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.

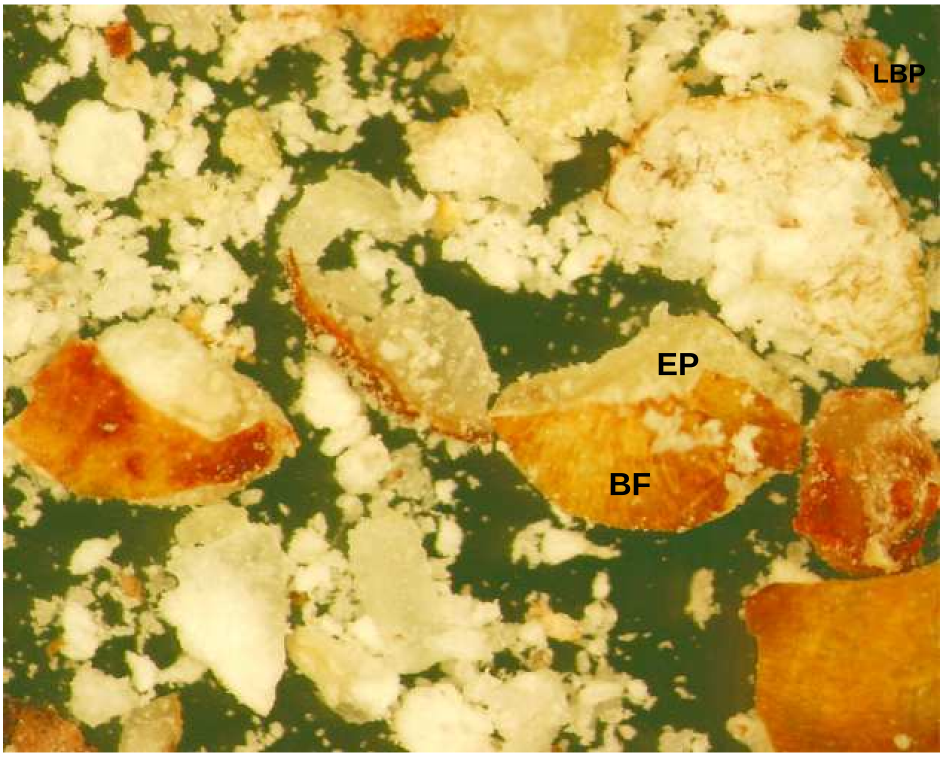

Fig. 4.2. **Stereomicrograph of roller milled meal of a red sorghum type (SNK) showing bran fragments (BF) attached to endosperm particles (EP) and loose bran particles (LBP). Magnification – X40.**

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.

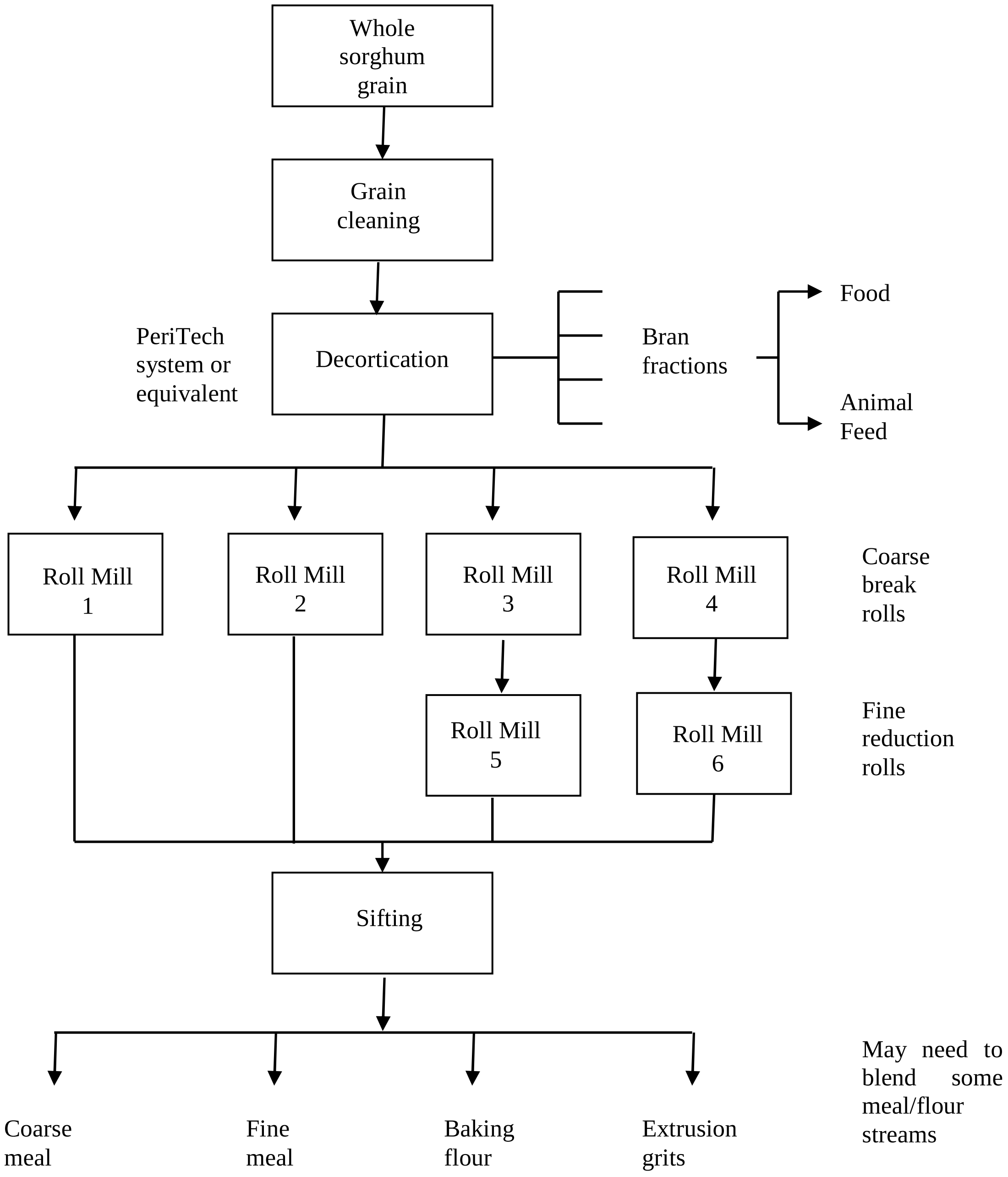

Fig 4.3. Diagramatic illustration of the proposed large-scale commercial sorghum milling process

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.