrasive 'Vertical Debranner VCW' (Fig. 2.5) that debrans by abrasion, in the first stage, and friction, in the second stage. The VCW debranner operates on continuous mode and comes in different input capacities ranging from 2.0 to 10.0 tonnes per hour of grain (Satake 2007). Foods Botswana (Pty) Ltd, one of the largest sorghum processing companies in Botswana, recently installed this system for decorticating sorghum (Mr R. Mmeriki, Production Manager, Foods Botswana (Pty) Ltd, personal communication). Unlike for decortication with the PRL-Dehuller, and contrary to claims by Perten (1984), the PeriTec procedure requires conditioning of grain with 1-3% moisture (by weight of grain) for 3-5 min before debranning (Dexter and Wood 1996). In wheat, this conditioning is believed to permit gradual stripping of the pericarp layers, leaving the aleurone layer intact (Dexter and Wood 1996). Possibly, this conditioning has the same effect in sorghum.



1. Clamping nut
2. Abrasion distribution scroll
3. Abrasive wheels
4. Abrasion chamber and screen
5. Autoweight on abrasion outlet
6. Friction rotor
7. Friction chamber and screen
8. Exhaust duct
9. Friction inlet screw feeder
10. Main drive
11. Friction distribution scroll
12. Friction outlet flap gate
13. Fan

Fig. 2.5. **Schematic diagram of the PeriTech VCW debranning machine (used with permission from Satake corporation)**

Conditioned grain is fed at the top of the machine and gets distributed evenly around the top abrasive chamber (4), where the outer paricarp layers of the grain are abraded by revolving carborundum wheels (3) and hexagonal slotted screen (abrasive chamber). The grain then flows through a weighted flap (5) (which controls degree of abrasion) and falls into a screw conveyor (9) which then feeds it into the friction chamber (7), where the remaining inner pericarp layers are removed by friction. The grain is finally discharged (12) and proceeds to the milling machine. Air is continuously blown through the system and exhausted at the bottom of the unit to remove bran (8). The degree of debranning is regulated by the screw and wheels (stones) speeds, outlet gate gap, grit roughness, screen slots and airflow through the chambers (Posner and Hibbs 1997). The PeriTec system is said to offer advantages of controlled rate of bran removal, uniformly debranned grains, and improved power efficiency over the horizontal type dehullers (Satake 2004).

It should be stated that dry abrasive decortication has the benefits of reducing fungal contamination, insect fragments, micro-organisms, pesticide and fumigant residues, mycotoxins and heavy metals on the surface of the grains before milling into flour (Satake 2004).

2.3.3 Roller Milling

In a conventional roller milling process, flour is produced by gradually reducing the particle size of the feed stock by a series of grindings (pairs of counter-rotating rolls), with intermediate separation of bran, germ and endosperm meal streams by sifters and purifiers (Posner and Hibbs 1997). In each pair, the rolls are separated by a small gap and are set to rotate at different speeds, such that the grain passing between the pair become subjected to shear and compressive forces imposed by corrugations on the roll surfaces and pressure exerted by the rolls as they revolve (Hague 1991, Posner and Hibbs 1997). The rolls used usually range from 225 to 300 mm in diameter and vary from 450 to 1500 mm in length. They either have corrugated surface (called break rolls) or smooth surface (called reduction rolls). For wheat flour milling, up to 16 roller milling operations may be used to achieve flour with minimal bran contamination and optimal extraction rates (Campbell and Webb 2000).

As stated, early attempts to apply wheat roller milling technology directly to sorghum grain produced products of very poor quality and low yields. Perten (1984) compared the roller milling performance of sorghum, pearl millet and wheat using identical processing conditions and observed that sorghum and pearl millet flour yields (extraction rates) were lower and that their flours had relatively coarse particles. The sorghum flour had 3.3% fat and 1.30% ash, while wheat flour had 2.2% and 0.5%, respectively. The author attributed the comparatively higher fat and ash in the sorghum flours to the easily pulverisable sorghum pericarp and germ. Miche (1980) compared extraction rates and the purity of meals produced by dry abrasive milling using a Decomatic abrasive system (Schule) with those obtained with fluted roller mill (Socam laboratory pilot plant) after tempering the grain to 17% moisture. The former process gave extraction rates ranging from 62 to 81%, while the latter gave lower rates of 65 to 68%. However, the roller milling process generally gave lower ash and fat in the flours than the Schule abrasive system.

The beneficial effect of tempering sorghum grain on roller milling performance has been reported by several researchers (Cecil 1992, Gomez 1993, Hammond 1996). Cecil (1992) described a semi-wet process that involved tempering the grain to 26% moisture for 6 hr at 60ºC, prior to milling directly in a small scale wheat roller mill. This process was found to effectively separate bran and germ from the endosperm, but was disadvantageous in that the flour yield was rather low and the flour required drying from about 16% moisture to 14% before storing. Gomez (1993) investigated the effect of tempering on the quality of the flour using a simple double roll roller mill with a processing capacity of about 500 kg/hr (Fig. 2.6). In these trials, grain which was previously tempered to 16% for 24 h at 4ºC and roller milled directly, generally gave higher flour yields, lower ash and lower fat content than a process where the grain was first dry decorticated before roller milling (without tempering). According to Hammond (1996), the refrigeration temperature (4ºC) used by Gomez (1993) during grain tempering would never be feasible technologically. Consequently, in the study of Hammond (1996), the grain conditioning process was modified such that the grain was tempered to

16% for 4 hr at ambient temperature. Using a similar roller mill to that used by Gomez (1993), fine flour with yields ranging from 80 to 84% (particles <500 µm) were achieved. Compared to abrasive decortication, the author found that roller milling generally gave lower fat in the fine meal fraction (<500 µm); 0.6-2.0% for roller milling compared to 2.1-2.7% for abrasive decortication and hammer milling. Ash content of the roller milled flour was also lower, (0.6 to 1.2% for roller miling and 1.4 to 1.8% for decortication).

Tempering is generally applied to adjust the moisture content of the grain to an optimum level, either by removal or addition of water, such that the differences in the grinding characteristics (relative toughness or friability) of the grain components (pericarp, germ and endosperm) are magnified, thus easing their separation (Posner and Hibbs 1997). Very few studies on sorghum tempering have been reported in the literature. Suroso et al (2000) investigated the effect of tempering time and temperature on the ash and fat content of grits obtained with sorghums of different endosperm texture, using a maize decorticator-degerminator. The authors found that a white sorghum with white endosperm (presumably a hard type) required conditioning at 40ºC for 40 min, whereas a red sorghum with white endosperm (presumably a soft type) needed 20ºC for 10 min to give grits with 0.22% ash and 0.36% fat, and 0.20% ash and 0.22% fat at about equal extraction rates of 45.3% and 44.2% grits, respectively. McDonough et al (1997) studied the effect of variable tempering moisture content on the structural characteristics of the sorghum endosperm, but this study focused specifically on steam flaking behaviour of the endosperm. Much detailed knowledge about wheat tempering has been generated (for example Glenn and Johnston 1992, Haddad et al 1999, Mabille et al 2001), and perhaps this knowledge may be applied to sorghum. The optimum roller milling moisture for wheat varies between 14 and 17%, with the actual amount of water added depending on the original moisture content of the grain, the physical properties of the grain (Posner and Hibbs 1997, Kent and Evers 1994), the type of flour produced (Kent and Evers 1994), and the specific machine characteristics of the roller mill (Posner and Hibbs 1997). For example, hard grains require higher moisture conditioning (typically 16-16.5%) than soft grains (15-15.5%), and grain for production of high extraction flour (80-85%) is tempered at 1-1.5% lower moisture than grain for white flour of 70-75% extraction rate

(Kent and Evers 1994). Tempering involves wetting the grain with cold or warm water (often 3-3.5% water is added), then resting the grain for 1 to 3 days (but commonly 12 to 18 hr) to allow water to penetrate evenly throughout the kernels (Kent and Evers 1994). Ideally, at the time of milling bran should be slightly damper than the endosperm, and hence, the grain is sometimes dampened lightly (0.5% water) and rested for 20 min just before milling (Posner and Hibbs 1997). In essence, the pericarp (Glenn and Johnston 1992) and the germ (Posner and Hibbs 1997) become tough and pliable, while the endosperm becomes mellow (Glenn et al 1991). According to Posner and Hibbs (1997), if the endosperm is not mellowed, it will act as a hard background against which the bran breaks excessively. Clearly complete tempering depends on the moisture content, time and temperature used (Kent and Evers 1994, Posner and Hibbs 1997, Haddad et al 1999). Ambient temperature (called cold conditioning), temperatures up to 46ºC (warm conditioning) or 65.5 to 71ºC (referred to as hot conditioning) are common temperature regimes used to temper the grain (Kent and Evers 1994). Conditioning at higher temperatures expands the kernels, distending their capillary tubes (Posner and Hibbs 1997), hence, accelerating moisture entry and distribution within the grain such that grain conditioning time shortens from about 1 day to 1.5 hr (Kent and Evers 1994).

Tempering of grain before milling is not only important for improving bran removal and achieving optimal flour yields, but is also important for reducing the amount of damaged starch (Posner and Hibbs 1997) and optimising the particle size distribution of the flour (Posner and Hibbs 1997, Fang and Campbell 2003). Fang and Campbell (2003) reported that proportions of particles generated at the large and small ends of the particle size distribution increased with the increasing moisture content of the endosperm, whereas particles in the mid range decreased. Similar findings were reported earlier by Hsieh et al (1980).

The gap between the two rolls, the ratio of the speeds of the slow and fast rolls (differential speeds) of the rolls, the type and condition of the roll surfaces, the flow rate of stock (combined endosperm and bran milled stream) to the rolls, and the properties of the stock particles affect the magnitudes of forces imposed on the stock by the rolls, and therefore are important parameters for optimal roller milling performance for wheat (Posner and Hibbs 1997, Prabhasankar et al 2000, Campbell et al 2001, Hague 1991), and probably also for sorghum. Campbell and Webb (2001) found that the mean output particle size of the milled stock increased with the increasing size of the roll gap, and decreased with the increasing feed particle size. These investigators noted that widening the roll gap from 0.3 mm to 0.4 and 0.6 mm shifted the mean particle size from 700 µm to about 800 µm and 1100 µm, respectively. These parameters can be modified to influence the characteristics of the meal streams produced, thus allowing flexibility for the production of intermediate products for various food applications (Prabhasankar et al 2000).

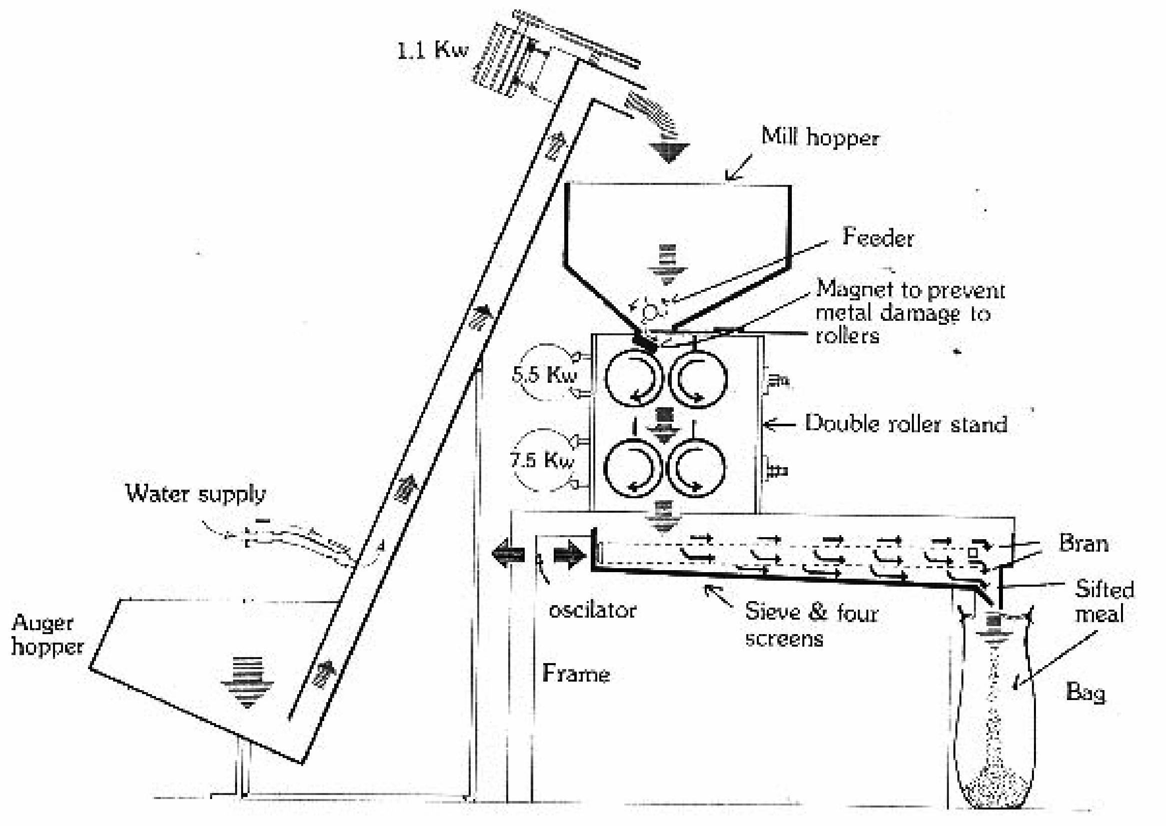


Fig. 2.6. **A typical double roll roller mill designed to process sorghum (Courtesy of Maximill, Kroonstad, South Africa)**

2.4 Quality evaluation procedures

2.4.1 Grain evaluation and quality standards

A detailed review of the common sorghum grain quality evaluation procedures and standards is given by Shipman and Eustrom (1995). It is generally accepted that the quality requirements of the grain are defined based on the intended end-use. For example, the sorghum milling and brewing sectors demand different grain qualities which are specific for their production needs. Different countries, such as the USA, Australia, Argentina, Botswana, and South Africa have instituted grain quality standards to facilitate local and international trade. Perhaps the most developed and widely cited quality standards for sorghum are the US Standards for Grain. In these standards sorghum is graded into five grades, Nos 1, 2, 3, 4, and Sample grade, with No 1 designating the highest quality and Sample grade the lowest (Shipman and Eustrom 1995). The standard further divides sorghum into four classes, namely Sorghum, Tannin Sorghum, White Sorghum, and Mixed Sorghum. FAO and WHO (2006) has also established an international quality standard for sorghum intended for human consumption (Standard 172-1989; reviewed 1-1995). This standard prescribes acceptable limits in terms of moisture, ash, protein, fat and total defects. The total defects include blemished, diseased, insect- or vermin-damaged grains, broken kernels and others. Generally, all these standards are primarily aimed at ensuring the wholesomeness of grain for human consumption, and do not specify kernel characteristics that are important to processors. However, guidelines for quality evaluation of the grain have been issued by several researchers to assist the industry (Gomez et al 1997, Taylor 2001). Following evaluation of numerous sorghum cultivars for milling and malting applications in Southern Africa, SADC-ICRISAT developed and published quality evaluation guidelines and recommended optimal sorghum quality limits for these sorghum end-uses (Gomez et al 1997). Guidelines recommended by SADC-ICRISAT for sorghum intended for milling are given in Table I. These generally emphasize the importance of grain colour, endosperm texture, grain hardness, pericarp thickness, grain density (test weight), absence of tannins and grain size uniformity in sorghum milling.

Table I
Grain quality parameters for sorghum and their optimal ranges for milling[1]

Parameter	Recommended optimal limit	
Grain colour	White/Cream/Yellow/Red	Visual examination of kernel colour
Pericarp	Thin	Scraping kernel with scalpel and observing thickness with magnifying glass
Testa	No	Visual examination for brown tissue on kernel after scraping off pericarp with a scalpel
Endosperm texture	Pearly to intermediate	Visual examination of kernels using a 3 point scale; 1 – pearly, 2 – intermediate and 3 - chalky
Visual hardness	3.0 to 5.0	Visual grading of floury to vitreous endosperm on scale of 1 to 5; 1 denoting completely vitreous and 5 completely floury
Kernel weight	>2.0 g	Weight of 100 representative kernels
Floaters	<40%	Determination of amount of kernels floating in sodium nitrate solution of known density
Milling yield	>75%	Known amount of samples dehulled with a Tangential Abrasive Dehulling Device (TADD) are milled in an Udy cyclone mill. Milling yield is calculated as percent of meal produced
Size fractions	>80% in medium/large	Known amount of sample is fractionated by size using test sieves. Size fractions are classified as; large = >4.0 mm; medium = 4.0-2.6 mm; and small = ≤2.6 mm
Dry Agtron reading	>75%	Measurement of degree of whiteness of milled sample using Agtron colour meter
Water absorption	<12.5%	Amount of water absorbed by sample after soaking for in excess water for 30 min
Tannins	Intermediate to low/none	Prussian Blue method – subjective grading of colour intensity of the ferricyanide-ferrous complex formed following reduction of ferric ions to ferrous ions by tannins. Yellow = none; Light green = low; Blue-green = intermediate and Dark blue = high

[1] Source – Gomez et al (1997)

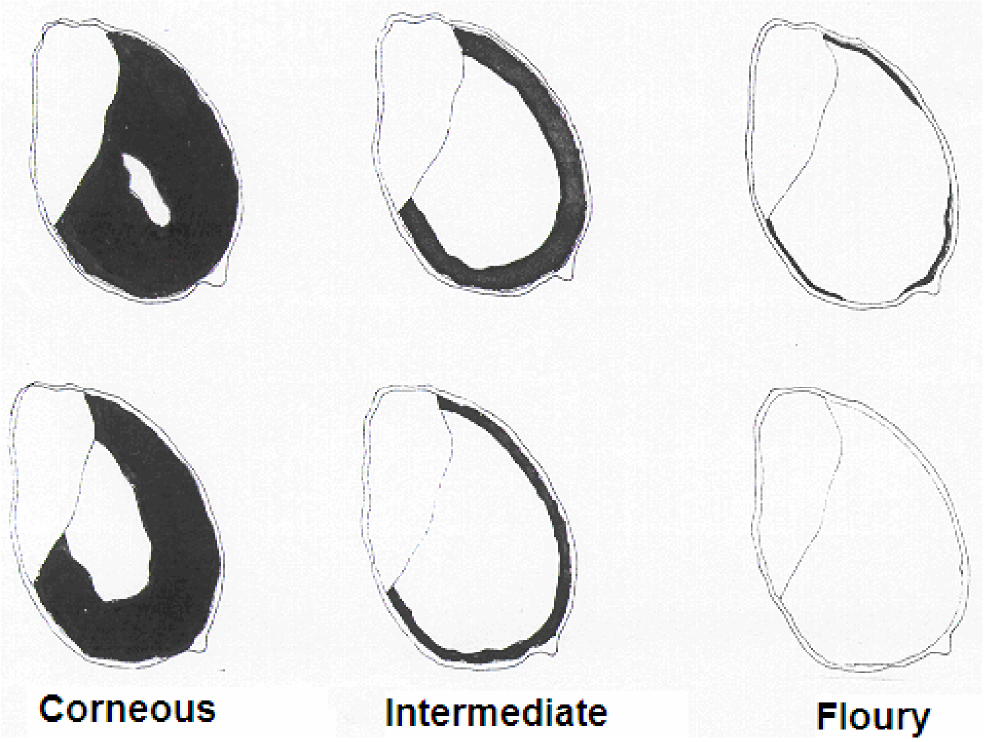


Fig. 2.7. Illustration of a 3-point rating system for evaluating sorghum endosperm texture (Taylor 2001).

Recently, Taylor (2001) also recommended simple grain evaluation procedures for determining sorghum grain end-use quality. These procedures are now adopted by the International Association for Cereal Science and Technology (ICC) as draft ICC standard methods. The methods include detection of tannin sorghum grain by the bleach test, classification of sorghum grain according to colour, estimation of sorghum grain endosperm texture, determination of germinative energy of the grain (for malting purposes), and determination of total defects in sorghum grain. To estimate the grain endosperm texture, the ICC method recommends a simple 3-point grading system (Fig. 2.7), instead of the 5-point scoring system (Fig. 2.8) of Rooney and Miller (1982).

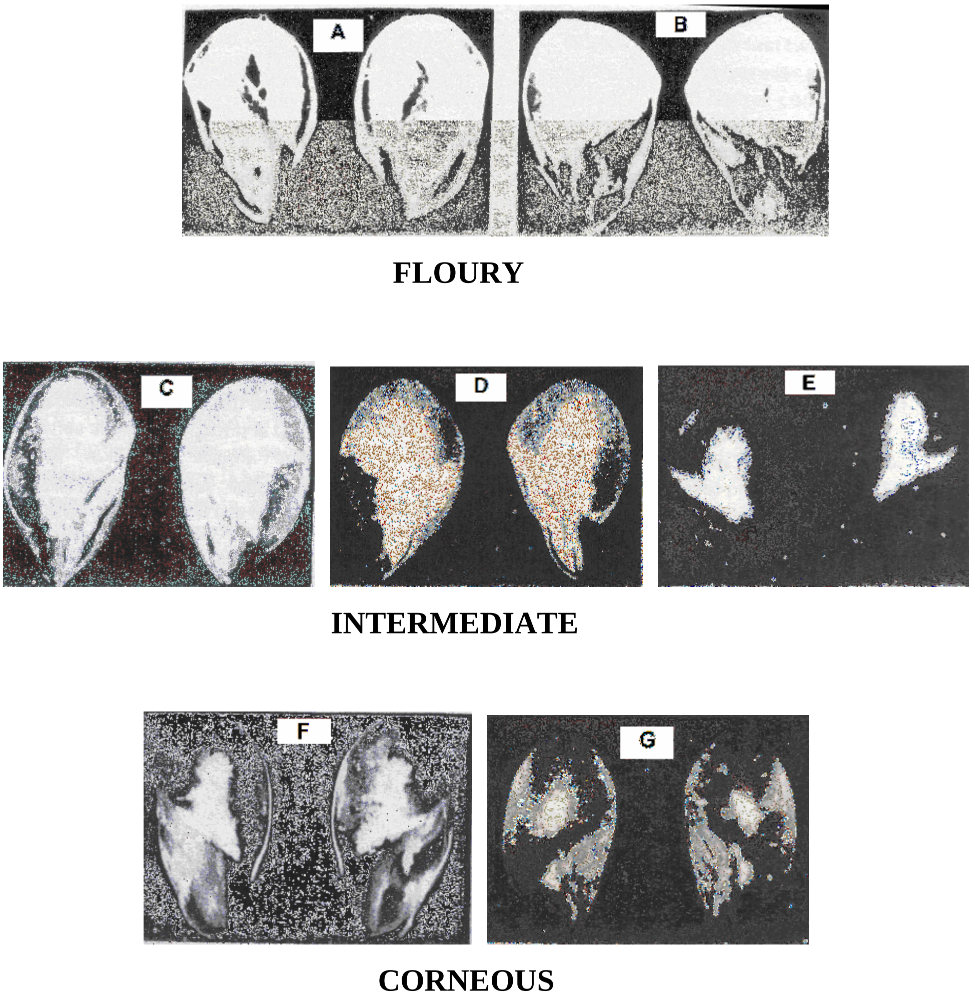


Fig. 2.8. Illustration of a 5-point rating system for evaluating sorghum endosperm texture. Kernel ratings are A and B = 5, C = 4, D = 3, E and F = 2 and G = 1 (Rooney and Miller 1982)

2.4.2 Meal (flour) evaluation and quality standards

Ash content and colour brightness of flour are well established indicators of flour refinement in milling (Posner and Hibbs 1997, Scanlon et al 1993, Shuey 1976). Ash is simply a measure of the mineral residue remaining after incinerating a sample under conditions that destroy organic matter. The minerals are concentrated in the aleurone layer and bran (pericarp and germ), and thus ash is used as an index of bran contamination (Pomeranz and Meloan 1994, Shuey 1976). Flour colour influences consumer preferences and is therefore the most practical parameter that is used to evaluate mill performance and product quality (Posner and Hibbs, 1997). The colour of the milled product is generally affected by bran content, foreign materials and natural pigments present in the processed grain. Instruments such as Agtron colour meter (Gomez et al, 1997, Posner and Hibbs, 1997), Kent Jones and Martin colour grader and tristimulus meters (Kent and Evers, 1994, Posner and Hibbs, 1997) have found wide application in the milling industry for colour evaluation of the milled products. Ash content is commonly determined by dry-ashing in a muffle furnace (Pomeranz and Meloan 1994). Other suggested flour (or meal) refinement monitoring procedures include NIR (Posner and Hibbs, 1997) and aleurone and pericarp fluorescence imaging (Symons and Dexter, 1996).

As for the sorghum grain, FAO and WHO (2006) have formulated a standard for sorghum flour produced specifically for human consumption (Codex Stan 173-1989). This standard specifies acceptable limits for moisture content, tannin content, ash, protein, crude fat, crude fibre, colour and particle size distribution of the flour. It also states limits for contaminants (heavy metals, pesticides and mycotoxins), and recommends analysis methods that should be used for evaluation of the flour. To evaluate the flour, standard methods of the American Association of Cereal Chemists (AACC) (http//cerealchemistry.aaccnet.org), International Association for Cereal Science and Technology (ICC) (http//www.icc.or.at), FAO and WHO Food Standards (http//www.codexalimentarius.net) and the International Organization for Standardization (ISO) (http//www.iso.org) are generally applied for standardization.

2.5 Conclusions

This review has clearly revealed that sorghum grain is very variable in terms of physico-chemical characteristics. The differences in the sorghum characteristics are potential causes of variations in the quality of the end-use products. It has also been established that different milling processes operate on different principles, which may affect the extraction rate and refinement of flours (meals) differently. These parameters may further be affected by the interactions of the milling process and the grain characteristics. Hence, variations in the quality of the final sorghum products may be understood by establishing relationships between the grain physico-chemical characteristics, composition of the meal, and the quality characteristics of the final product.

The review also determined that the milling processes presently used for sorghum are inadequate in terms of output and product quality control. The roller milling process appears to be an alternative process that can potentially increase throughputs, but its potential for production of meals of good porridge making quality has not been determined.

2.6 Hypotheses

(a) Different sorghum types differ in physico-chemical characteristics, and therefore they will produce sorghum porridges with varied sensory attributes.

(b) Hand pounding and abrasive decortication-hammer milling operate on the same principle by removing the pericarp from outside and inwards, but removing it as large flakes and fine particles, respectively. Roller milling on the other hand de-bran by breaking the kernel and scraping the endosperm from inside the bran flakes. Hence, the three milling processes will produce meals with different qualities, thus affecting the sensory characteristics of the derived porridges differently.

2.7 Objectives

(a) To characterise the physico-chemical properties of sorghum varieties, with varied kernel types, that are commonly grown in Botswana.

(b) To determine the effect of sorghum type and milling process (traditional hand pounding, abrasive decortication-hammer milling, and roller milling) on the flour and porridge quality.

(c) To determine the descriptive sensory profiles of the porridges prepared from sorghum flours obtained in (b) above.

(d) To determine relationships between a selected important porridge sensory attribute determined in (c) and the physico-chemical properties of the sorghum grain and meal.

(e) To devise an improved sorghum milling process, based on the above findings, suitable for large-scale industrial use.

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).

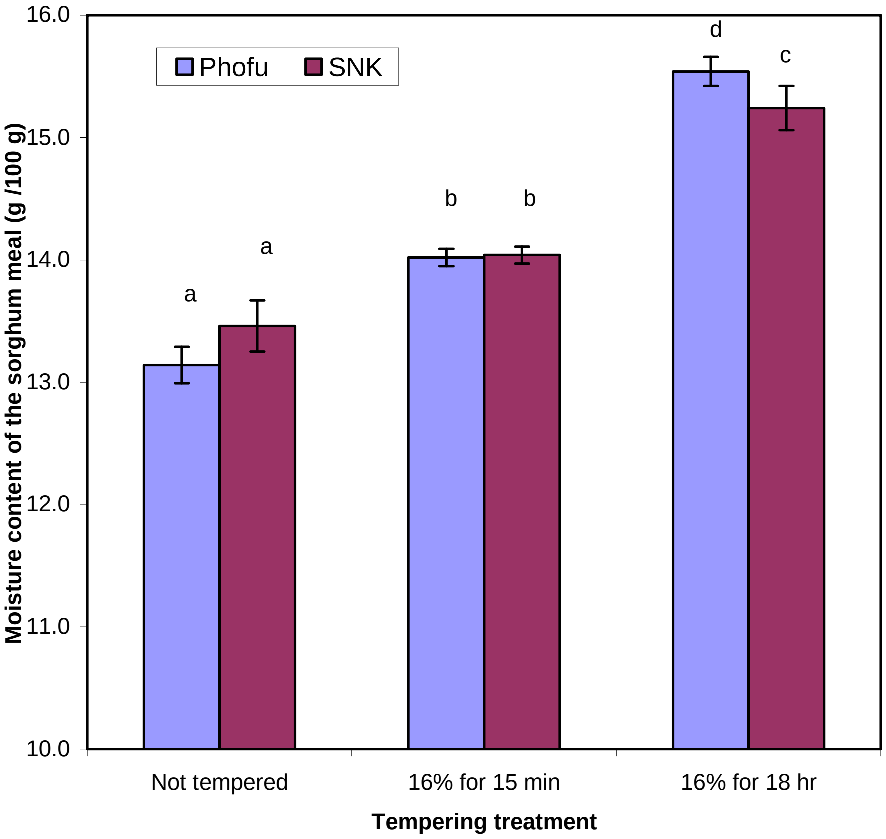

Figure 3.1.4. **Effect of tempering sorghum grain to 16% for 15 min and 18 hr on the moisture content of sorghum meal produced by two-stage roller milling (Data bars with different letter notations are significantly different at p<0.05 and the error bars are standard deviations).**

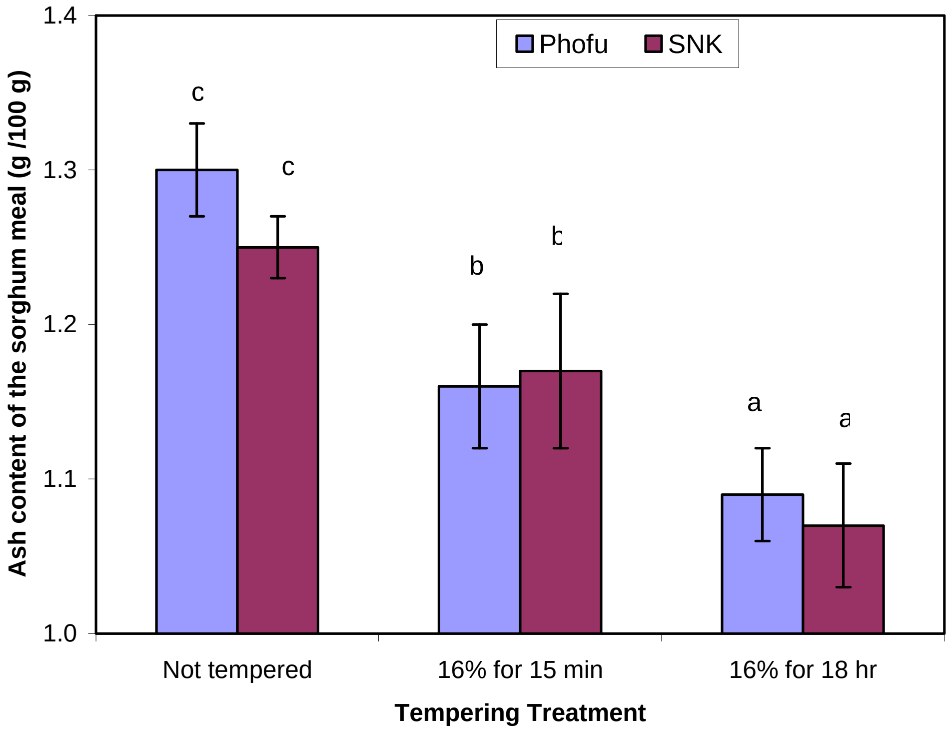

Fig. 3.1.5. **Effect of tempering sorghum grain to 16% for 15 min and 18 hr on the ash content of sorghum meal produced by two-stage roller milling (Data bars with different letter notations are significantly different at $p<0.05$ and the error bars are standard deviations).**

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.

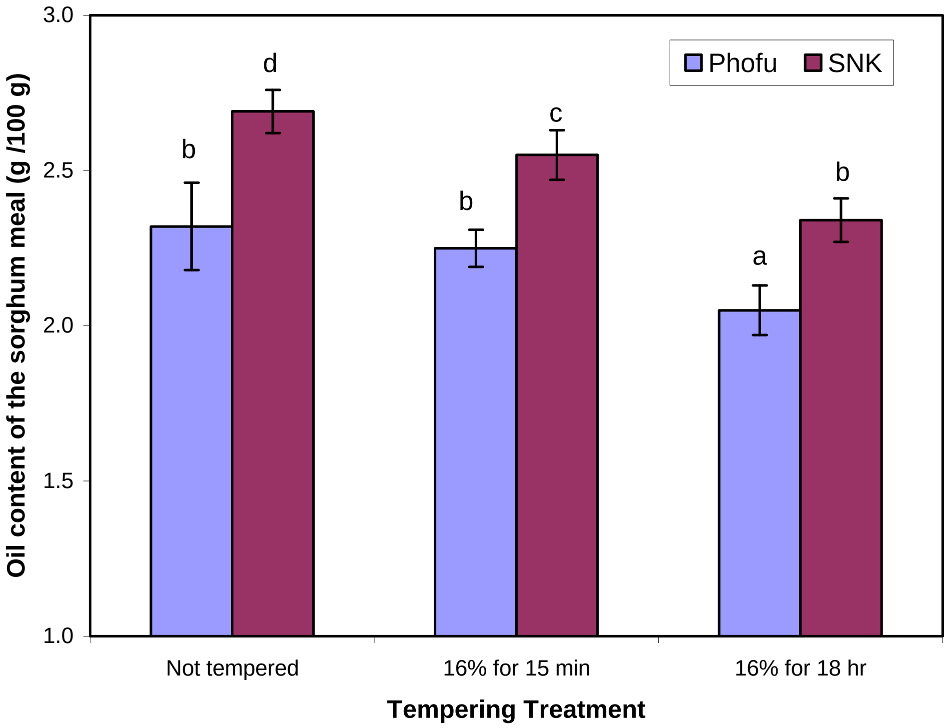

Fig. 3.1.6. **Effect of tempering sorghum grain to 16% for 15 min and 18 hr on the oil content of sorghum meal produced by two-stage roller milling (Data bars with different letter notations are significantly different at $p<0.05$ and the error bars are standard deviations).**

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.

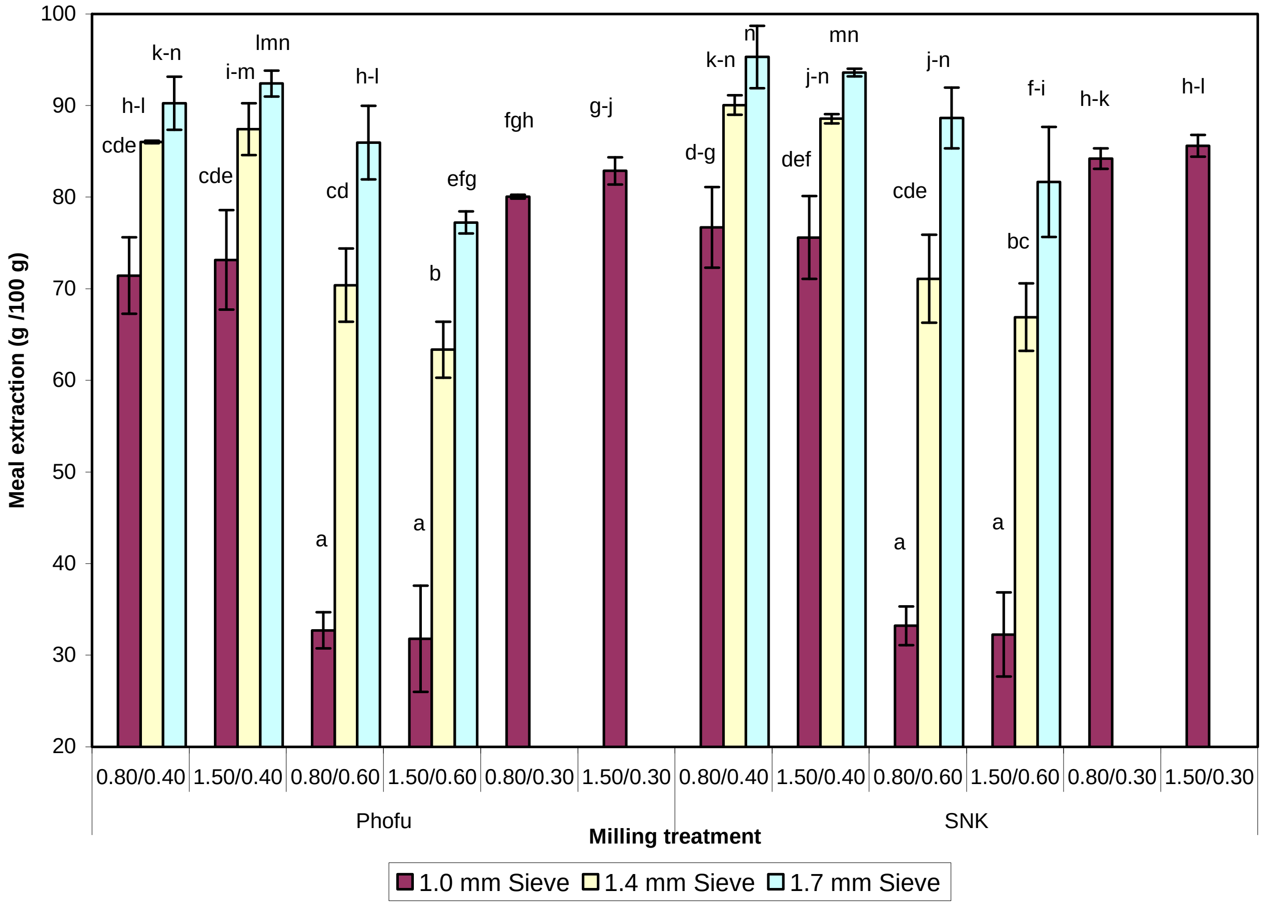

Fig. 3.1.7. **Effect of roll gap size (first number top gap, second number bottom gap) and sieve opening on the extraction rates of corneous (Phofu) and intermediate (SNK) endosperm sorghum types milled using a two-stage roller mill (Data bars with different letter notations are significantly different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

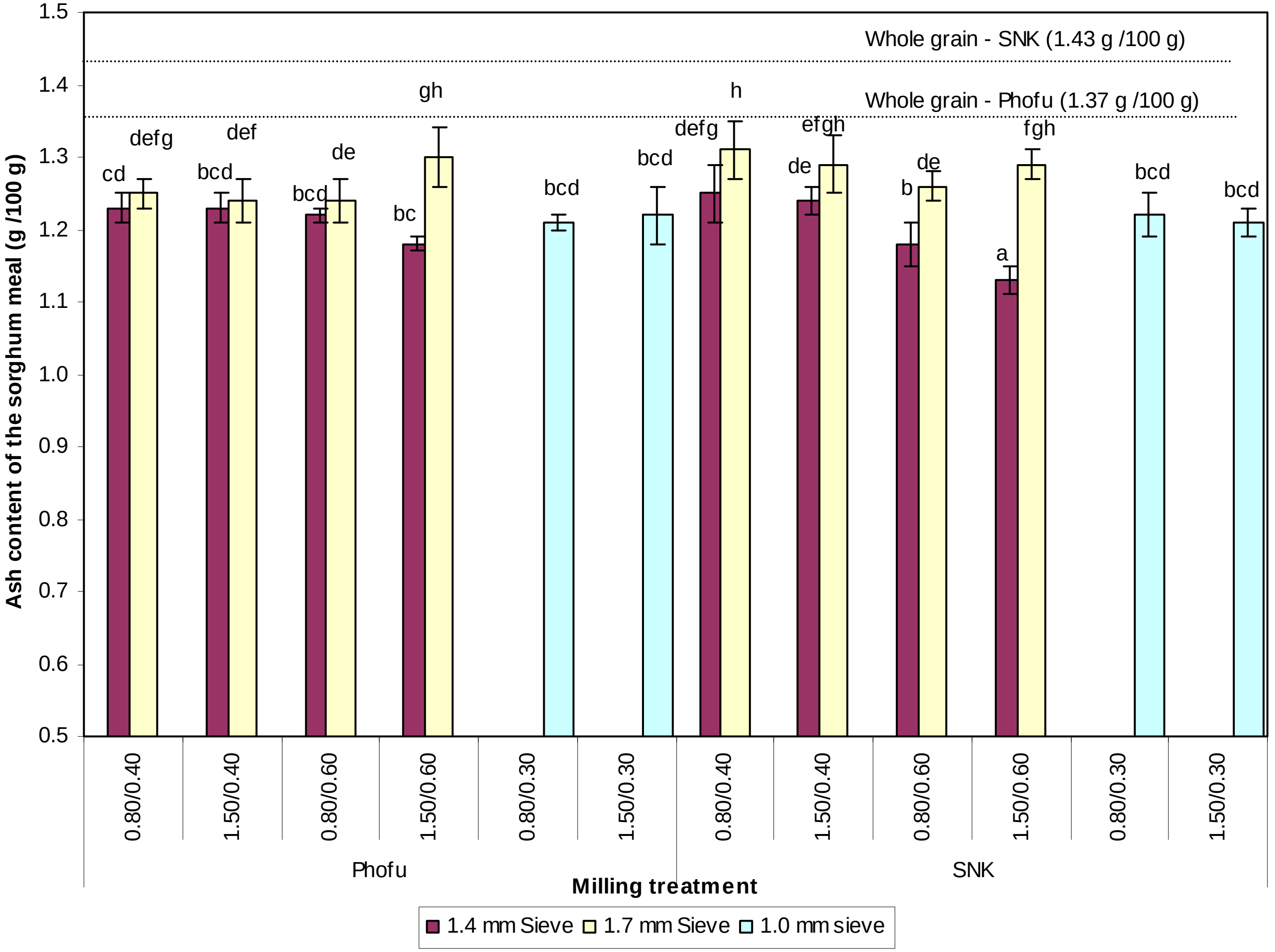

Fig. 3.1.8. **Effect of roll gap size (first number top gap, second number bottom gap) and sieve opening on the ash content of meals produced from corneous (Phofu) and intermediate (SNK) endosperm sorghum types milled using a two-stage roller mill (Data bars with different letter notations are significantly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

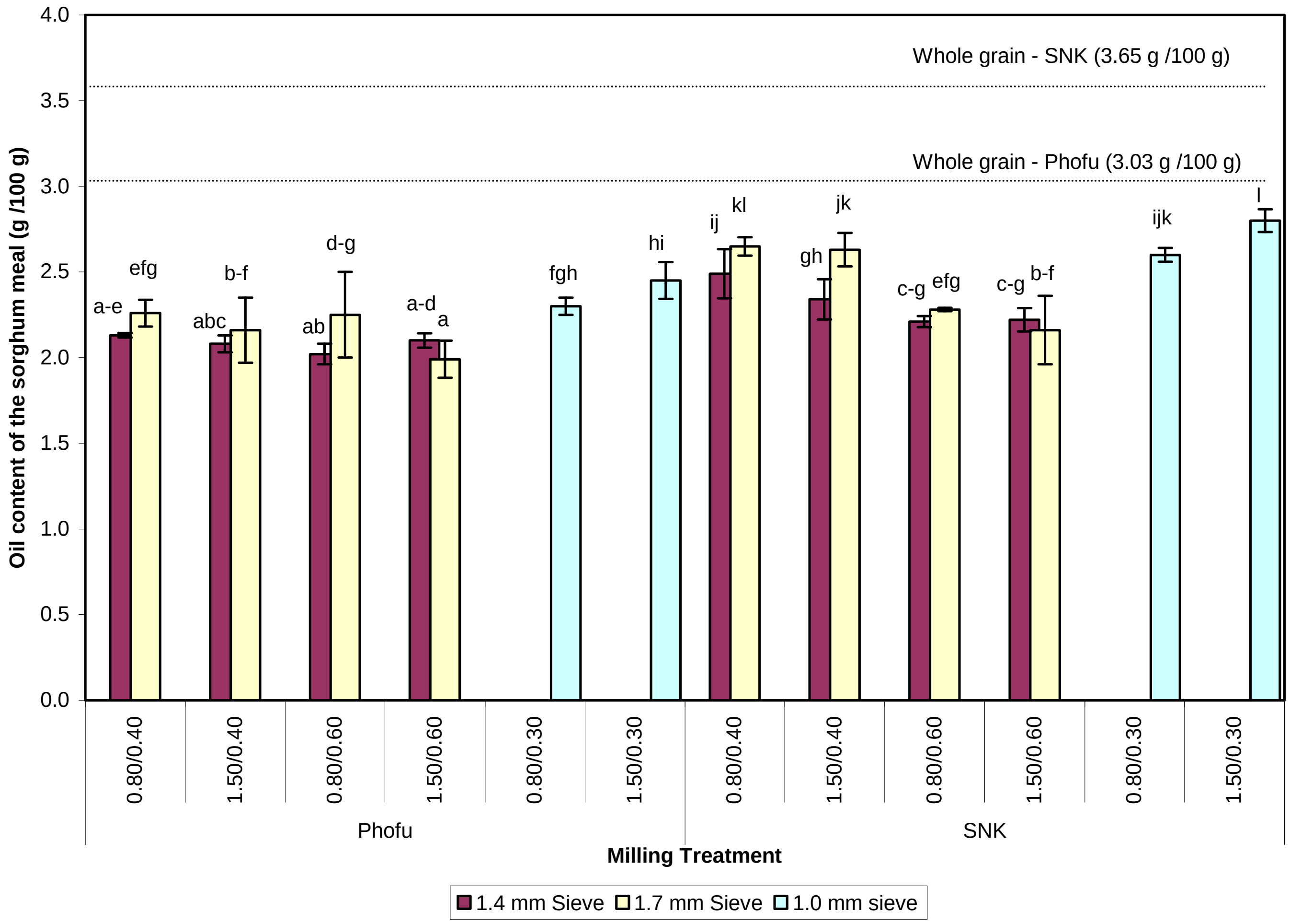

Fig. 3.1.9. **Effect of roll gap size (first number top gap, second number bottom gap) and sieve opening on the oil content of meals produced from corneous (Phofu) and intermediate (SNK) endosperm sorghum types milled using a two-stage roller mill (Data bars with different letter notations are significantly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

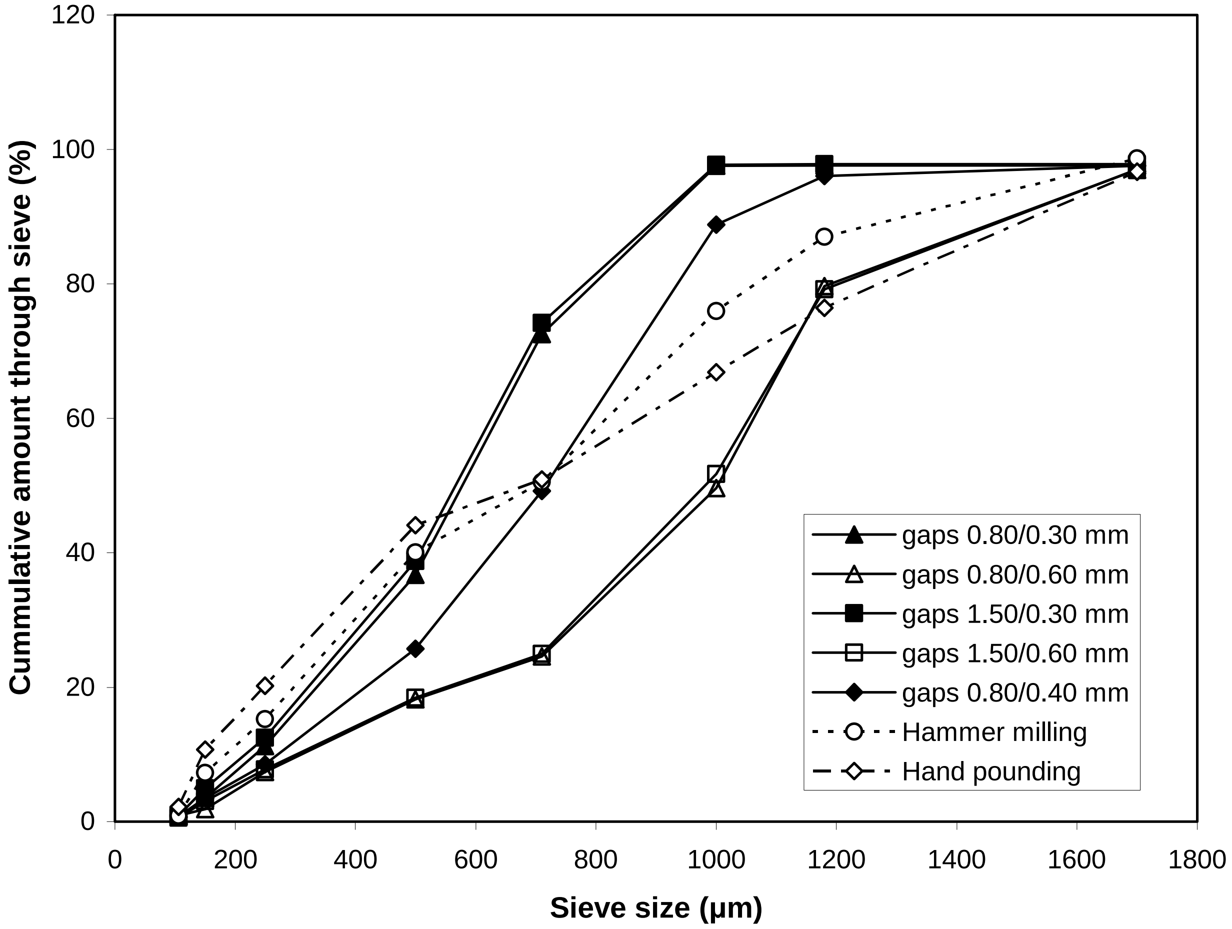

Fig. 3.1.10. Effect of milling process on the particle size distribution of sorghum meals produced from corneous endosperm sorghum (Phofu) by hand pounding, hammer milling and roller milling, using different roll gap settings.

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

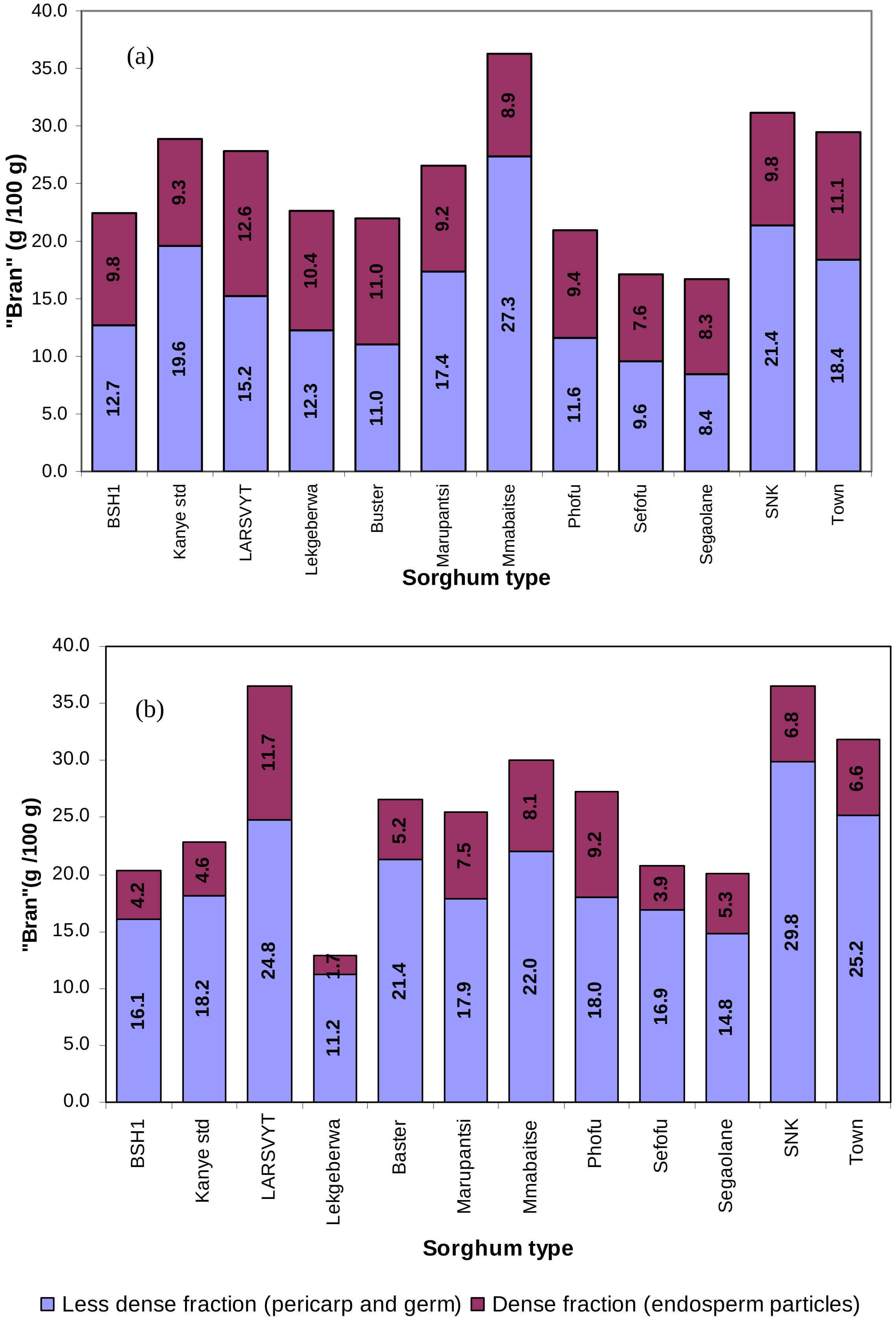

Fig. 3.1.11. **Effect of abrasive decortication (a) and hand pounding (b) on the composition of sorghum ‘‘bran’’ (mixture of bran and endosperm particles) produced.**

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

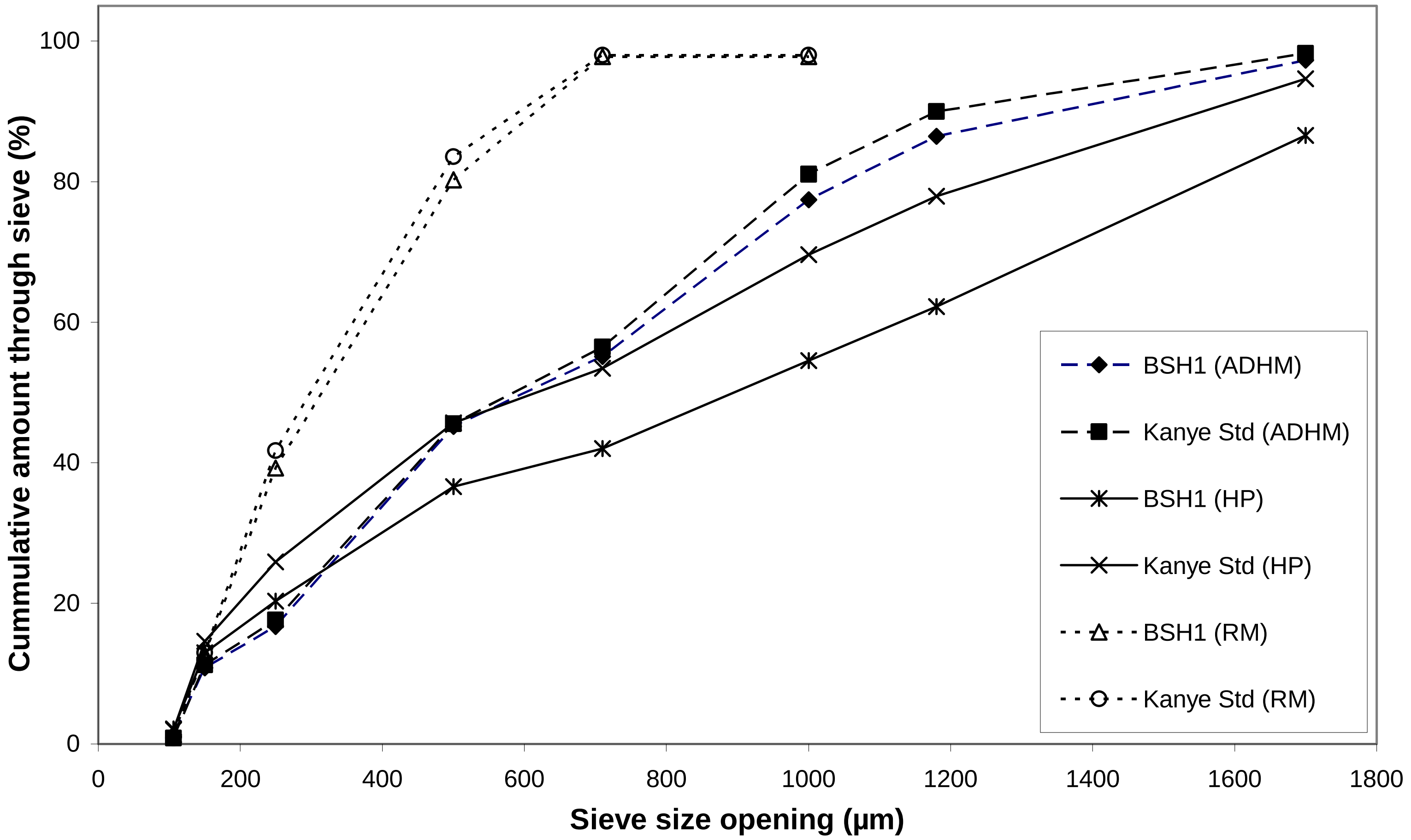

Fig. 3.1.12. Effect of milling process on the particle size distribution of sorghum meals produced from corneous (BSH1) and intermediate (Kanye Std) endosperm grains by hand pounding (HP), abrasive decortication-hammer milling (ADHM) and roller milling (RM).

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 (±45°C) 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 ith panelist on the y-value, β_j = effect of the jth sorghum type on the y-value, γ_k = effect of the kth milling process on the y-value, δ_l = effect of the lth session on the y-value, $(\alpha\beta)_{ij}$ = interaction effect of ith panelist and jth sorghum type on the y-value, $(\alpha\gamma)_{ik}$ = interaction effect of the ith panelist and the kth milling process on the y-value, $(\beta\gamma)_{jk}$ = interaction effect of the jth sorghum type and the kth 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.

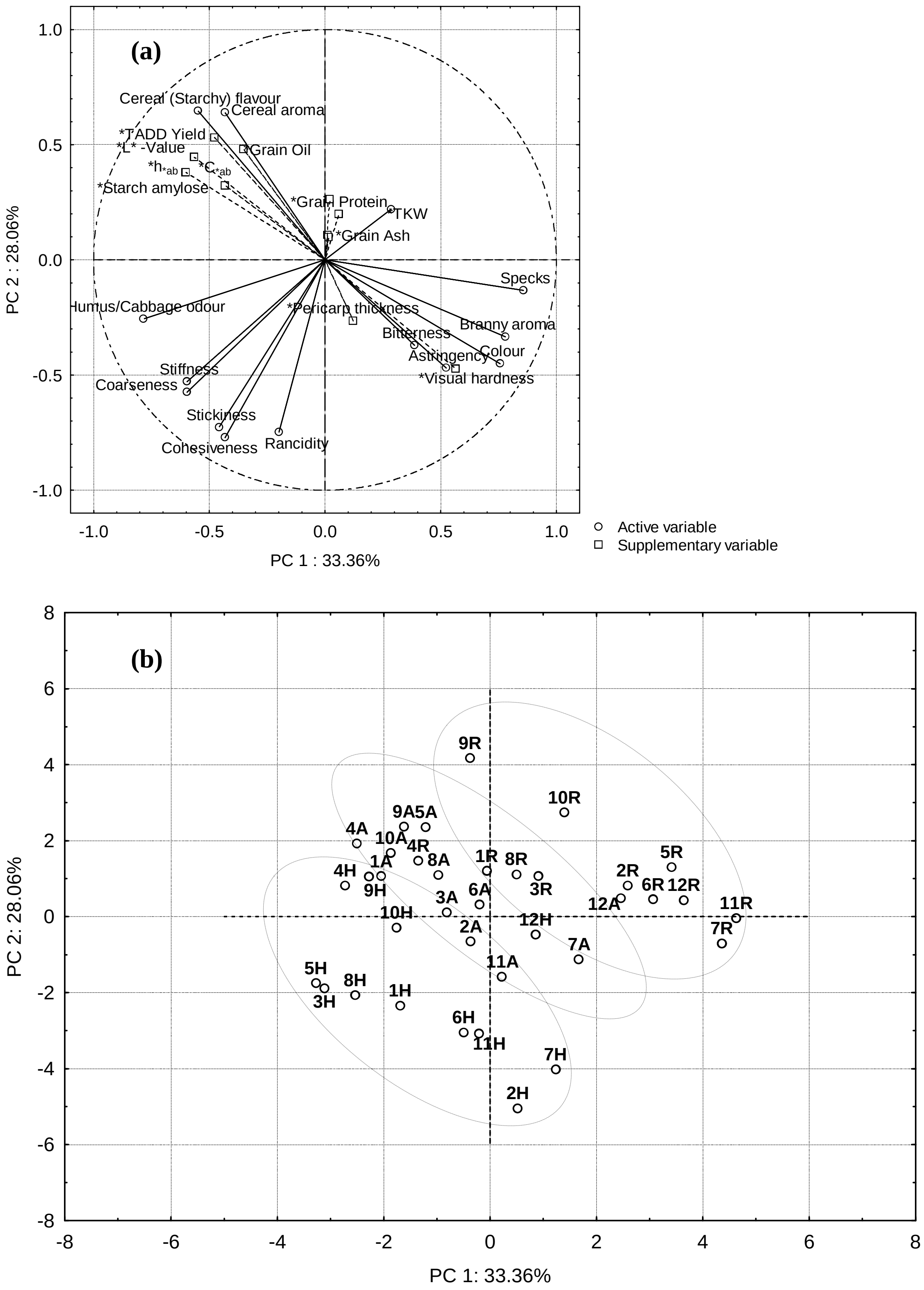

Fig. 3.2.1. **PCA plots of 36 sorghum porridge samples prepared from 12 sorghum types milled by hand pounding (H), abrasive decortication–hammer milling (A), and roller milling (R). (a) loadings projections of sensory variables, (b) score plot of the porridges on PC1 and PC2. The numbers 1-12 represent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

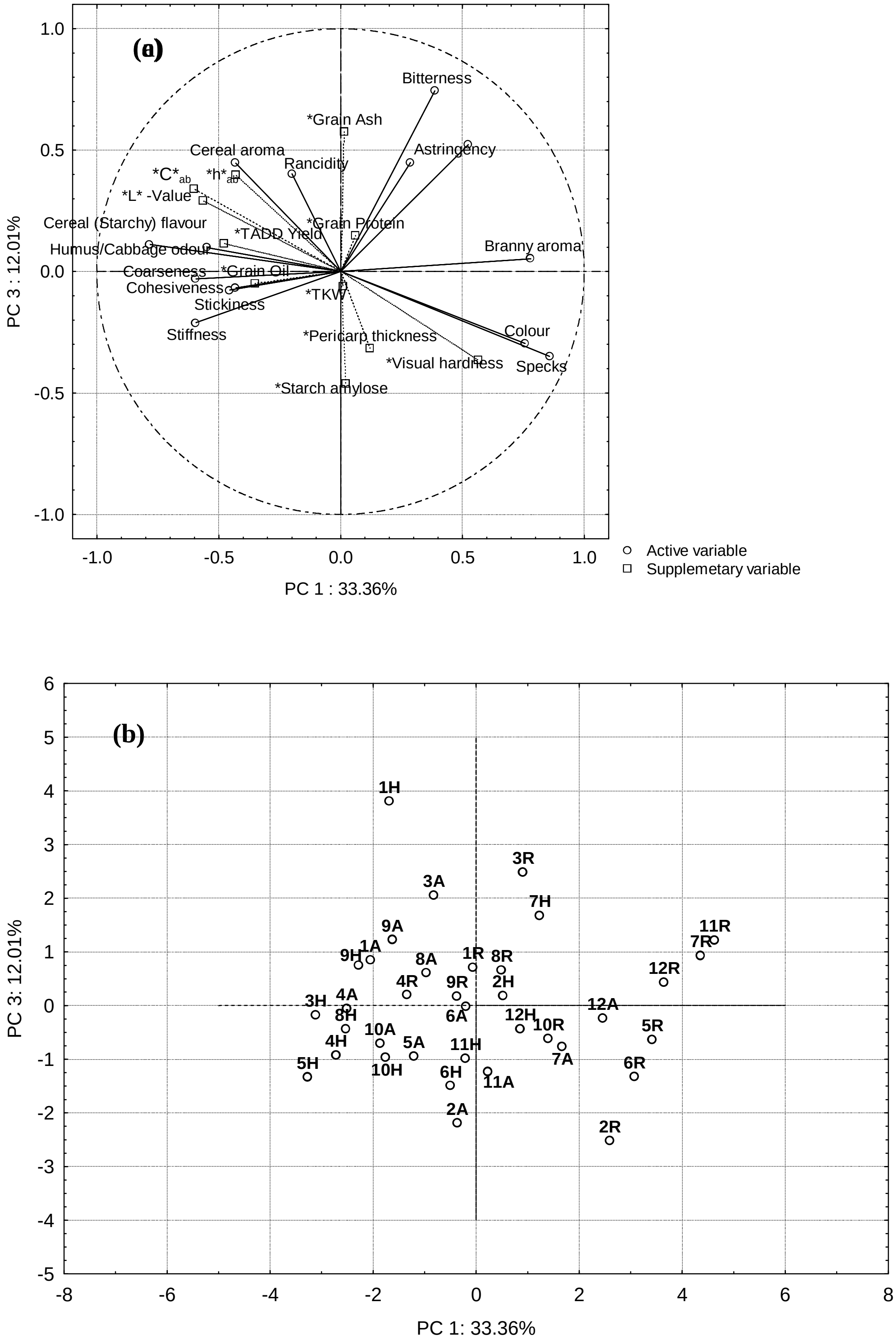

Fig. 3.2.2. PCA plots of 36 sorghum porridges on PC1 and PC 3, prepared from 12 sorghum types milled by hand pounding (H), abrasive decortication–hammer milling (A), and roller milling (R). (a) loadings projections of sensory variables, (b) score plot of the porridges on PC1 and PC3. The numbers 1-12 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.

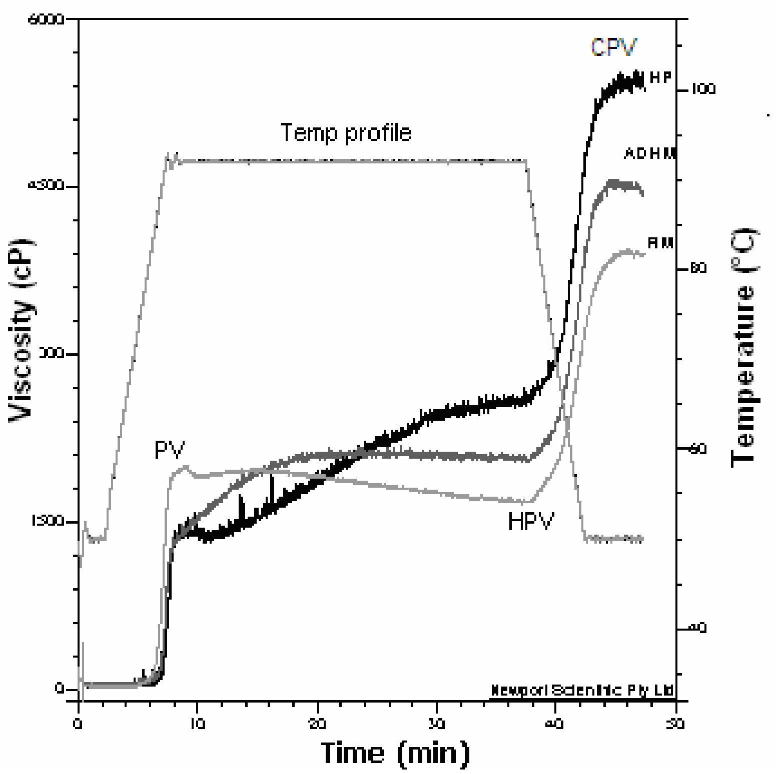

Fig. 3.3. 1. Effects of hand pounding (HP), abrasive decortication-hammer milling (ADHM) and roller milling (RM) on the pasting profiles of sorghum meal samples obtained with Town sorghum type. PV – peak viscosity, HPV – hot paste viscosity, and CPV – cool paste viscosity

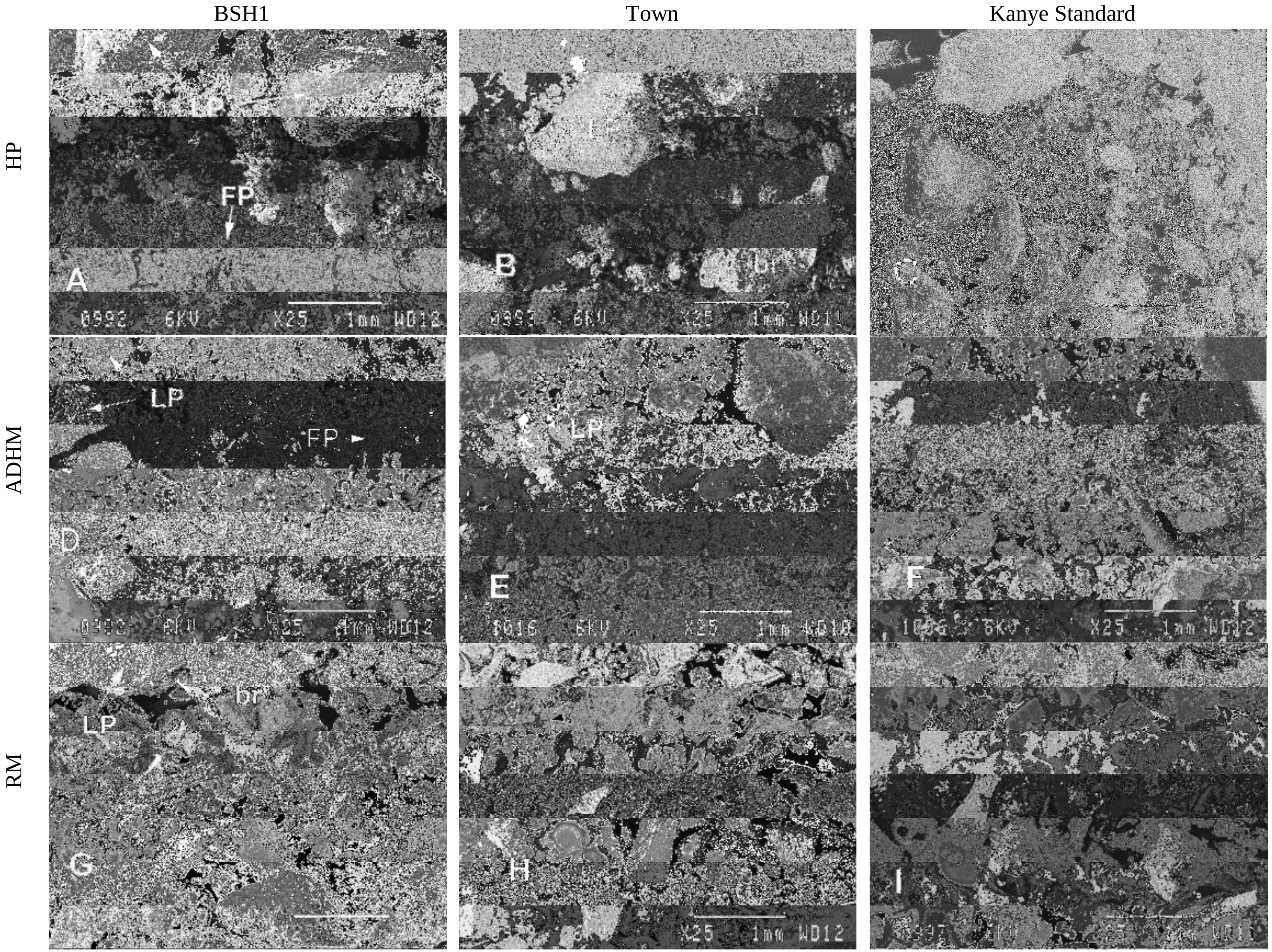

Fig.3.3. 2. **Scanning electron micrographs of meals obtained by milling three sorghum types (BSH1 - ADG, Town – BEH, and Kanye Standard - CFI) by hand pounding (HP), roller milling (RM) and abrasive decortication followed by hammer milling (ADHM). LP – large endosperm particle, FP – fine endosperm particle,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

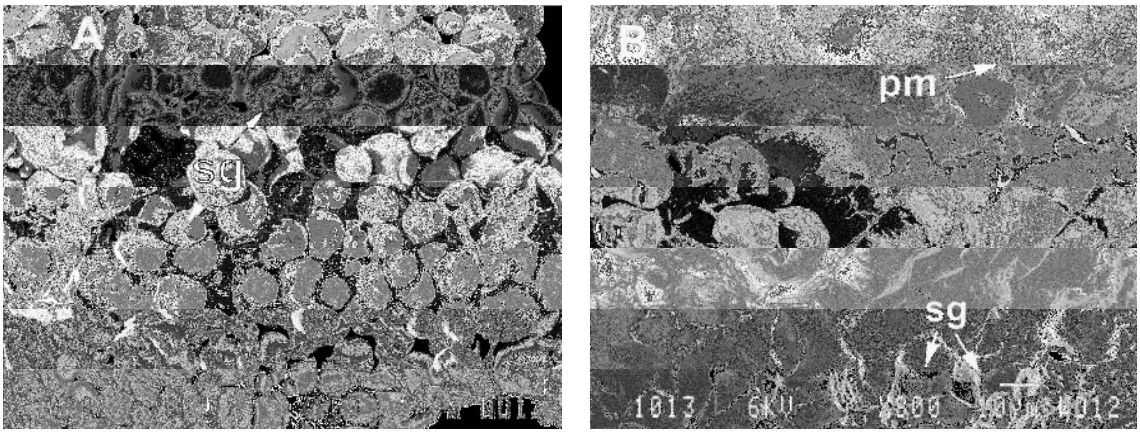

Fig. 3.3.3. **Scanning electron micrographs of sorghum meals produced from sorghum type Phofu using abrasive decortication - hammer milling (A) free starch granules (sg) in a soft endosperm meal particle, and (B) starch granules (sg) compactly bound with protein matrix (pm) in a hard endosperm meal particle**

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.

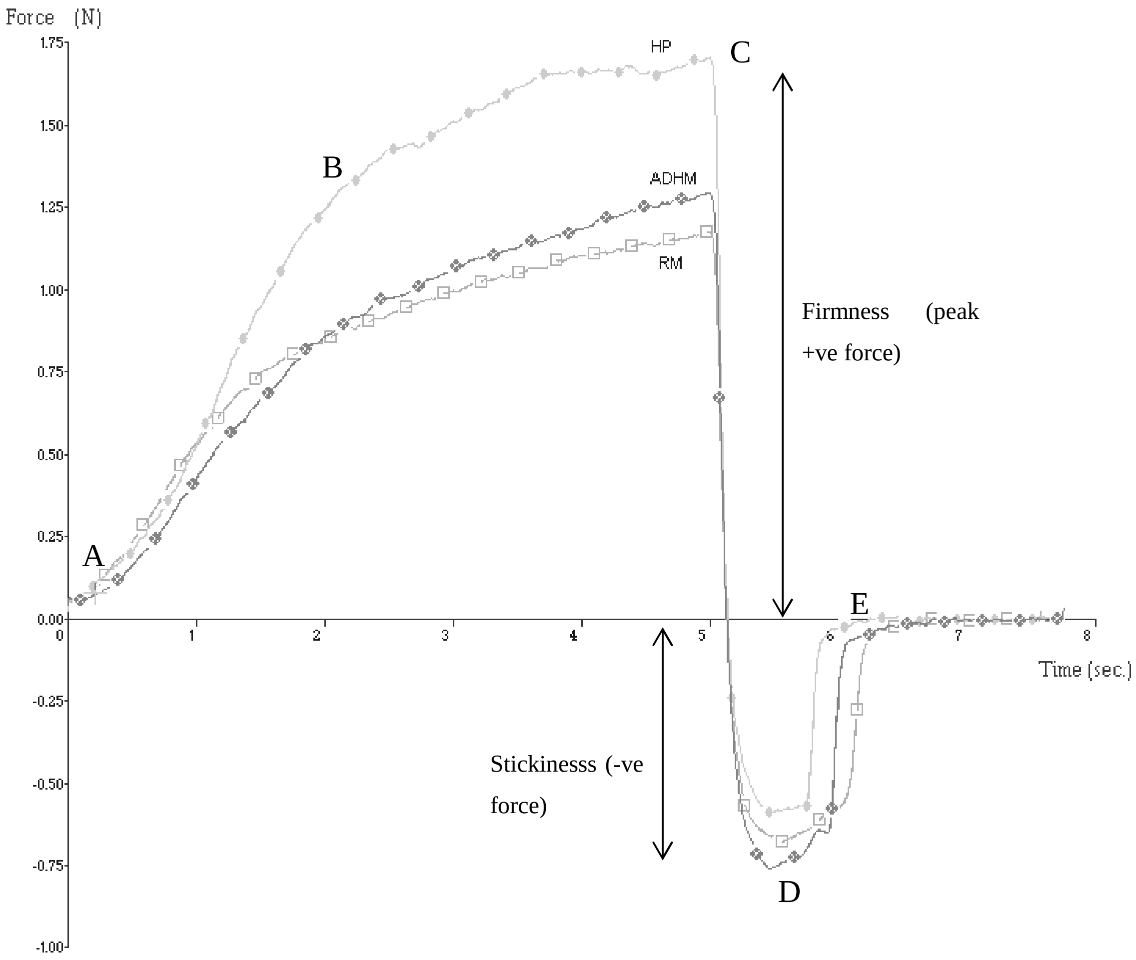

Fig. 3.3. 4. Effect of milling process (hand pounding (HP), abrasive decortication-hammer milling (ADHM) and roller milling (RM)) on the textural properties of sorghum meal obtained with sorghum type Kanye std. Each curve is an average of six plots

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.

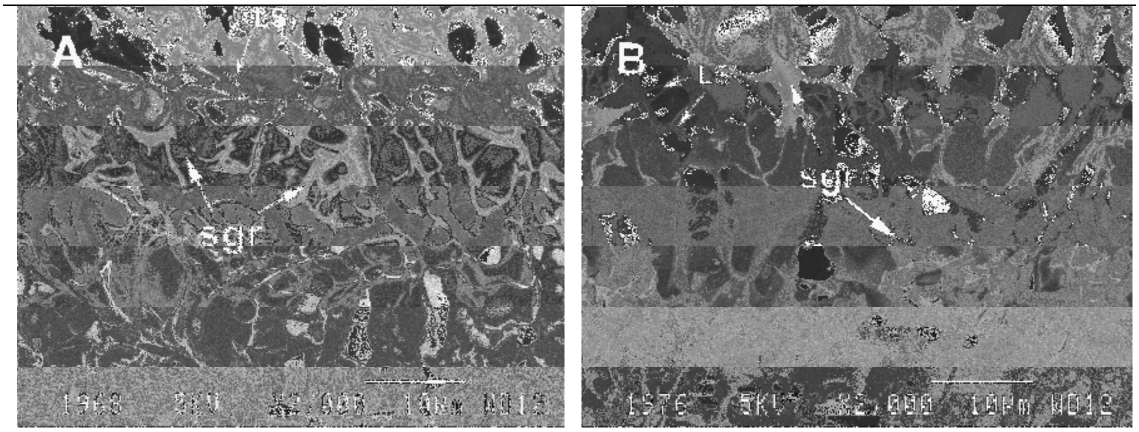

Fig. 3.3. 5. **Scanning electron micrographs of cryofrozen and freeze-dried sorghum porridges showing starch granule remnants (sgr) in porridges prepared from abrasively decorticated and hammer milled (A) Phofu and (B) Town sorghum types.**

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

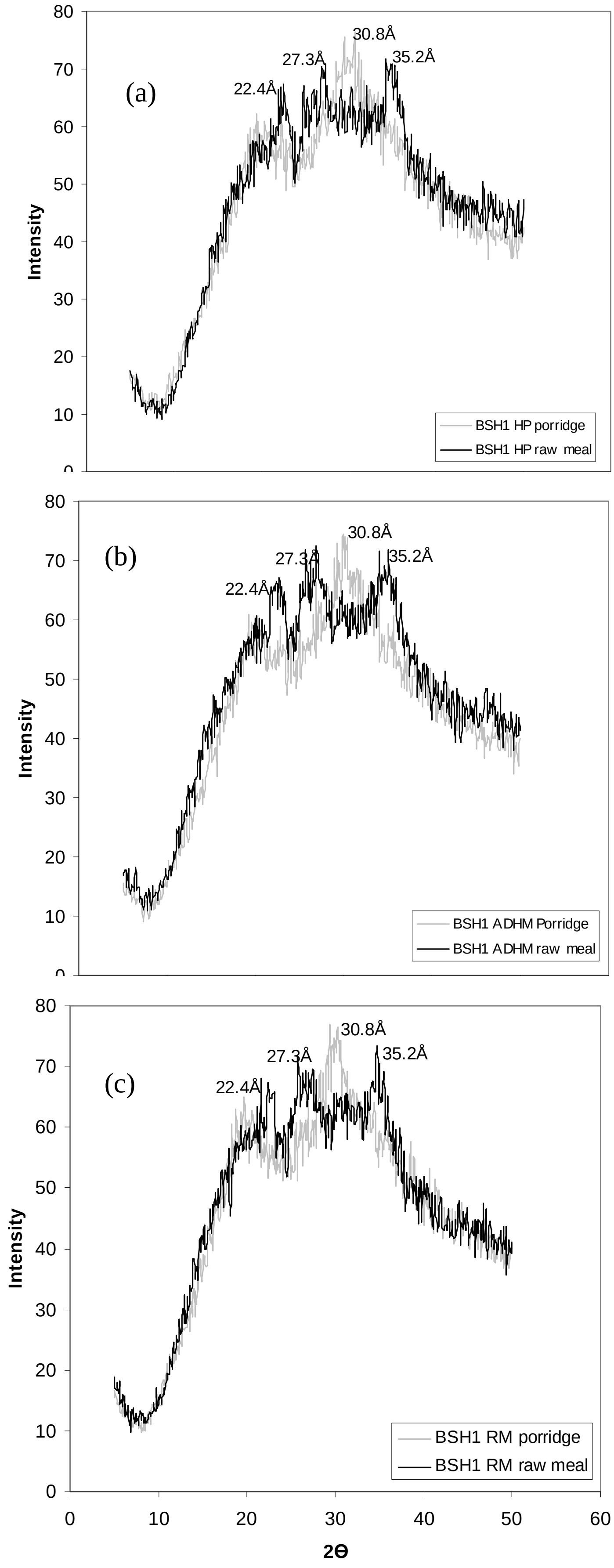

Fig. 3.3.6. X-ray diffractograms of raw sorghum meals, and freeze-dried porridges prepared therefrom, obtained with BSH1 sorghum type milled by (a) hand pounding (HP), (b) abrasive decortication-hammer milling (ADHM) and (c) roller milling (RM). Solid black line depicts A type X-ray diffraction pattern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

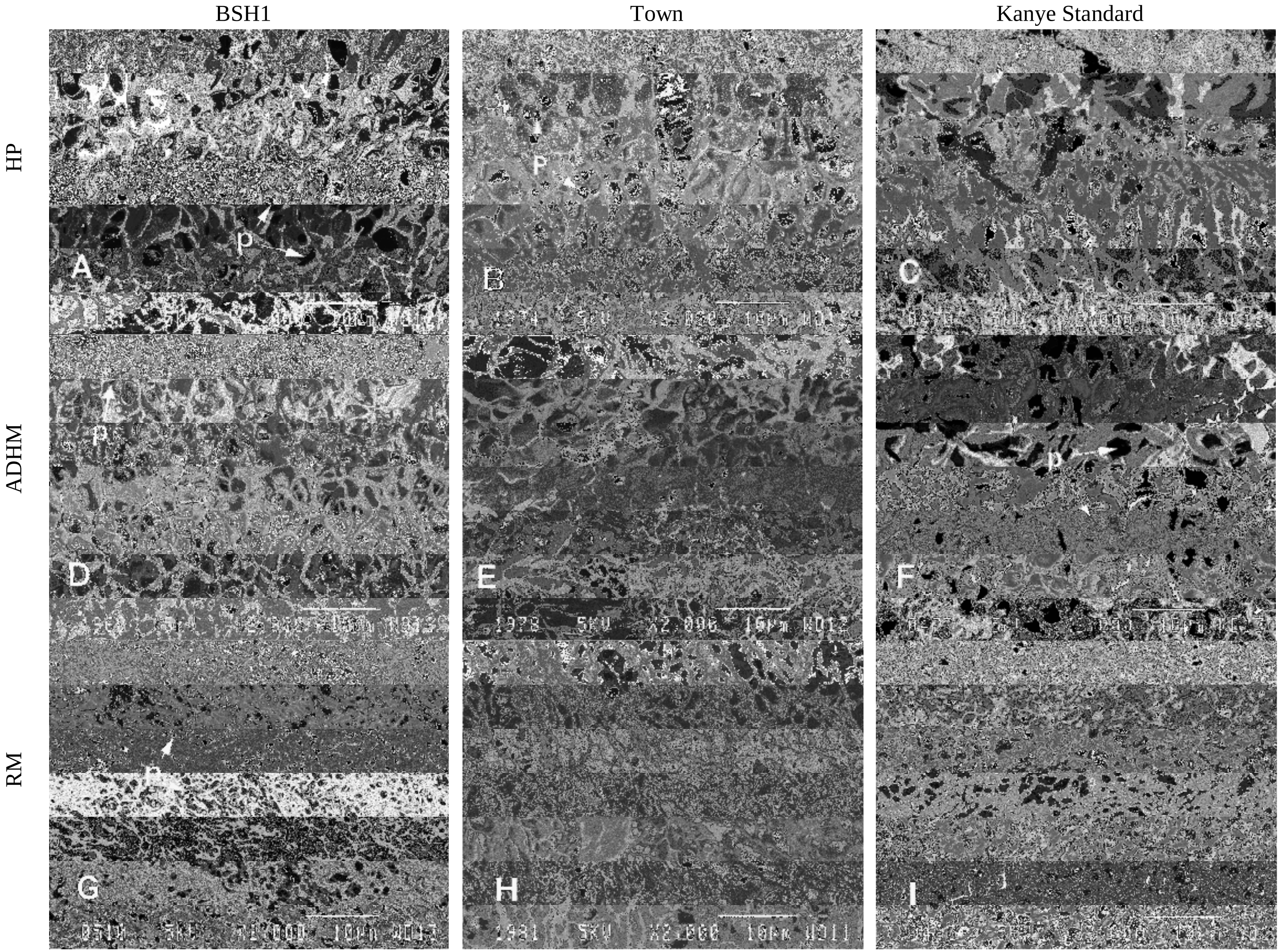

Fig. 3.3.7. Scanning electron micrographs of cryofrozen and freeze-dried components of sorghum porridges prepared from meals obtained by milling three sorghum types (BSH1 - ADG, Town – BEH, and Kanye Standard - CFI) by hand pounding (HP), roller milling (RM) and abrasive decortication followed by hammer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

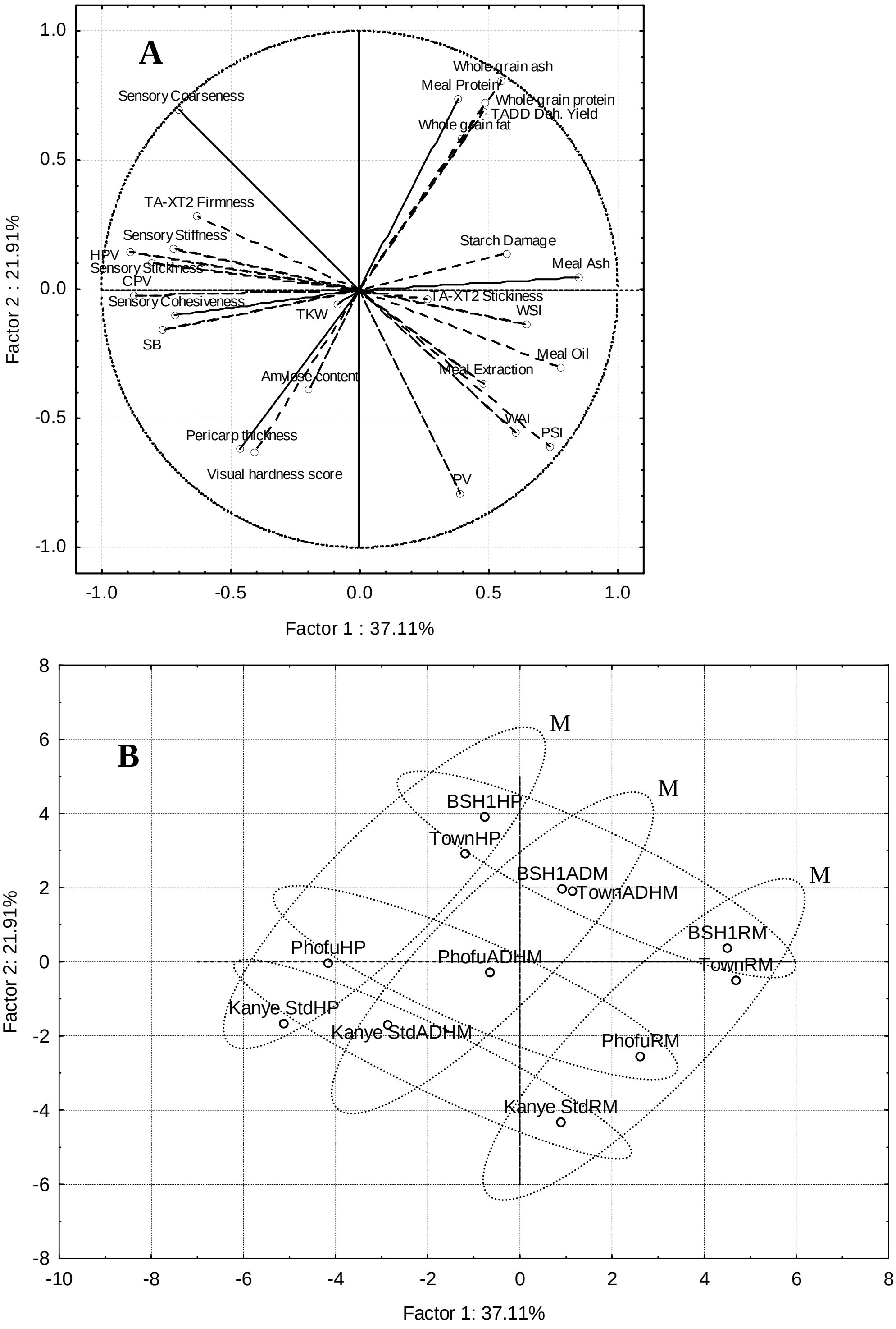

Fig. 3.3. 8. **Principal component analysis (PCA) plots of sorghum porridge samples prepared from four sorghum types (BSH1, Phofu, Kanye Std and Town) milled by hand pounding (HP), abrasive decortication – hammer milling (ADHM), and roller milling (RM). (A) loadings projections of determined variables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

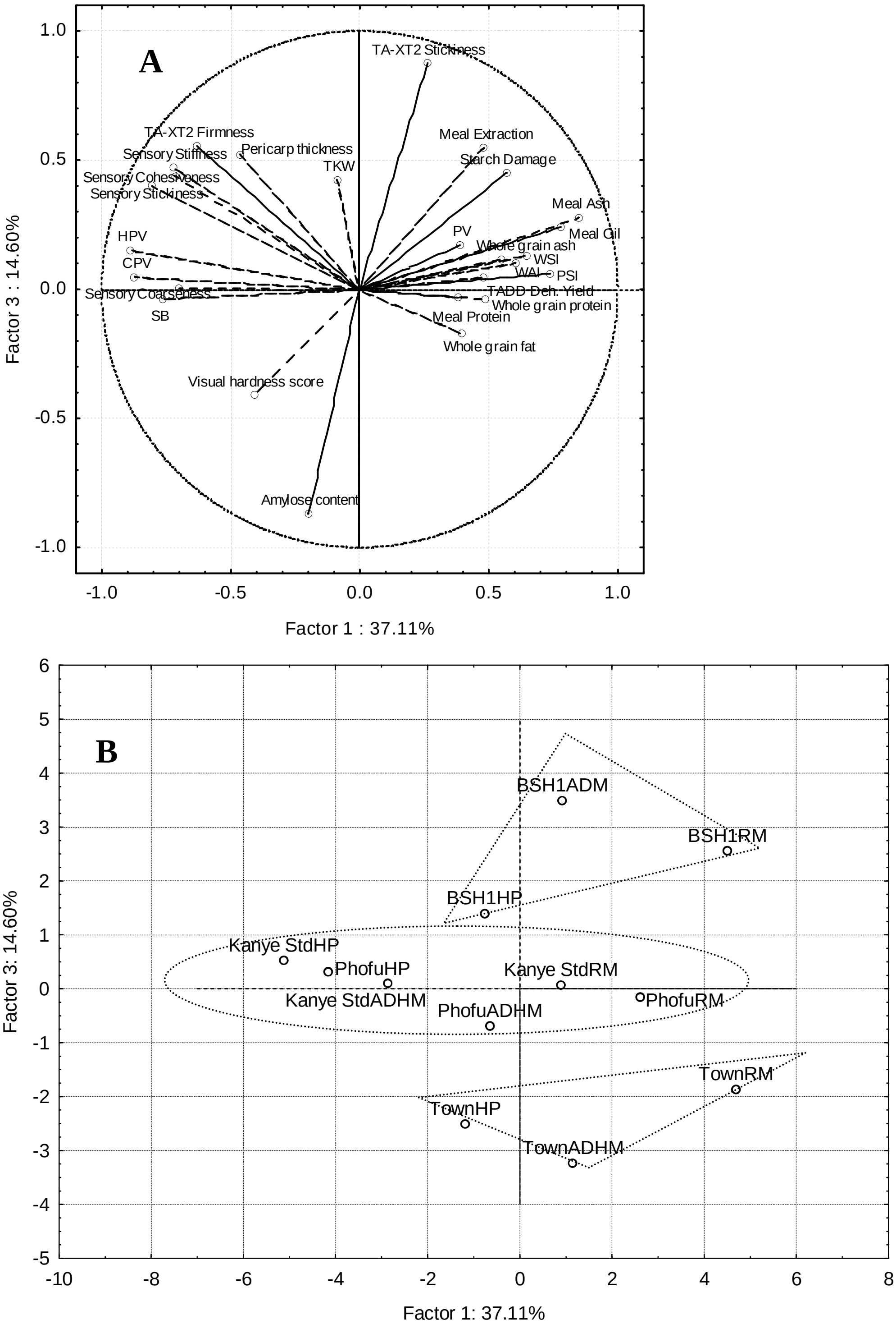

Fig. 3.3. 9. **Principal component analysis (PCA) plots of sorghum porridge samples prepared from four sorghum types (BSH1, Phofu, Kanye Std and Town) milled by hand pounding (HP), abrasive decortication – hammer milling (ADHM), and roller milling (RM). (A) loadings projections of determined variables 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.

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4 GENERAL DISCUSSION

The discussion starts by critiquing the way key methods were applied in this study with the objective of revealing strengths and weaknesses in the applications, as well as making suggestions for applying the methods better in the future. It then compares the performance of the different milling processes in respect of extraction rates, production throughput, energy efficiencies and the quality of meals and porridges derived therefrom, highlighting critical characteristics of sorghum grains (sorghum types) that affect meal and porridge quality. A summary of the advantages and disadvantages of each of the three milling processes used is given, and recommendations for a more effective milling process design for industrial milling of sorghum are furnished. Finally, recommendations for further research work are given.

4.1 Methodologies: A critical review

4.1.1 Sampling of sorghum types

As stated, a total of 12 non-tannin sorghum types that are popularly used for porridge making in Botswana were selected and used in this study. These were all harvested in 2004, and were selected to represent kernels with a wide variety of physico-chemical characteristics. However, the collection included only sorghum types with intermediate to corneous endosperm texture, and none with the floury endosperm. This was the case because none of the farmers produced types with completely floury endosperm, probably indicating that floury endosperm sorghums are not popular for porridge making in Botswana. It may as well be that sorghums with floury endosperm are too susceptible to abiotic stress than the intermediate and corneous types, and therefore do not perform well under the local climatic conditions. Because of the lack of these floury sorghums, the study could not establish how the completely floury endosperm would behave when subjected to the different milling treatments. More complete data would have been generated if soft endosperm sorghums could have been sourced elsewhere. Only sorghums harvested in a single year were used, thus limiting the sampling design. Sampling in the following year would have been ideal, because the effect of the cultivar could have been determined together with the effect of the sorghum type. However, sufficient harvest in the next year could not be guaranteed, because of the unpredictable rainfall in the sampling areas selected. This consideration was particularly important because this study was time bound. Nonetheless, the selection of the sorghums used was reasonably comprehensive as it included at least two sorghums with similar or identical specific characteristics (e.g. red grain colour, thick pericarp type, corneous endosperm type, etc). This sampling plan was presumed to be essentially equivalent to replicating specific grain characteristics that were considered to be important for milling. Consequently, the term “sorghum type” was used to refer to grain with specific characteristics. Since sorghum grain characteristics can vary significantly depending on the growing environment (Rooney and Miller 1982), the use of the terms ‘variety’ and ‘cultivar’ were not appropriate, because the sorghums selected were neither produced under identical environmental conditions, nor sampled to represent the different growing environments.

4.1.2 Selected milling processes

A weakness in this study was that hand pounding and abrasive decortication-hammer milling, which have been perfected over time on the basis of feedback from consumers, were compared with two-stage roller milling, a process which is at an early development stage for sorghum milling. Thus, roller milling, as was applied to sorghum in this study, may not have been satisfactorily optimized, and hence, its performance was probably unfairly compared to those of the other proven milling processes. Another area of possible contention is that the control of the milling treatments was very subjective. For example, for hand pounding and abrasive decortication-hammer milling control of milling was left entirely to the operators, who subjectively determined the end point of dehulling, and the subsequent quality of the final meal. As such, some degree of variability in the ability to judge the completion of the milling treatment among the different sorghum types may have resulted, thus influencing the quality of the data. Thus, one sorghum type may have unnecessarily received more than enough decortication treatment than another, hence being wrongly portrayed as yielding low meal than it would otherwise yield if the judgment was fairly applied across all the sorghum types. However, while this may be perceived as a weakness in the control of the study treatments, it reflects one of the most important features of the employed milling processes, the precision in the control of the process. That is, the extent of grain decortication, and hence, the time spent to decorticate a batch of grain, can be very variable (even with the same operator) with hand pounding and abrasive decortication–hammer milling, because completion of the decortication process is dependent entirely on the judgment of the operator. With roller milling, the choice of the processing parameters is also subjective, since the roll gap settings and sieve size openings are selected by the operator, but the control is more precise than for the other two milling processes because the intervention of the operator (judgement of meal quality) is very minimal during the process.

4.1.3 Descriptive sensory analysis

Whereas duplicate meal samples were produced for each milling treatment, composites of these duplicates were used for preparation of porridges for descriptive sensory analysis. Composite meals were used to reduce the number of samples evaluated, thus shortening the evaluation period and minimizing the sensory workload on the panelists. Ideally, porridges prepared from the individual meals should have been used for replication of the sensory test. However, preliminary analysis of the meals had revealed that the duplicate meals were essentially the same in terms of quality, and therefore could be combined to save time.

Einstein (1991) defines Descriptive Sensory Evaluation as “the identification, description and quantification of the sensory attributes of a food material or product using human subjects who have been specifically trained for this purpose”. As such, the success of the descriptive sensory analysis exercise relies primarily on the collective ability of the descriptive panel to reliably and precisely grade given attributes. To test for the normal distribution of the descriptive sensory data generated, the Shapiro-Wilks test, was applied. As shown in Table XI, the Shapiro-Wilks test gave significant results for all but four attributes (coarseness, stickiness, cohesiveness and colour). In other words, these four stated attributes were normally distributed, while the rest were suspicious for non-normal distribution. Considering the results of the Shapiro-Wilks test alone would have invalidated the results for application of parametric statistical tests. It was therefore necessary to examine the data further using additional statistical parameters. These were the skewness and kurtosis, which were all found to be within the acceptable interval limits of -2 and 2 for normally distributed data sets (StatPoint 2005) for all the attributes. Skewness and kurtosis measure the symmetry and peakedness, respectively, of statistical data distributions (Bower 1998). In addition to these statistical tests, the normality plots for residuals (examples shown in Figure 4.1) showed that distributions of data sets for all the attributes were reasonably symmetric, showing that they were normally distributed. This was shown by the bell-shaped distribution of the histogram (Fig 4.1A) (Bhattacharyya and Johnson 1977), the symmetrical distribution of data by the box-and-whisker plot (Fig 4.1B) (Miller and Miller 2000), and the almost perfect linearity of the normal probability plot (Fig 4.1C) (Bhattacharyya and Johnson 1977). Thus, the data were acceptable for parametric statistical tests that were subsequently applied.

The General Linear Model (GLM) results given in Table XII revealed that panelists and sessions were significant sources of variance for the attributes evaluated. Although various arguments have been advanced by different researchers (discussed in Chapter 3.2) to justify why these variables should be expected to contribute to the overall variance, it is worrisome that the panelists in particular were a significant source of variance. Their contribution to the overall variance simply implies that they did not collectively function as an accurate "instrument" in grading the attributes examined, and therefore probably failed to elucidate critical differences or similarities, or did not reveal the true magnitudes of differences, between some of the porridges evaluated. Extended training of the panelists and the inclusion of more reference standards for each of the attributes graded could have improved the attribute scoring precision of the panel. To circumvent the undesirable contributions of the panelists and session effects on the overall variance of the data, these two factors were included in the general linear model used for ANOVA calculations as fixed variables. This was done to remove their distorting influence on the effects of the variables investigated (i.e. sorghum type and milling process). As argued by Berry and Feldman (1993), omitting these sources of variance from the model would have left such effects “confused” with the main variables effects, and may have led to wrong conclusions from the data. Thus, including the two variables in the (GLM) made certain the effects of the main variables.

4.1.4 Differences in the solids concentrations of porridges for sensory and instrumental texture analysis

Another possible criticism is that the identified relationships between the sensory textural attributes and the porridge characteristics determined using instrumental methods were based on porridge samples that differed in solids concentrations. In order to determine the texture of porridge using TA-XT2 Texture Analyser, porridges containing 12% solids, compared to 20% for those used in the sensory studies, had to be analysed. Porridges containing 20% solids did not fill uniformly and repeatably into the sample vessels used for the TA-XT2 analyser, and hence, gave inconsistent results. Thus, the procedure was not reproducible. Highly repeatable and consistent results (with coefficient of variance of <5%) were achieved with porridges containing 12% solids. However, it is very probable that the 40% difference in the solid concentration of the porridges caused significant differences in the structure of the matrices of the porridges, thus affecting the relationships between the data sets generated by the two methods. Perhaps using larger sample vessels (probably 3 times the size of those used) and a larger instrument probe would produce consistent results with the 20% solids porridges. Nonetheless, significant positive correlations were noted between the instrumental porridge firmness and the sensory textual attributes, showing that these parameters were similarly affected by the intrinsic factors of the porridge. In order to study the microstructure of the porridge specimens, and to relate the observed microstructures directly to the instrumental texture measurements, the same porridges used for the TA-XT2 analyser were also used to generate SEM micrographs. The 20% solids concentration used in sensory studies was based on the practical recipe for porridge making commonly used in Botswana, and was used to reflect the exact sensory attributes perceived in porridges prepared by the consumers.

```
                     (A)                            #       (B)                                   (C)
 3.75+***                                           8        ¦           3.75+                                               +***
     .***                                           9        ¦               ¦                                            +****
     .*******                                      20        ¦               ¦                                         +****
     .***************                              44        ¦               ¦                                      *****
     .***********************                      68        ¦               ¦                                  *****
     .**********************                       66     +-----+            ¦                               ****
     .*****************************************   121     ¦     ¦            ¦                           *****
     .*************************                    75     *--+--*            ¦                         ***+
     .********************************             95     ¦     ¦            ¦                     *****
-0.75+**************************                   77     ¦     ¦       -0.75+                   ***
     .*********************                        61     +-----+            ¦                ****
     .******************                           54        ¦               ¦             ****
     .*************                                37        ¦               ¦          ****
     .*******                                      20        ¦               ¦       +***
     .******                                       18        ¦               ¦    +****
     .****                                         11        ¦               ¦ +****
     .**                                            6        0               ¦***
     .*                                             1        0               ¦*
-5.25+*                                             1        0          -5.25+*
      ----+----+----+----+----+----+----+----+-                               +----+----+----+----+----+----+----+----+----+----+
      * may represent up to 3 counts                                              -2        -1         0        +1        +2
```

Fig. 4.1. **Distribution plots of residuals for cereal aroma of 36 sorghum porridges prepared from 12 sorghum grain types milled by hand pounding, roller milling and abrasive decortication - hammer milling. (A) Histogram, (B) Box and Whisker plot, and (C) Normal probability plot.**

4.1.5 Porridge microstructure

Microscopic observations of specimens obtained after drying the porridges were done using conventional SEM, which requires that samples be dried before they can be observed. To produce the specimen, fresh porridges were first cryo-frozen by submerging in liquid nitrogen for 20 min, and were then freeze dried. This sample preparation process was chosen because it was found practical for the nature and the number of samples dealt with, and had been used successfully in other similar studies, for example, to elucidate structures of wheat dough blends (Kim et al 2003). Generally, visualisation of the exact food structure is extremely difficult because specimen preparation techniques used alter the food structure to some extent (Aguilera 2005; Bozzola and Russell 1999). With the sample preparation procedure described, alteration of the original structure of the porridges was highly probable, because liquid nitrogen tends to boil vigorously when it gets into contact with wet samples, generating an insulating gaseous phase which slows the rate of freezing, hence, allowing ice crystals to form and distort the sample structure (Bozzola and Russell 1999). Also, because the porridges had high moisture content, the structures of specimen may have shrunk, caused by contraction of the viscoelastic material into void spaces previously occupied by the removed water (Aguilera 2005). Thus, structural artifacts probably occurred in the specimen, caused by the sample preparation procedures used. Therefore, to minimize the distorting effects of artifacts in the structural interpretations, all the porridges were frozen and dried in one batch, so as to obtain specimens that had been exposed to identical treatment conditions. Perhaps the artifacts could have been minimized by first freezing the porridges in liquid-nitrogen chilled liquid (called quenchant), such as isopentane, liquid Freon or liquid propane, before freeze drying (Bozzola and Russell 1999). Quenchants permit more rapid freezing of specimen than when liquid nitrogen is used directly, because they wet the surface of the specimen, and hence, do not boil vigorously like nitrogen. An alternative drying technique would have been Critical Point Drying, which entails dehydrating the samples in an ethanol concentration series (30, 50, 75, 95, 100%), then displacing the ethanol with a pressurised transitional fluid such as liquid carbon dioxide (in a bomb), before drying off the transitional fluid at its critical points (critical temperature and pressure). Arguably, this technique is also not completely free of artifacts, because of the numerous steps that involve treatment with chemicals (ethanol series and carbon dioxide), but is generally considered to be better than freeze drying in preserving the ultrastructure of the specimen (Yamamoto et al 2001). However, critical point drying is outclassed by freeze drying in that much more specimen shrinkage occurs with critical point drying (Bozzola and Russell 1999). A technique superior to the conventional dehydrating and chemical fixation procedures stated, called High Pressure Freeze Fixing, would have been more appropriate for preserving the original structure of the porridge samples (Mr A. Hall, Scientific Researcher, Microscopy lab, University of Pretoria, personal communication). Unfortunately, this procedure was not available at the time of this project, but has now been acquired by the University of Pretoria. Other 3-D microscopy techniques, such as the Confocal Laser-Scanning Microscopy (CLSM), a light microscopy technique that scans and images a sample at different sections using a laser beam, could also provide additional images with more useful information, such as the relative positions of protein bodies and starch granules in the porridge matrix (Kaláb et al 1995). Unlike the physical sectioning or smearing techniques, CLSM reveals the structure of the sample without distorting or destroying the sample, and therefore preserves the original structure of the sample.

4.2 Comparative performance of the milling processes

4.2.1 Extraction rates

The most notable observation concerning performance of the three processes was that on average roller milling gave much higher meal extraction of approximately 11% (84 g/100 g) more than hand pounding (74 g/100 g) and abrasive decortication-hammer milling (76 g/100 g). The latter two processes gave essentially the same extraction rate. Extraction rate in this case was determined as the level of yield at which the meal was considered acceptable in quality, which was practically judged subjectively. Maximum extraction rates are desirable because they translate directly into maximum profits, and are therefore important for every miller. High extraction rates mean more endosperm meal, which fetch a premium price as a starch source, whereas low extraction rates mean more bran production, which is a low value by-product. Not withstanding the inefficiency of the milling process, the observed differences and similarities in the extraction rates were presumably caused by factors that are intrinsic to each of the milling process. These are factors primarily linked to the milling principles of the processes, specifically the splitting process of the grain into its anatomical parts, and the subsequent bran separation techniques employed. For example, with hand pounding and abrasive decortication-hammer milling, the abrasive action which gradually removes the pericarp, coupled with the visual determination of the decortication endpoint, presumably removed the pericarp more extensively than the ripping and crushing action of the roller milling process, thus causing relatively lower extraction rates than roller milling. The comparatively lower ash contents associated with hand pounded and abrasively decorticated-hammer milled meals (Table VII) further support this observation. Supposedly, this thorough removal of the pericarp was inevitably accompanied by loss of some endosperm material to the bran, caused by over abrasion of the endosperm and breakage of some endosperm material into fine particles that could not be separated from the bran. The fine endosperm particles escaped separation because the winnowing and the aspiration processes used to separate bran with hand pounding and abrasive decortication-hammer milling, respectively, separated fractions using differences in the particle weights, and presumably, these fine endosperm particles were comparable in weight to the bran particles. Apparently, these bran separation processes failed to recover the endosperm particles that did not differ sufficiently in weight with bran particles. Thus, winnowing caused losses of up to 12% of endosperm particles, while the aspiration process failed to recover up to 13% of the whole grain endosperm material (Fig.3.1.11). These losses indicate that the separation techniques used were very inefficient, and hence, were highly wasteful. In commercial milling of sorghum with abrasive decortication-hammer milling, such losses have serious repercussions on the meal yield, and subsequently, on the financial returns of the mill. Therefore, it is important to keep these to the most minimum.

Whereas hand pounding and abrasive decortication–hammer milling were similar in that the pericarp was abraded off and separated from the endosperm material before reducing the endosperm to meal, roller milling differed in that the whole grain was crushed before separating bran. As stated, the grain was tempered to 16% moisture for 15 min at ambient temperature to toughen the pericarp, thus facilitating its separation from the endosperm. Because no endosperm particles could be separated from the bran obtained with roller milling (Chapter 3.1), this shows that unlike hand pounding and abrasive decortication-hammer milling, this process was less wasteful in terms of endosperm losses with the choice of machine settings used. Thus, the bran produced was relatively endosperm-free, and could find applications as a relatively high-fibre source, such as in the production of high-fibre breakfast cereals and bakery products for the health market. However, visual inspection of the meals under stereo microscope revealed that bran fragments were present, with some still attached to the endosperm particles (Fig 4.2), showing that bran contributed to the increased meal yield. Thus, the roller milling process did not separate bran completely, suggesting that the pericarp was probably not sufficiently tempered, such that it was still substantially friable when the grain was fed to the mill. Earlier in this project it was shown that tempering the grain longer (18 hr) decreased bran (ash) contamination by 6 to 9% over the 15 min tempering period (Fig 3.1.5). However, the meal produced also still had some endosperm particles attached to bran fragments. The disadvantage of tempering longer was that the meal produced had moisture content exceeding 15% (Fig. 3.1.4), and therefore would require drying before storage. Also, because tempering involves subjecting the grain to high moisture levels, strict hygiene would need to be observed to control mould growth. In a large roller milling plant, where milling is achieved with multiple pairs of rolls (up to 16 pairs), heat generated by the plant is sufficient to dry the product to safe moisture levels (Gomez 1993, Posner and Hibbs 1997). With the two-stage roller mill, where the milling plant is less complex and does not generate sufficient heat, an additional drying operation would be required.

That bran fragments were found still attached to the endosperm particles raises some critical questions about the direct application of roller milling to whole sorghum grain, especially using the small industrial roller mill described in this study. Though not exhaustive, these questions include: “How much tempering is enough for sorghum to toughen the pericarp and soften the endosperm, and how best can this tempering be achieved?” “How exactly does tempering affect the different parts of the kernel?” “Upon interacting with the mill rolls, how does the sorghum pericarp separate from the endosperm?” The fact that the sorghum pericarp remained friable even after tempering in this work casts doubts as to whether separation of the endosperm from the pericarp in sorghum is in keeping with the theory that is generally associated with roller milling of other cereals, such as wheat. This theory holds that roller milling separates the endosperm from bran by scraping it from the inside of the pericarp (Posner and Hibbs 1997). Sherperd (1981) reported that the sorghum pericarp peels by separating at the mechanically weak mesocarp when decorticated abrasively. Following on Sherperd's report is the question whether the sorghum pericarp separates the same way with roller milling. If this author's theory holds true with roller milling, then the layer of pericarp observed still attached to the endosperm particles could most probably be the endocarp (Fig 4.2). Perhaps a decorticating process, such as abrasive decortication, need to be applied before roller milling to effectively remove this inner pericarp layer. Research into the above questions could go a long way in fine-tuning the application of roller milling to whole sorghum grain.

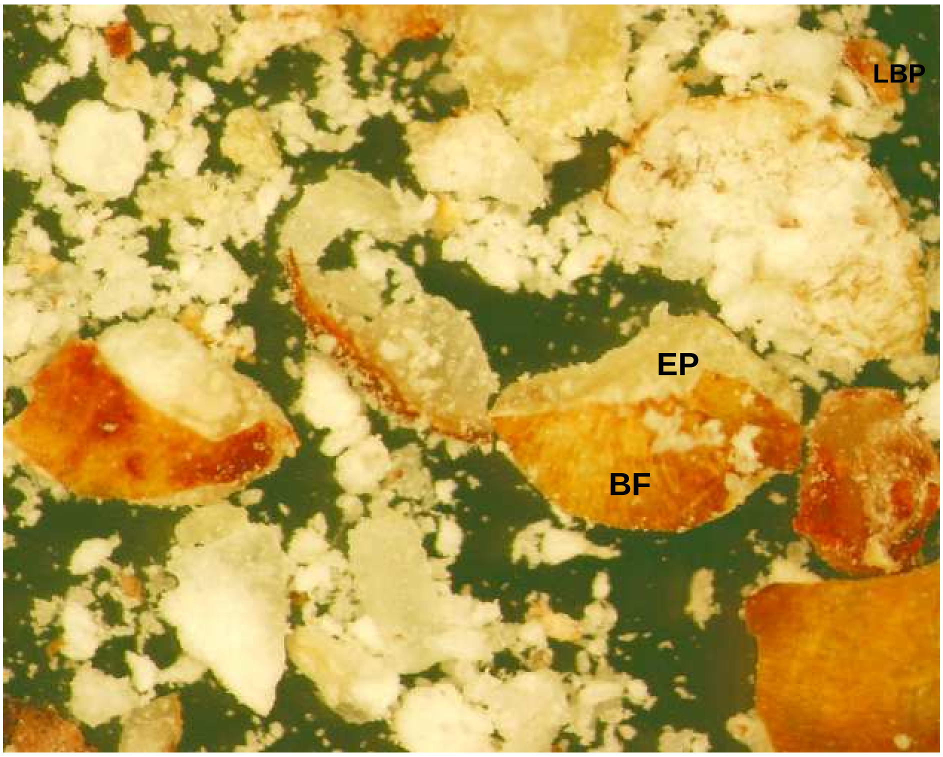

Fig. 4.2. **Stereomicrograph of roller milled meal of a red sorghum type (SNK) showing bran fragments (BF) attached to endosperm particles (EP) and loose bran particles (LBP). Magnification – X40.**

Grain characteristics, specifically grain hardness was found to influence extraction rates with hand pounding and abrasive decortication–hammer milling, but not with roller milling. Grain weathering adversely affected yields with abrasive decortication–hammer milling but not with hand pounding and roller milling (Chapter 3.1). These findings simply show that grain hardness and grain weathering are not as restrictive with roller milling as they are with abrasive decortication–hammer milling for achievement of maximum meal yields. However, these results emphasize the need to breed grains which possess hard endosperms and can resist weathering to achieve high milling extraction rates in general.

4.2.2. Throughput

According to Bassey and Schmidt (1989) the determination of meal extraction rate alone would mean little unless throughput (the amount of whole grain processed per hour) is also considered. Hand pounding, which was very labour intensive, took approximately 2 hr, depending on sorghum type, to process a 2 kg batch of grain into a meal. This processing period was found to be longer than periods reported for the same throughputs (1 hr for a 2 kg grain batch) in other similar studies (Munck et al 1982). The difference in the processing periods probably reflects variations in the hand pounding process used in different localities. With regard to abrasive decortication–hammer milling, although it is claimed that throughputs of up to 800 kg/hr can be achieved with the RIIC/PRL dehuller (Bassey and Schmidt 1989), it was practically observed that on average it took an experienced miller 8 min to load, decorticate and unload a batch of sorghum using the same dehuller to decorticate 12 sorghum types. Thus, when loaded to full capacity (25 kg) and operated to give optimally decorticated grain, the RIIC/PRL dehuller (in this author’s view) would process just under 200 kg/hr of whole grain. Probably higher throughputs could be realized with this dehuller if operated in continuous mode. However, essentially all presently existing sorghum mills known to this author use dehullers in batch mode, where several units are installed in parallel to meet larger throughput demands. In contrast to abrasive decortication–hammer milling, the two roll roller milling plant operated on continuous mode, and had a rated throughput of 500 kg/hr. This high throughput, which was further enhanced by the 11% extraction rate difference, was notably the most outstanding advantage of roller milling over the abrasive decortication-hammer milling. Table XXII compares the performance of roller milling and abrasive decortication–hammer milling in terms of meal output, and estimates that roller milling exceeded abrasive decortication–hammer milling by at least 194%. In practical milling, this difference represents more meal and less bran production in a given processing time interval, and therefore would translate into massive economic benefits accruing from sales of more meal for the miller.

Table XXII
Effect of the Milling Process on the Sorghum Meal Output

Milling Process	Grain throughput	Measured meal extraction rate	Meal output per hr
Abrasive Decortication – Hammer Milling[1]	188 kg /hr (25 kg per batch at 8 min per cycle; loading, decortication and unloading)	757 g /kg	142 kg
Roller Milling	500 kg /hr	836 g /kg	418 kg
Difference in meal output			**276 kg**
Percent gain in meal output due to Roller Milling			**194%**

[1] The 8 min cycle is derived from the observed practical maximum residence time for decorticating 10 kg sorghum batches by the commercial mill engaged in this study.

4.2.3. Energy efficiency

Milling generally aims at removing bran and yielding maximum endosperm meal with minimum energy as well as time expenditure. Therefore, the amount of meal achieved per unit energy is considered here to compare the energy efficiencies of the milling processes. The roller mill used in this study was driven by two 3-phase motors of 7.5 kW and 5.5 kW. Thus, in an hour this mill would use 13.0 kWh of energy to produce 418 kg of meal, expending on average 1 kWh for every 32.2 kg of meal produced. In comparison, the dehuller and hammer mill were driven by two 3-phase motors of 5.5 kW each. On average these motors would expend 11 kWh of energy to yield 142 kg of meal. Thus 12.9 kg of meal was produced per kWh of energy. These energy estimates demonstrate that the roller mill is superior to abrasive decortication-hammer milling (when applied in the batch mode) in energy efficiency. Much of the energy wastage with the abrasive decortication-hammer milling is probably associated with the loading and unloading stages. As such, for commercial production of sorghum meal with the abrasive decortication-hammer mill, a switch to the continuous process mode is probably necessary to minimize energy losses.

4.2.4 Comparison of meal and porridge quality

4.2.4.1 Effects of the milling process

Regarding meal quality, hand pounding produced the best refined meals, which contained lowest ash and oil content (0.8-1.3% and 1.5-2.4%, respectively) and were relatively coarser in texture (Chapter 3.1). Thus, much of the ash-rich pericarp and oil-rich germ were removed, suggesting that thorough softening of the grain by thorough soaking in water, which was the case with hand pounding, is necessary for effective decortication and degermination. However, soaking of the grain appeared to cause darkening of the meals, presumably because the water leached colour pigments from the pericarp into the endosperm. Again, soaking necessitated that the meal be dried to moisture content lower than 14% before storage (Chapter 3.1). Porridges derived from hand pounded meals were the most firm, coarse, and cohesive, but had the disadvantages of being sticky and having the most rancid and humus off-flavours (Chapter 3.2). Although hand pounding generally produced meals with the lowest oil content, with 30-50% by weight of the original whole grain oil content retained in the meal, the high moisture content of the meals and the subsequent drying process applied appeared to have exposed the meals to oxidative and microbial spoilage, resulting in off-flavours and bitter taste being perceived in the porridges. So, the advantage of high meal refinement attained by soaking the grain to facilitate decortication and degermination, was counteracted by the disadvantages of the compromised meal colour quality, off-flavours associated with drying, and the energy and time (costs) requirements for drying the meal. These results demonstrate that soaking grain (as opposed to tempering) before milling does not seem to be prudent for production of high quantities of sorghum meal. Soaking is probably only suitable for household processing, where small quantities of meal are often produced and used immediately. Consequently, hand pounding is at best suitable only as a benchmark process against which the performance of other milling processes, in terms of meal refinement and texture, can be matched, especially if such meals are intended for use in preparation of traditional foods.

Roller milling produced the least refined (1.0-1.5% ash and 2.2-3.6% oil) and the least coarse meals (Chapter 3.1). These meals were generally similar in colour darkness to hand pounded meals. The dark colour of the roller milled meals was presumably a consequence of the high bran content, and possibly, endosperm discolouration caused by water treatment (tempering), probably for the same reasons as with hand pounding. The high ash and oil contents (Chapter 3.1) indicate less complete debranning and degermination of the kernels, and/or contamination of the meal by fine bran and crushed germ particles that escaped sieving. This suggests two possible deficiencies associated with roller milling, that unlike hand pounding, the process was not so effective in degerming sorghum, and/or the sieving assembly could not effectively separate bran and germ fragments from the meal. Because of the higher bran content, porridges prepared from these meals were perceived to have apparently undesirable attributes, notably, dark colour, high quantity of specks, intense branny aroma and astringency (Chapter 3.2). The porridges were also the least firm, the least coarse and the least cohesive, caused by the fine meal texture (Chapter 3.3). Thus, to make porridges that are equivalent to those obtained with abrasive decortication-hammer milling in firmness, substantially more meal would be required in order to increase the solids concentration. Thus, the high solid concentration would form a porridge matrix with limited water and more swollen starch granules that are not disrupted, hence, causing increased porridge firmness. In contrast to other milling processes, roller milling produced meals with a narrow particle size distribution, which would be of benefit in food applications where process input materials with uniform particle sizes are required, such as in flour composites used in baking and in extrusion applications.

The presence of small bran and germ fragments in meals produced with roller milling possibly indicated that the tempering process was inadequate, causing fragmentation of the pericarp and shattering of the germ upon crushing the kernel. This shortcoming indicates that a systematic study of the tempering process is required, to devise a more appropriate tempering process that could minimize both bran and oil contamination of the meal. Possibly, additional bran separation techniques such as aspirators and purifiers could be installed to augment the sieving process, so as to reduce bran contamination. However, the costs associated with such modifications could make roller milling an expensive process, and hence, unaffordable and non-competitive with the abrasive decortication systems. Therefore, the cost-benefit economics of tempering and/or installing additional bran separation devices would need to be evaluated carefully. From a positive point of view, the high bran content of roller milled meals could present roller milling as a suitable process for production of high fibre sorghum products which could fit well in the health market niche, especially with the right choice of sorghum types, such as the light coloured grain.

Light coloured sorghum products are generally appealing to consumers (Aboubacar et al 1999, Boling and Eisener 1982), and therefore, because the abrasively decorticated meals were the lightest, they could be considered to be superior in colour to meals of the other milling processes. Of much importance again was that because of its gradual abrasive action that wears off the coloured outer layers of the sorghum kernel, abrasive decortication produced lighter meals with dark pigmented and weathered sorghums. These types of sorghums are commonly encountered in the sorghum market. This showed that abrasive decortication was highly suited for processing sorghums with highly variable colour and quality characteristics (Chapter 3.1). Ash and oil contents of meals obtained with abrasive decortication-hammer milling were significantly but slightly lower than those of meals obtained with roller milling, showing that the degree to which degermination and debranning was achieved differed only slightly between the two processes (Chapter 3.1). These slight differences in the oil and ash contents of the meals obtained by the two mechanical milling processes was possibly caused by the fact that both processes did not involve thorough conditioning of the grain, and hence, the germ and the pericarp remained firmly attached to the endosperm and could not be separated effectively with both processes. Porridges derived from abrasively decorticated-hammer milled meals were perceived to be intermediate in most sensory attributes, but were more intense in the apparently desirable attributes of cereal aroma, cereal flavour and light colour (Chapter 3.2), presumably because they were produced from more pure starchy endosperm meals. They were notably less intense in the apparently undesirable attributes (rancid, stickiness, humus odour, bitterness, astringency and branny flavour) because they were less contaminated with bran or leached bran compounds that apparently caused the undesirable sensory attributes. It therefore appears that with the current technology, superior meal and porridge quality characteristics are best achieved when sorghum grain is decorticated dry by abrasive processes.

As stated, meals produced by hand pounding and abrasive decortication-hammer milling were coarse in texture, with the former being relatively coarser (Chapter 3.1). These meals had wide particle size distributions, with sizes varying from 106 µm (very fine) to 1700 µm (very coarse) (Fig 3.1.12). In comparison, roller milled meals were relatively fine and had a narrow particle size distribution ranging from 106 to 710 µm. Porridges prepared from the former meals were relatively firmer than porridges obtained with meals produced by roller milling (Chapter 3.2). Studies of the pasting characteristics of the porridges made from these meals revealed that porridges of meals obtained with roller milling shear thinned, indicating that starch granules of the fine meal particles absorbed water, swelled and ruptured, releasing the granule polymers into solution (Chapter 3.3). In contrast, porridges of meals obtained with hand pounding and abrasive decortication-hammer milling did not shear thin, indicating that the starch granules in the meal particles were less disrupted, and relatively less starch amylose solubilised. These findings are consistent with the existing knowledge about starch gelation and retrogradation (reviewed by Morris 1990) that heating starch suspensions beyond the starch's gelatinization temperature (78°C for sorghum starch) causes irreversible swelling of the starch granules, which is accompanied by loss of molecular order, loss of crystallinity and solubilisation (leaching from granules) of amylose. Typically, little amylopectin is solulibilised, such that a starch fluid composed of swollen and gelatinised granules (containing unleached amylopectin molecules) suspended in hot amylose solution is formed. When the starch fluid cools, the solubilised amylose molecules reassociate (retrogradation), making junction zones between each other through hydrogen bonding to form a coarse network. The amylose network links porous granules, whereby the granules function as reinforcing particles (commonly referred to as deformable fillers) to strengthen the amylose gel. Thus, starch gels are essentially an amylose matrix with imbedded swollen starch granules, with the starch granules reinforcing the gel. However, in sorghum porridge, other components such as bran particles, proteins, minerals, and fats, also interact with the amylose matrix, presumably weaking or further strengthening the porridge matrix. Irrespective of the role played by these additional components, it seems differences between the firmness of the porridges can be explained largely in terms of the starch granule remnants. According to Evans and Lips (1992), the characteristics of the starch gel are strongly influenced by the phase volume and the degree of deformation of the swollen granules, rather than solubilised starch. Fannon and BeMiller (1992) also reported that the structural differences of the swollen granule remnants correlate strongly with the rheological properties of the starch gel. Against this background of starch knowledge, it can be deduced that the reason why meals with a wide particle size distribution, ranging from very fine to to very coarse (i.e. hand pounding and abrasive decortication-hamer milling meals), are used for porridges like *bogobe*, is primarily to control the degree of amylose solubilisation and the proportion of non-ruptured gelatinised starch granules in the porridge matrix. The fine particles are presumably required to release solubilised starch, which upon cooling forms the amylose matrix. Water absorption by the coarse meal particles is slow, retarded by the small surface area and possibly by the intact cell walls of the endosperm particles, thus restricting starch granule swelling. Consequently, rupturing of the granules and solubilisation of amylose become impeded, such that a higher proportion of intact starch granules that reinforce the porridge matrix results. Thus, porridge firmness is enhanced by increasing the proportion of coarse meal particles, which increase the proportion of the intact swollen starch granules in the porridge. An interesting contrast is observed with *tô* (thick porridge of West Africa), whereby very fine sorghum flour (mean particle size > 150 µm (Fliedel 1995)) is usually used. Fliedel (1995) reported that *tô* firmness correlated strongly and positively (r = +0.81) with starch amylose content, perhaps indicating that unlike for *bogobe*, firmness in *tô* was more determined by the gel strength of the solubilised amylose network than by the proportion of the swollen starch granules. The contrast drawn here between *bogobe* and *tô* illustrate some important fundamental differences in the physico-chemical processes that occur in the different porridges made from sorghum, and these must be taken into consideration when producing meals for preparation of the different porridges. Because the roller mill is able to produce very fine or coarse meals, depending on the machine settings selected, roller milling is perhaps a versatile industrial milling proccess for production of meals suitable for any porridge making process. However, because preparation of some porridges, such as *tô* (Fliedel 1995), require the use of highly purified sorghum flour, a decortication treatment would be critical prior to roller milling.

4.2.4.3 Effects of the sorghum type

The sorghum types used in this study exhibited different physico-chemical characteristics, which variably affected the meal and porridge quality characteristics (Chapter 3.1). Whole grain colour determined meal and porridge colour, where light coloured sorghum types gave light meals and porridges regardless of the milling process used (Chapter 3.2). Pigmented sorghums intensified speckiness of the meals and of the porridges, which were perceived to be bitter, possibly because they contained flavonoids (Hahn et al 1984). Pericarp thickness correlated negatively with meal ash content with abrasive decortication-hammer milling and roller milling ($r=-0.59$, $p<0.05$; $r=-0.57$, $p<0.10$, respectively), indicating that the thin pericarps resulted in high ash content of the meal (Chapter 3.1). This probably indicates that thin pericarps are difficult to remove with these processes, and is consistent with the fact that thin pericarps attach tightly to the endosperm, while the thick types attach loosely (Bassey and Schmidt 1989). This finding appears to contradict the existing knowledge that thin pericarps perform better with abrasive decortication processes (Maxson et al 1971, Scheuring et al 1982). However, although thick pericarps seem to decorticate easily, giving low meal ash content (presumably low bran content), these types of pericarps are prone to weathering (Serna-Saldivar and Rooney 1995), which causes lower extraction rates (Chapter 3.1), imparts bitterness to porridge, and darkens meal and porridge (Chapter 3.2). Because of the deleterious effects associated with weathering, the thick pericarp seems to be an undesirable characteristic in sorghum intended for milling by mechanical means.

Grain hardness correlated negatively ($r=-0.55$) and positively ($r=0.58$) with meal ash and oil content, respectively, with abrasive decortication-hammer milling (Chapter 3.1). Thus, this implies that the softer the grain the higher the meal ash content (more bran contamination), the more intense the porridge branny aroma, the higher the astringency, the more the specks quantity, and the darker the porridge colour (Chapter 3.2). These negative meal and porridge attributes were especially pronounced with roller milling. Also, hard endosperm grains degermed less with abrasive decortication-hammer milling and roller milling, resulting in high meal oil content. Hard endosperm sorghums not only produced meals with minimum bran contamination, but also gave high extraction rates of coarse and light coloured meals, which subsequently produced firmer and light coloured porridges. These properties underscore the importance of sorghum endosperm hardness in milling, and are in agreement with previously reported studies (Aboubacar et al 1999, Awika et al 2002, Desikachar 1982, Jambunathan et al 1992, Maxson et al 1971, Reichert et al 1982). Since the endosperm hardness appears to be important for both the quality of the meal and the subsequently derived foods, an understanding of how hardness arises, and how it can be controlled in sorghum is of great importance. As stated in Chapter 2, a review done by Chandrashekar and Mazhar (1999) sheds light about the biochemical basis of sorghum grain hardness and reveals knowledge gaps about factors that control the expression of this characteristic. According to these authors, high amounts of kafirins, especially γ-kafirins, appear to be responsible for hardness in sorghum kernels. It is perceived that hardness results from the structural arrangement of the kafirins, where the γ-kafirins link α-kafirins together (through disulphide bonding) in hard endosperms. Consequently, genetic and environmental factors that influence the quantities and the distribution of the different prolamins determine grain hardness. Other factors suspected to influence the endosperm hardness are the cell wall composition and the amounts of starch amylose in the grain. It has been observed that hard endosperms contain high amounts of pentosans, more hexoses and less pentoses than the soft endosperms (Chandrashekar and Mazhar 1999). Also, differences in the amounts of prolamins associated with the endosperm cell walls between the hard and the soft endosperms have been reported, but the trends seem to be not clear. Besides explaining differences in the hardness of the sorghum types, perhaps these variations in the prolamin deposits on the cell walls could also explain some differences in the textural characteristics of the derived sorghum products. Prolamins are generally perceived to be hydrophobic (Rooney 1973), and therefore, their association with the cell wall possibly imparts some degree of water impermeability to the cell walls. Considering that different sorghum types are reported to vary in the amounts of the kafirins deposited on the cell walls, it would be expected that the sorghum types would absorb water at different rates, probably explaining some of the variations in the degrees of starch granule swelling (and porridge firmness) between the sorghum types. With regard to starch amylose content, hard grains were shown to contain high amounts of starch amylose than soft grains (reviewed by Chandrashekar and Mazhar 1999). Clearly, these findings highlight factors that could help in identifying primary causes of hardness in sorghum grain. The identification of these causes could greatly assist breeders to speedily and economically generate grains that are very suitable for milling and subsequent food applications.

Certain compounds in some of the grain types, assumed to be phenolic compounds other than condensed tannins, were suspected to cause astringency in some sorghum porridges. For example, porridges made from the sorghum types BSH1, LARSVYT and Sefofu were perceived to be bitter and astringent, irrespective of the milling process used, while porridges of Buster, Marupantsi and Segaolane were not bitter and astringent (Chapter 3.2). Astringency has long been associated with condensed tannins (Drewnoski and Gomez-Carneros 2000), but since all the sorghum types used in this study were tannin-free, the astringency sensation must have been caused by some other compounds. Lekalake-Kobue et al (2007) also reported astringency sensation in bran infusions of tannin-free sorghums. The authors attributed the astringency sensation to some non-tannin phenolic compounds. However, the identity of the particular compounds responsible for astringency in bran infusions was not verified analytically, suggesting that the assertion was only speculative. Sorghum types that were perceived to be non bitter suggest an opportunity for production of high fibre meals from such sorghums, specifically using roller milling. Sorghum type also predominantly influenced the intensity of the porridge cereal aroma and cereal (starchy) flavour. This flavour is possibly what some consumers refer to as “traditional” sorghum flavour (Kebakile et al 2003), and is apparently important for acceptance of sorghum products. Sorghums with strong flavour are perhaps desirable for sorghum porridge, in which flavour is considered to be important (Aboubacar et al 1999). In contrast, sorghums with bland flavour would be desirable for some novel products, such as extruded snacks, where flavourants of choice would be recquired. Porridge stickiness was variable among the sorghum porridges, and was negatively correlated with starch amylose content ($r=-0.80$, $p<0.01$) (Chapter 3.3), suggesting that it was a characteristic that primarily depended on the sorghum type. Thus, sorghums with lower starch amylose content produced sticky porridges. Sticky texture could be an undesirable characteristic in stiff porridges, because these are commonly consumed by hand, but may be desirable in infant foods, which are usually thin and often contain several ingredients that must bind together.

Considering all data, it appears that the sorghum type Lekgeberwa, which was characterized by white grain colour, hard endosperm, thick pericarp, and was not weathered, produced the best meal and porridge quality characteristics with all the milling processes. This indicates that sorghum types which fit the characteristics of Lekgeberwa would be ideal for production of high quality meals and porridges. Clearly, these findings could assist both breeders and millers produce sorghums and sorghum products, respectively, that satisfy consumer sensory expectations.

4.3 Suggested improvements for sorghum milling processes

The foregoing discussion clearly demonstrates that thorough removal of the pericarp is prerequisite to achieving meals that are lighter and porridges with superior sensory characteristics. The findings presented revealed that presently the biggest challenges in sorghum milling are associated with the difficulty to remove the pericarp and the germ from the endosperm. Other challenges include the inefficiencies of the bran separation techniques, and the low throughputs of the existing sorghum milling processes. This study revealed that abrasive decortication presently appears to be the most appropriate debranning process for production of meals and porridges with generally good qualities. This process is therefore considered to be of fundamental importance in any sorghum milling process, where it could be applied to whole grain sorghum prior to reducing the endosperm to flour, meal, or grits, by either hammer milling or roller milling. In recommending improvements for the milling processes, it is critical to make distinctions between requirements for a small-scale service and/or semi-commercial milling setup (which remain important in most parts of Africa) and requirements for a large scale commercial milling plant. These different applications shall be discussed separately.

4.3.1 Small-scale service and/or semi-commercial milling

While a diverse choice of small abrasive decorticators exists (Bassey and Schmidt 1989), only the RIIC/PRL type dehuller will be considered here. This dehuller is perhaps the most suitable for most sorghum processors as it seems to be the most affordable in terms of capital and maintenance costs, when compared to other available decorticators, such as the PeriTech. However, given the milling losses associated with this dehuller (Chapter 3.1), there is urgent need to modify its design, specifically to maximize recovery of endosperm particles from the bran and to improve flow of dehulled material out of the barrel. Fitting a suitable pore-size sieve (say about 2.0 mm) that would not clogg easily from the bran between the decortication chamber and the bran extraction fan could significantly reduce milling losses. For semi-commercial milling, it would be prudent to use the dehuller in continuous mode, instead of a batch processor, to minimise bottle necks in the process and maximise throughput. A hammer mill could still be used to reduce the decorticated grain to a meal.

4.3.2 Commercial milling plant

A large scale commercial milling plant needs to cope with high product demands, meaning that it should have reasonably high throughput. If sorghum is to compete with other major cereal products, such as maize and wheat, the milling plant should also be versatile enough to produce a variety of products of the highest possible quality. For this kind of plant, the PeriTech decorticating system (or a similar type), which has throughput of at least 2000 kg/hr (http//www.satake.co.uk), could be the most appropriate decorticator. This decorticator has the advantage of allowing precise control of the decortication end-point (Satake 2004), thus eliminating the subjective judgment of the operator. Grain may be tempered with about 4% moisture for 5 min before decorticating (Satake 2004) to toughen and facilitate the separation of the pericarp from the endosperm. However, this tempering process may raise the moisture content of the final meal above microbiologically safe threshold levels, and could also result in production of damp bran that may require drying if it is to be stored. Trials done with non-tempered grain using the PeriTech system in Botswana showed that the grain decorticates just as well as tempered grain (Mr R. Mereki, Production Manager, Foods Botswana, personal communication). The system removes bran from the abrasive chamber as decortication proceeds by blowing (as opposed to sucking in PRL-type dehullers) bran through sieves and out of the system

(Satake 2004). Another advantage of the system is that bran can be collected as separate fractions with different chemical composition, which result as the different layers of the grain pericarp are progressively decorticated. Such fractions could find applications as fibre ingredients, or antioxidant sources, where tannin sorghums are used (Rooney and Awika 2005). Because roller milling appears to be more energy efficient, and can produce meals of different particle profiles depending on the gap settings and the roller corrugations, four two-stage roller mills (with coarse break rolls) could be linked in parallel to the PeriTech system to absorb the output of the decorticator (Fig. 4.3). The roller gaps of the mills could be set such that they produce meal streams of different particle profiles. To produce fine flour, reduction rolls could be installed after the coarse break rolls (linked in series) to grind the meal further. Such meals and flours could be blended together as required, to produce a variety of products with different quality characteristics for different food applications. Alternatively, the PeriTech could be coupled with a hammer mill to produce meal the conventional way.

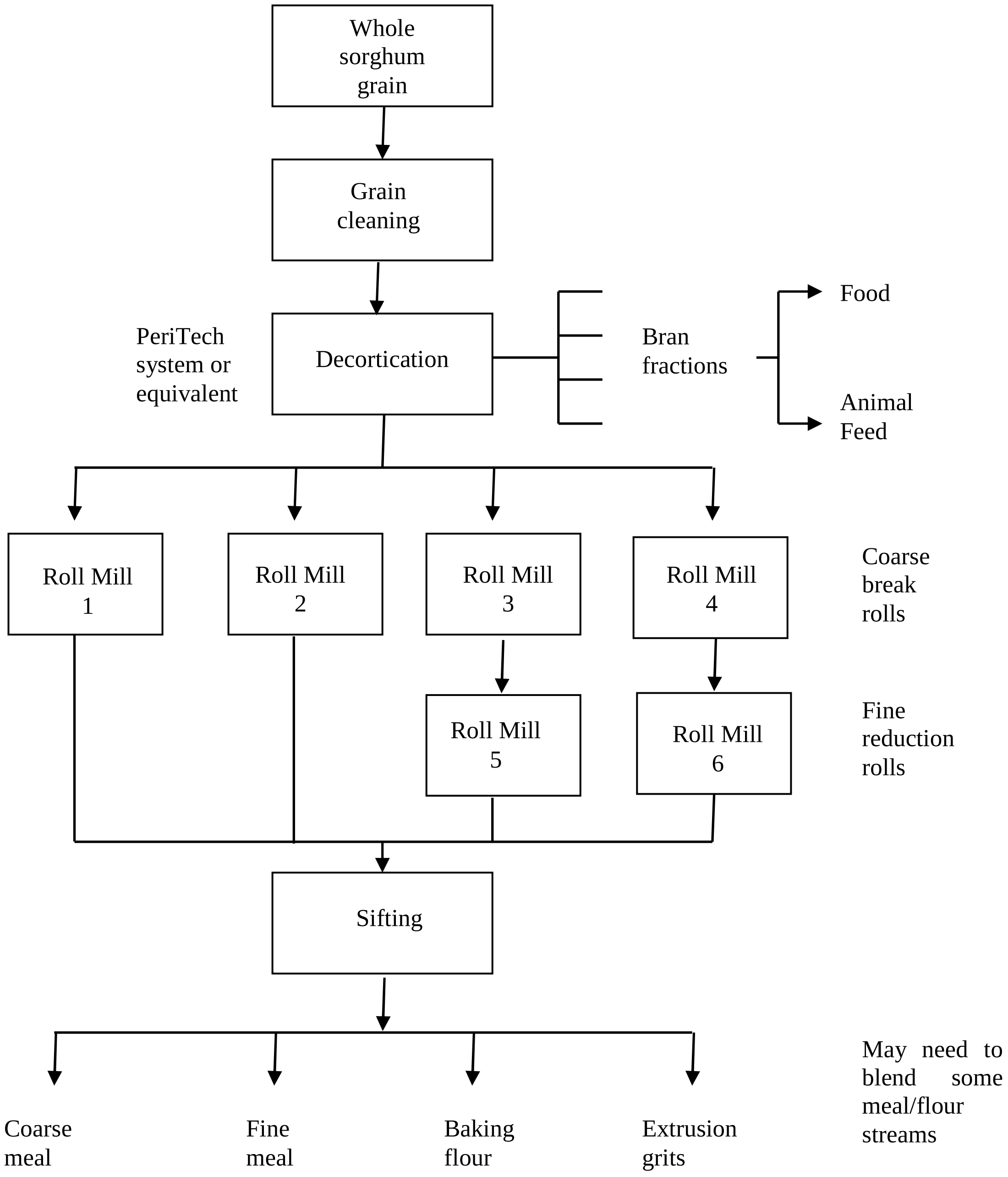

Fig 4.3. Diagramatic illustration of the proposed large-scale commercial sorghum milling process

4.4 Recommendations for future research

As follow up to the milling studies reported here, it would be desirable to test the suitability of prototype meals obtained with the proposed roller milling system for application on different food products, such as bakery products, tortilla, extruded and baby foods. Promising products developed, including the sorghum porridges, would need to be subjected to general consumer acceptance studies.

As stated, for roller milling of the grain without pre-decorticating, it appears the tempering process which is supposed to facilitate separation of the pericarp is still not optimized for sorghum. As such, a detailed systematic study of sorghum types of different physico-chemical characteristics should be given the highest priority, to improve direct roller milling of sorghum with the existing two-stage roller mill. Parameters of importance that must be determined should include the maximum tempering moisture content required, the optimum tempering temperature, appropriate tempering periods, and the number and intervals of tempering cycles. Changes in the physical properties of the grain’s anatomical parts with tempering, particularly the pericarp and the endosperm, would need to be studied. To study these, two approaches may be considered. In the first approach, the procedure used by Glenn and Johnston (1992) to characterise moisture-dependent changes of the mechanical properties of isolated wheat bran could be adopted. This procedure involves tempering isolated bran strips of different grain types and subjecting them to tension tests, where the mechanical properties of the strips (tensil strength, modulus of elasticity and deformation to fracture) are determined. Isolated sorghum endosperms could also be tempered likewise and be subjected to compression tests, to determine differences in their physical properties. The second approach could be made simpler by not isolating the pericarp and the endosperm, but instead, tempering whole grains of the same kernel size that represent a wide range of endosperm hardness (floury to corneous) and pericarp thickness (thin to thick). The differently tempered grains could then be subjected to compression tests (crushing), using a TA-XT2 analyser fitted with specially designed corrugated probe and grain holding plate that could mimic the crushing action of the mill rollers. Parameters such as compression stress (resistance to deformation) could be determined from the resulting force-time curves. The pericarps of the crushed grains could then be observed using stereomicroscope to evaluate their degree of intactness, and if possible, determine the surface areas of the bran fragments. A predictive model for sorghum tempering that relates the treatment conditions to the response variables could then be determined from the data.

This study has demonstrated that overall the sorghum type and the milling process affect the appearance, texture, flavour and aroma characteristics of sorghum porridge. In order to control these porridge sensory characteristics, it will be important to determine factors that are intrinsic to the grain, and those caused by the milling process, that directly or indirectly influence the quality of the meal, and subsequently, the quality of the porridge. In this respect, only factors causing variations in the textural characteristics were investigated. Because several studies have identified flavour, taste, and colour as additional factors that determine consumer acceptance of sorghum porridge (Aboubacar et al 1999, Boling and Eisener 1982, reviewed by Murty and Kumar 1995), factors that cause variations in these characteristics also need to be explained. Specifically, factors that cause astringency, other than condensed tannins, and compounds responsible for the sorghum flavour, should be determined. Also, factors contributing to the colour of the porridge, especially those caused by tempering and soaking must be ascertained.

5 CONCLUSIONS AND RECOMMENDATIONS

This study revealed that both the sorghum type and the milling process affect the quality of the meal and the sensory characteristics of the porridge, but the milling process has more effect on these characteristics than the sorghum type, because of the diverse milling principles of the different milling processes. Abrading off the sorghum pericarp first before reducing the endosperm into a meal appears to be the most appropriate milling approach for sorghum presently, because the process gives meals that are better refined (low ash and oil contents, and brighter meal colour) and porridges with enhanced positive attributes, such as light colour and cereal flavour. Compared to abrasive decortication, milling whole grain sorghum directly with roller milling, even with some pre-tempering treatment, gives meals with relatively darker colour, slightly higher ash and oil contents, and undesirable porridge sensory characteristics, caused by bran contamination of the meal and incomplete degermination. Clearly, the tempering treatment for sorghum before roller milling is inadequate, because the sorghum pericarp remains friable during milling, such that it fragments into small pieces that remain firmly attached to the endosperm particles or cannot be separated by sieving. Research into sorghum tempering should be given priority if roller milling is to be applied directly to whole grain sorghum.

Except for the slightly compromised meal refinement (more ash and oil contents, and slightly darker meals) caused by the substantially higher extraction rate (11% over that of abrasive decortication and hammer milling), roller milling, which simply crushes whole grain before separating bran by sieving, promises great potential for commercial sorghum milling because it gives far much better throughput and output at apparently superior energy efficiency than the existing industrial abrasive decortication-hammer milling process. Enhanced bran removal by either improved tempering of the grain or decorticating prior to roller milling could lead to the unlocking of this roller milling potential.

The sorghum types with pigmented pericarps, and weathered grains are not desirable for milling, because they produce darker meals, caused by staining from the pericarp pigments (anthocyanins). Light grains with hard endosperms are advantageous because they give high extraction rates, produce coarse and light coloured meals that give firm and lighter porridges with enhanced cereal flavour. This justifies the need to intensify breeding and production of hard light coloured grains.

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.

As follow up to this work, the proposed industrial milling process need to be piloted, and the meals, flours and grits produced ought be processed into prototypes of the various products suggested, which should then be subjected to consumer sensory testing. It is envisaged that findings from this work could help pave way for the adoption of the proposed process by the sorghum industry.

Because cereal aroma intensity varies considerably among sorghum porridges, influenced by both the milling process and the sorghum type, it is recommended that the physicochemical determinants of this sensory attribute be investigated. This information would be crucial in formulating products in which the intensity of this attribute would need to be regulated, for example in snack foods that utilise added flavourants.

It is also recommended that the process of tempering sorghum such that it mills better without decorticating first be studied in a more systematic way. If tempering is improved sufficiently such that better refined meals and flours are achieved, it could simplify the proposed industrial sorghum milling prcess by omitting the abrasive decortication process.

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Appendix

Publications and presentations from this work

Scientific papers

Kebakile, M.M., Rooney, L.W., and Taylor, J.R.N. 2007. Effects of hand pounding, abrasive decortication, roller milling and sorghum type on sorghum meal extraction and quality. Cereal Foods World 52:129-137.

Kebakile, M.M., Rooney, L.W., De Kock, H.L., and Taylor, J.R.N. 2007. Effects of sorghum type and milling process on the sensory characteristics of sorghum porridge. Cereal Chem. 85:307-313.

Conference paper

Kebakile, M.M., Rooney, L.W., De Kock, H.L., and Taylor, J.R.N. 2007. Effect of sorghum variety and milling process on the physicochemical properties of sorghum meal. Paper presented at the 18th Biennial SAAFoST Conference. 5-7 September 2005, Stellenbosch, South Africa

Conference poster

Kebakile, M.M., Rooney, L.W., De Kock, H.L., and Taylor, J.R.N. 2007. Effects of sorghum type and milling process on the sensory properties of sorghum porridge. Poster presented at the 19th Biennial SAAFoST Conference. 4-6 September 2007, Durban, South Africa.