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 Recently, unpublished findings of consumer market studies conducted in Botswana by the National Food Technology Research Centre revealed that some newly developed varieties with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).

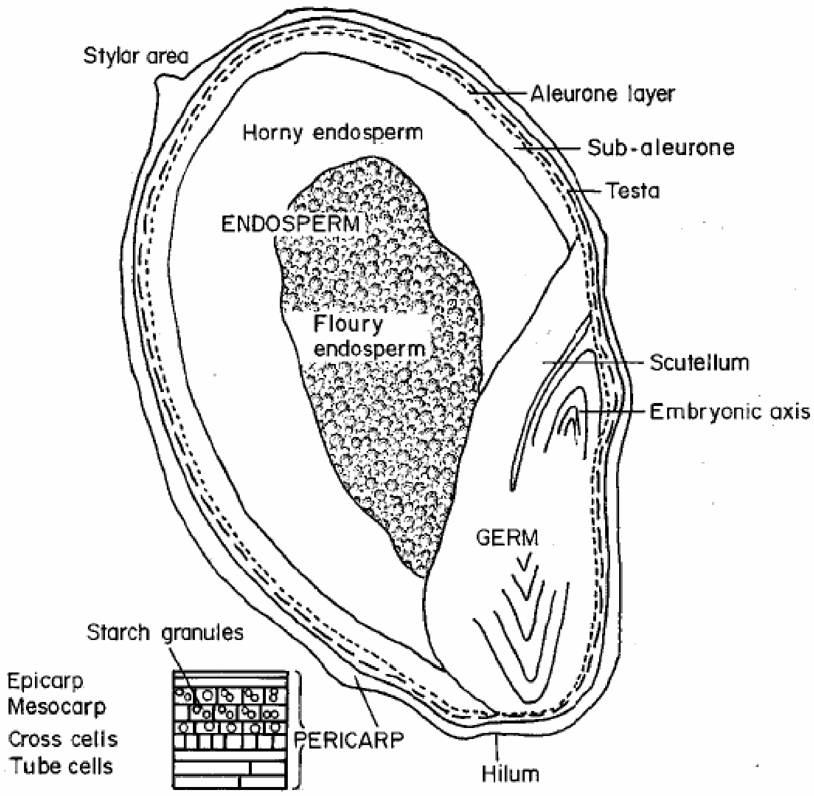

Fig. 2.1. **Section through a sorghum kernel (Rooney and Miller 1982)**

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).

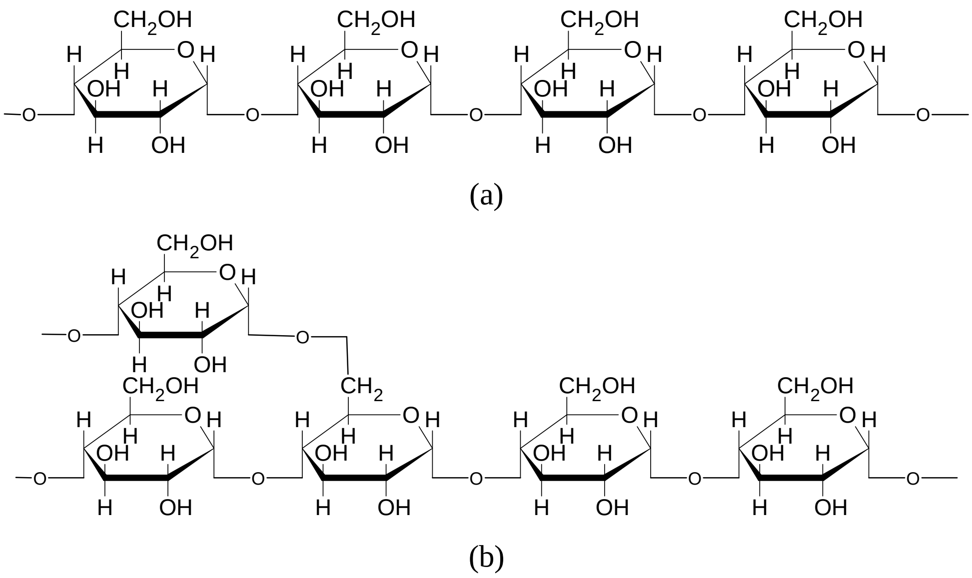

Fig. 2.2. **Haworth representation of (a) amylose, a linear molecule composed of 1,4-α-linked D-glucose, and (b) amylopectin, a 1,4-α linked polymer with 1,6-α branch points. Only parts of the macromolecules are shown to illustrate fundamental differences in the molecular structure (after Cornell 2005).**

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.

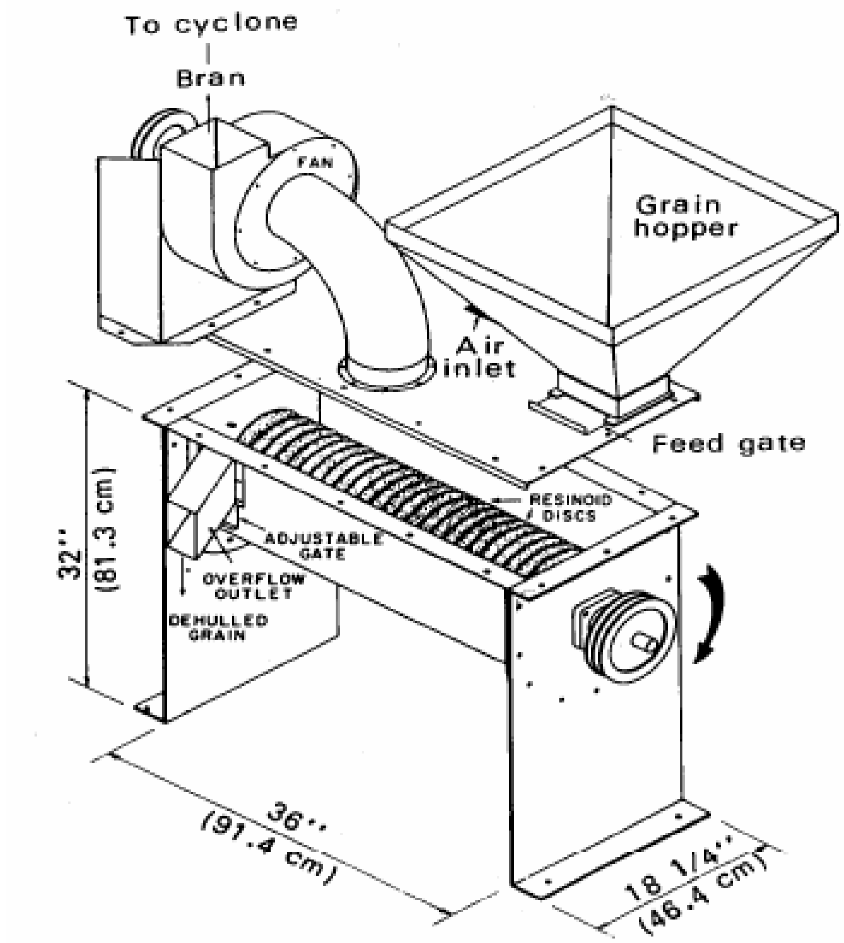

Fig. 2.4. **PRL type dehuller used to decorticate sorghum (Reichert 1982)**

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.

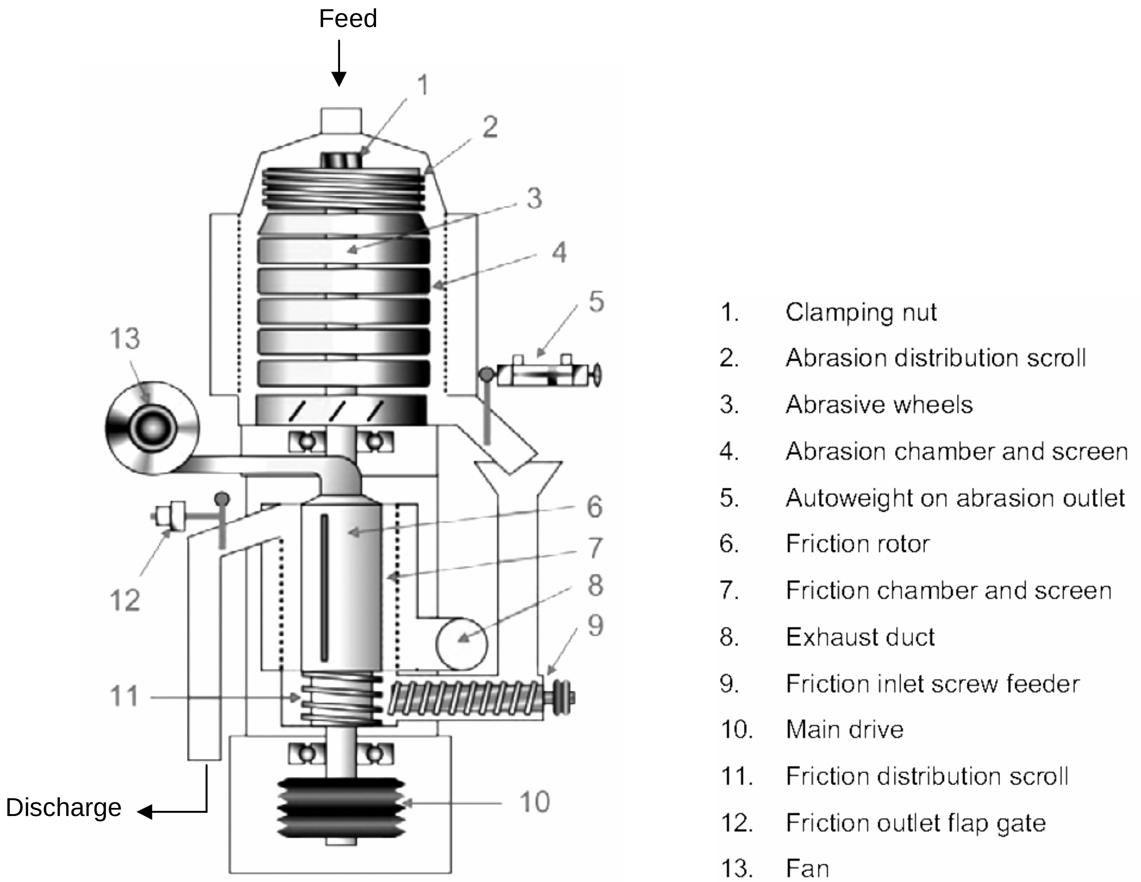

Fig. 2.5. Schematic diagram of the PeriTech VCW debranning machine (used with permission from Satake corporation)

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).

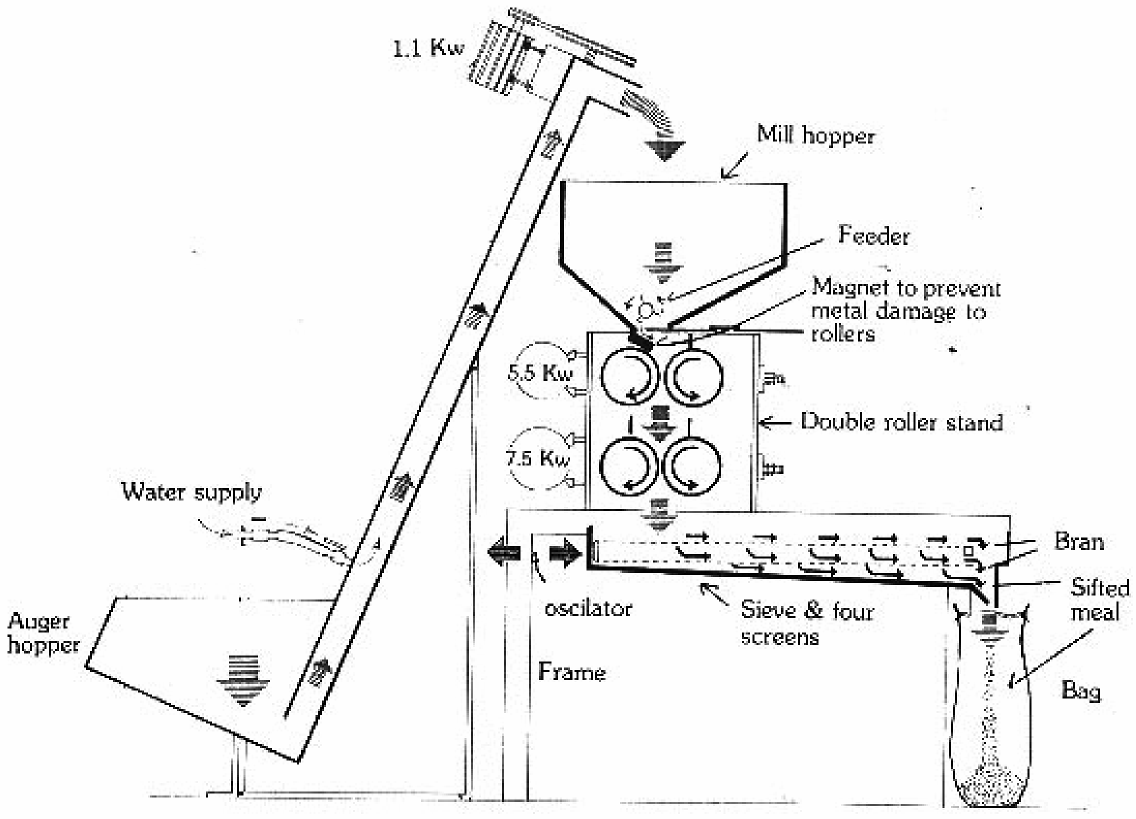

Fig. 2.6. A typical double roll roller mill designed to process sorghum (Courtesy of Maximill, Kroonstad, South Africa)

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)

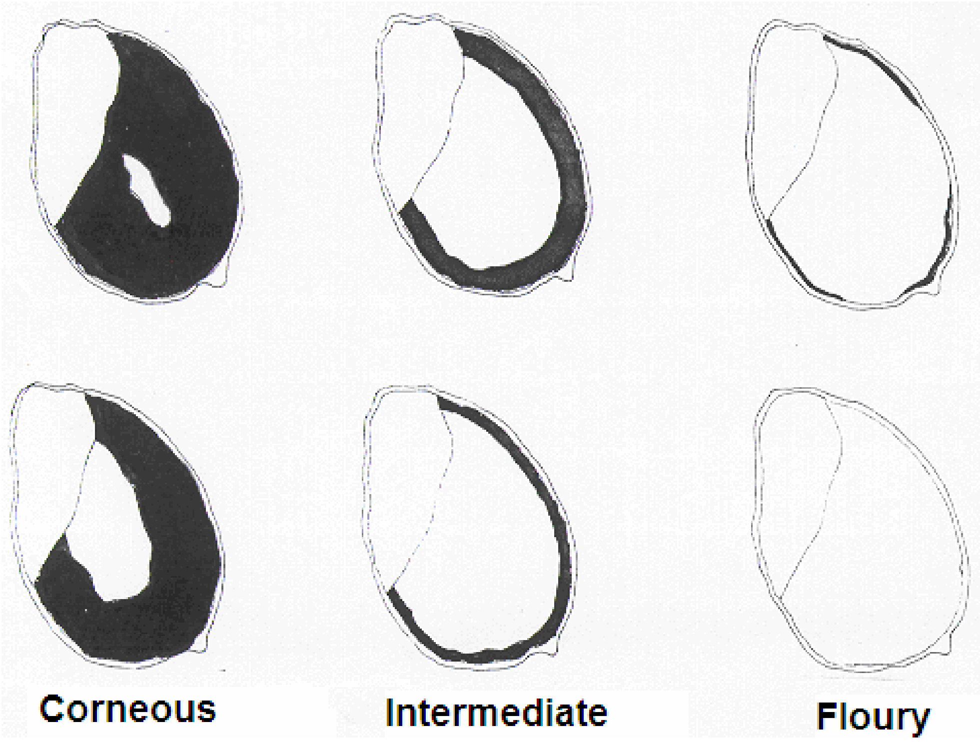

Fig. 2.7. Illustration of a 3-point rating system for evaluating sorghum endosperm texture (Taylor 2001).

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).

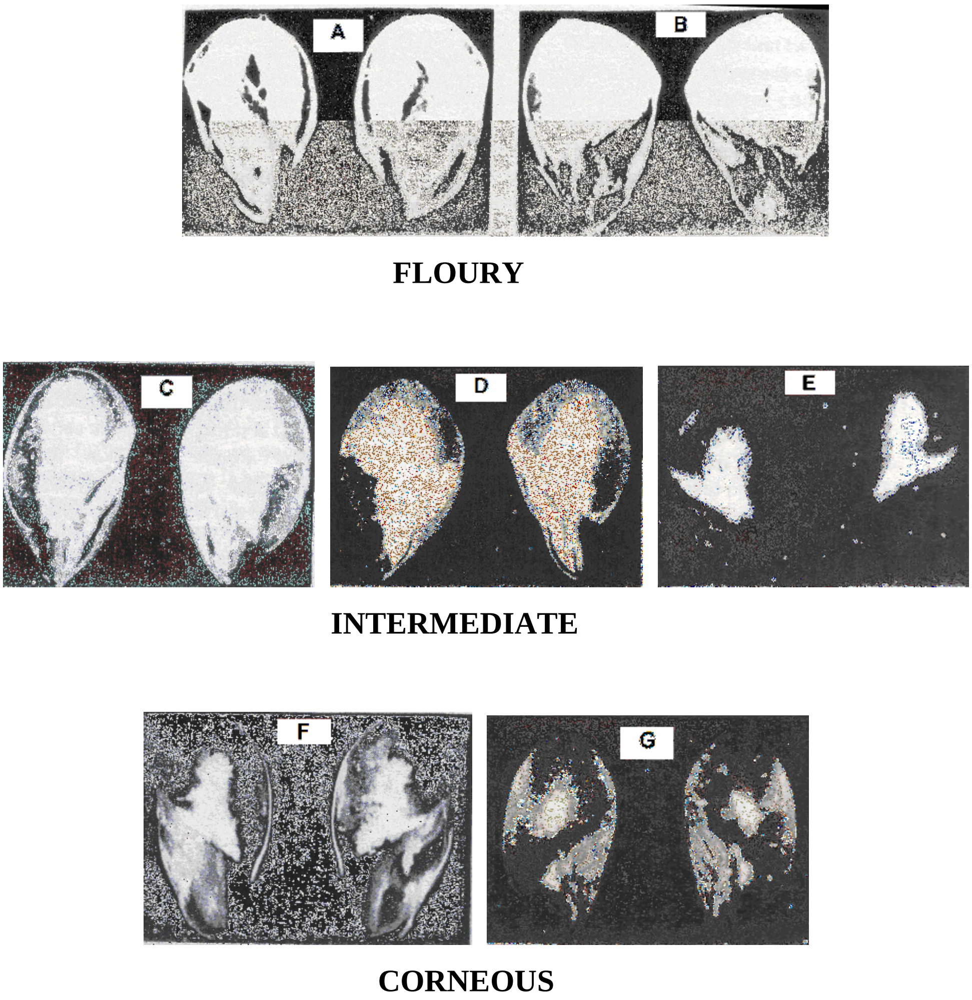

Fig. 2.8. Illustration of a 5-point rating system for evaluating sorghum endosperm texture. Kernel ratings are A and B = 5, C = 4, D = 3, E and F = 2 and G = 1 (Rooney and Miller 1982)

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.