DEVELOPMENTS IN SORGHUM FOOD TECHNOLOGIES

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I. INTRODUCTION

Sorghum (*Sorghum bicolor* (L.) Moench), an indigenous African cereal, is a member of the grass family, Poaceae. Cultivated sorghum, first domesticated some 3000 to 5000 years ago (reviewed by House, 1995), probably originated in east central Africa, in, or near, Ethiopia or the Sudan (reviewed by Doggett *et al.*, 1970). Irrespective of its exact origin, sorghum is grown today primarily in the semi-arid areas of the world. In addition to being grown over a large part of sub-Saharan Africa, it is also found in India, Pakistan, Thailand, central and northern China, Australia, South America, Mexico, southwestern United States, France and Italy (House, 1995). However, developing countries account for 90% of sorghum land and 70% of production (Anon., 1996).

In terms of production, sorghum is ranked the fifth most important grain, after wheat, rice, maize and barley (Dendy, 1995b). World production is approximately 64 million tonnes (Anon., 1996), or less than 5% of the world grain production (FAO data, reviewed by Dendy, 1995b). However, although a relatively minor contribution to the total world cereal production, this figure masks the importance of sorghum as human food. In the semi-arid zones of Africa and Asia sorghum constitutes a major source of energy and protein for millions of people. Indeed, from FAO data (reviewed by Dendy, 1995b) it would appear that sorghum represents around 70% of the total cereals produced in West Africa, 30% in East Africa and 10% in Southern Africa. Sorghum is a most valuable grain in these regions in that it is somewhat drought tolerant and can withstand a considerable degree of water logging (Doggett, 1988). In fact, sorghum can consistently produce a crop under arid conditions where other cereals, such as maize, fail (Osmanzai, 1993) and is likely to be of disproportionate importance as a subsistence crop in areas where rainfall is too low for other staples. As a consequence of the severe droughts of recent years, the world's attention has been attracted to the vital importance of sorghum to the people of the semi-arid tropics (Hulse, 1988). Indeed, in 1983, the Southern African Development Community (SADC) set up SADC/ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) Sorghum and Millet Improvement Program to focus on this very issue.

The world appears to be moving towards a time when its supplies of food will be insufficient for its people (FAO, 1995). The population is projected almost to double in the next generation and it is likely that the challenge of feeding billions of newcomers on reducing choice cropland will probably be an onerous global issue. According to De Wet (1995), it is unlikely that production of the four major cereals can be greatly extended and it is probable that vast amounts of less fertile, marginal land will have to produce food. In view of the proven versatility of sorghum as a crop in terms of hardiness, dependability, and yield stability under adverse conditions (Dendy, 1995b) it appears to offer great potential for supplementing the world's food resources. Furthermore, with the threat of the global warming, and more recently, widespread manifestation of the El Niño phenomenon, it is possible that sorghum will be of importance not only in the semi-arid tropics, but could well become the crop of choice over large parts of the world. In fact, it is anticipated that sorghum production will grow at 1.2% per year to reach 74 million tonnes by 2005 with a 15% increase in its food use globally, and a huge, 39% increase in its food use in Africa (Anon., 1996).

However, due to its origin in the developing world the science and technology of sorghum has up until about 20 years ago lagged far behind that of other major cereals. More recently, as a consequence of its inherent agronomic advantages becoming more widely recognized, great strides have been made in addressing the nutritional deficiencies in sorghum and developing technologies to produce added-value, quality sorghum food products. These advances have been made by scientists world-wide and have been made possible by the support of international research and co-ordinating bodies such as ICRISAT, IDRC (the International Development Research Centre, Canada), INTSORMIL (the sorghum/millet collaborative research program of the US Agency for International Development), the European Union (through its collaborative research projects with developing countries) and the ICC (International Association for Cereal Science and Technology) through its Study Group 32 on sorghum, millets, legumes and composite flours.

This review will describe the major advances that have taken place in the development of sorghum food processing technologies, and examine the challenges that still have to be met.

II. SORGHUM STRUCTURE AND CHEMISTRY

The detailed structure (morphology), chemical composition (carbohydrates, proteins, lipids, minerals, vitamins, enzymes, antinutritional factors) and nutritional value of the sorghum grain have been comprehensively reviewed elsewhere (Rooney and Serna-Saldivar, 1991; Serna-Saldivar and Rooney, 1995). It would therefore be pointless to merely repeat what can be found in these excellent reviews. However, it is informative to compare sorghum structure and chemistry with that of other major cereals i.e. wheat, maize and barley from the viewpoint of processing it into foods.

A. STRUCTURE

Except for its much smaller size and oval shape (Fig. 1), the structure of the sorghum grain is remarkably similar to maize (Table I). This means that the processing technologies applied to maize can and are applied to sorghum. Problems associated with processing maize are also common to sorghum. Sorghum and maize both have a proportionally large germ relative to the size of the endosperm. This results in a high oil content in the kernel, approx. 3.4% in sorghum compared to 2.2% in wheat (Kent and Evers, 1994), which in turn can lead to a high oil content in the flour (Hahn, 1969) and hence problems with rancidity (Hoseney, 1994).

When compared to wheat, although the sizes of the grains are similar, there are a number of differences in grain structure that influence processing. Unlike wheat, the sorghum grain does not have a furrow (crease) in the kernel. This in theory should make the milling of sorghum more straightforward. However, this advantage is counter-balanced by the problems in removing the large, integral germ. The pericarp (outer bran layer) of sorghum grain appears to be more friable than that of other cereals,

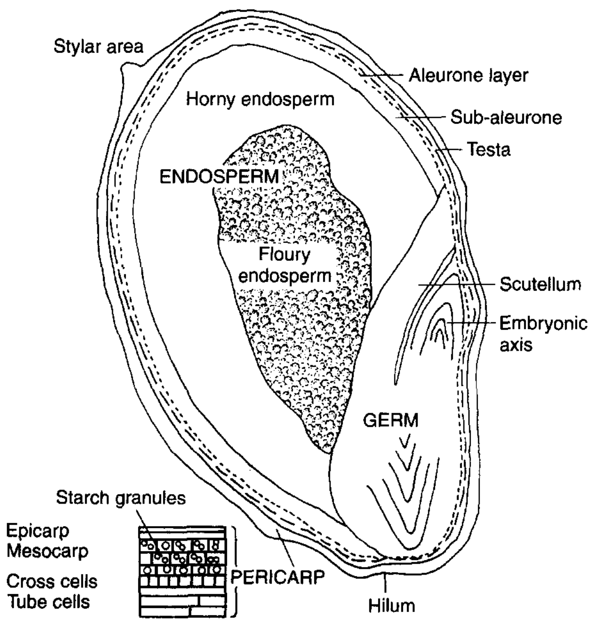

FIG. 1. Section through a sorghum grain. Source Rooney (1973). Used with permission.

TABLE I
SORGHUM GRAIN STRUCTURE COMPARED TO WHEAT, MAIZE AND BARLEY

Sorghum	Other cereals
Oval shape	Wheat and barley more elongated Maize flattened kernel
Size – diameter about 3 mm	Wheat and barley similar Maize several times larger
Naked grain – absence of hull (husk)	Wheat and maize also naked grains Barley generally has hull
Absence of ventral furrow (crease)	Maize the same Wheat and barley have furrow
Starchy mesocarp	Wheat, maize and barley mesocarp not starchy
Large integral germ	Maize the same Wheat and barley have small germ
Endosperm in two clear parts – corneous and floury	Maize the same Wheat and barley generally have uniform endosperm
Endosperm cell walls remain intact during malting	Maize the same Wheat and barley endosperm cell walls degraded during malting

which is rather disadvantageous in milling. The friable nature of the sorghum pericarp is probably related to the fact that sorghum, uniquely among the major cereals, has a starchy pericarp (Fig. 1) (Rooney, 1973). A further complication in milling sorghum is that the starchy endosperm, unlike in wheat, comprises both a hard or corneous outer part and a soft or floury inner part. The relative proportion of hard and soft endosperm varies between different sorghum varieties. Sorghums with a high proportion of corneous endosperm are preferred for milling as they give higher yields of endosperm flour (Maxson *et al.,* 1971).

The absence of an outer hull (husk) in sorghum grain, although simplifying its milling process, affects the brewing process when sorghum is used to brew lager and stout beers (Little, 1994). Also of importance in brewing is the fact that the cell walls of sorghum endosperm, unlike those of barley, are not degraded during malting (Glennie, 1984). This appears to have an adverse influence on the extract that can be obtained from sorghum malt when it is used in brewing lager beer (Taylor, 1993).

B. CHEMISTRY

Sorghum is unique among the major cereals in that some varieties, the so-called "bitter", "bird-proof", "bird-resistant" or "brown" types contain condensed tannins (Table II) (reviewed by Serna-Saldivar and Rooney, 1995). The condensed tannins, otherwise known as proanthocyanins, are located in the testa (seed coat) and pericarp of the grain (Fig. 1). Tannins confer considerable agronomic advantages to these high-tannin sorghums. Bird-predation, a major problem in the bush-veld areas of southern Africa, is reduced as the tannins are bitter. Further, the tannins protect these sorghums from insect and fungal attack (Waniska *et al.,* 1989). However, the drawback of these high-tannin sorghums is that the tannins can bind with both the grain proteins (Daiber, 1975a) and with enzymes of the digestive tract (Price and Butler, 1980), reducing the nutritional value of the grain. The tannins can also adversely affect the quality of malt made from high-tannin sorghum (Daiber, 1975b). The efficient and effective inactivation or removal of the tannins during processing is a major challenge.

All varieties of sorghum, like other cereals, contain greater or lesser

TABLE II
SORGHUM GRAIN CHEMISTRY COMPARED TO WHEAT, MAIZE AND BARLEY

Sorghum	Other cereals
Some varieties contain condensed tannins	Not present in wheat, maize and barley
All varieties contain greater or lesser amounts of polyphenols	Present in wheat, maize and barley, but generally in lower amounts
Many varieties highly pigmented	Some varieties of wheat, maize and barley also highly pigmented
High starch gelatinization temperature	Maize starch slightly lower gelatinization temperature Wheat and barley starch considerably lower
Endosperm non-starch polysaccharides predominantly insoluble	Maize the same Barley rich in soluble non-starch polysaccharides Wheat contains both insoluble and soluble types
Endosperm protein apparently highly inert	Maize protein similar Barley protein somewhat less inert Wheat protein will form visco-elastic dough
Protein digestibility reduced after cooking	Protein digestibility not reduced after wheat, maize and barley is cooked
Malt contains low levels of ß-amylase	Maize the same Wheat and barley contain high levels

amounts of polyphenolic compounds and many sorghums are pigmented by certain of these compounds: the anthocyanins, anthocyanidins and other flavonoids, which color or stain the grains red, brown or purple (reviewed by Serna-Saldivar and Rooney, 1995). The pigments are concentrated in the pericarp and/or in the glumes (modified leaves partially enclosing the grain), but may extend into the endosperm. Pigmentation of sorghum may be desirable in certain food products, such as traditional African, opaque beer, but can be undesirable in flour and porridges.

The gelatinization temperature range of sorghum starch, 68–78°C, is slightly higher than that of maize (62–72°C), but very much higher than that of wheat (58–64°C) and barley (51–60°C) (Hoseney, 1994). This high gelatinization temperature requires changes in process when brewing with sorghum and may have some adverse consequences when using sorghum in making baked products.

The endosperm cell wall, non-starch polysaccharides of sorghum are rich in the water-unextractable "water-insoluble" glucuronoarabinoxylans (Verbruggen, 1996). In contrast, the cell walls of barley are mainly of the "water-soluble" β-glucan type (Bamforth, 1982), whereas those of wheat are arabinoxylans of both the "water-soluble" and "water-insoluble" types (Fincher and Stone, 1986). These differences may have important consequences when sorghum is used in brewing and bread making.

Sorghum proteins, like those of all cereals except wheat, and to a much lesser extent rye and triticale, do not have the ability to form a gas-holding, visco-elastic dough. Hence, the use of sorghum flour for leavened baked products demands very considerable technical innovation. The protein of sorghum, like most other cereals, is deficient in the essential amino acid lysine. A further protein quality problem, in this case apparently unique to sorghum, is that the digestibility (and hence nutritional value) of sorghum protein is reduced when the grain is cooked during food processing (Axtell *et al.*, 1981; Mertz *et al.*, 1984). As a consequence, improving the protein quality of sorghum food products has been the subject of considerable research.

Sorghum malt, unlike barley malt, contains low levels of ß-amylase (Novellie, 1960; Taylor and Robbins, 1993), the enzyme which sequentially cleaves maltose units from the non-reducing end of starch molecules. Since the production of maltose, a fermentable sugar, is an important aspect of the brewing process, modifications to the process may be required for lager beer brewing with sorghum malt.

III. MILLING

A. DRY MILLING

The objective of milling is not simply to reduce the kernel into fine particles, but also to achieve an anatomical separation, in order to obtain the maximum yield of clean endosperm. The endosperm should have as little as possible contaminating pericarp and germ, as the former discolors the flour and the latter contains oil, which becomes rancid.

In essence, there are two general approaches in milling cereal grains. Either one can first remove the pericarp (bran) and germ, in milling terminology "degermination", then reduce the endosperm. This is generally the practice in maize milling. Alternatively the kernel can be broken open and the endosperm scraped from the bran. This is done in wheat and rye milling, primarily on account of the deep ventral furrow in these grains. In sorghum milling, both approaches are in use. Hahn (1969) reviewed the then current state of sorghum milling technology and several of his observations are still pertinent. When sorghum is milled in the same way as wheat, by straight roller milling, the pericarp, which is more friable (fragile) than wheat bran, breaks into small pieces which contaminate the endosperm flour, rendering it in milling terminology "specky". If degermination is practiced using a degerminator (a machine that tears off the pericarp and germ), as is done in maize milling, it is difficult to cleanly remove the germ. Fracture through the endosperm often takes place, hence contaminating the endosperm meal with bran. This is on account of the roundish shape of the sorghum kernel and the integral nature of the germ (Fig. 1). An alternative way of removing the bran and germ is to abrade off the outer layers of the kernel, keeping kernel breakage to a minimum; a process known as pearling, decortication or dehulling. The term "dehulling" although widely used in milling is in fact a misnomer since the sorghum grain is naked, without a hull, and it is the pericarp and germ which is being removed.

Today, abrasive decortication, followed generally by hammer milling of the endosperm material into meal or flour is the most common way of milling sorghum. An advantage of this approach to milling sorghum is that the decortication step can be used to abrade off the testa of high-tannin sorghums and hence reduce the tannin content of the grain (Serna-Saldivar and Rooney, 1995). Probably the most popular type of decorticating machine is the PRL (Prairie Research Laboratory) dehuller (Schmidt, 1992). This dehuller was developed in Canada from a barley thresher by the IDRC. A PRL-type dehuller comprises a horizontal barrel containing some 13 evenly spaced carborundum disks (25 cm diameter, 2.1 cm wide) that rotate clockwise against the grains at approx. 2000 rpm (Fig. 2) (Schmidt, 1992; Mmapatsi and Maleke, 1996). Power may be provide by an electric motor, diesel or petrol engine. The barrel may be lined with rubber to provide greater abrasion and reduce noise levels. Dry sorghum (5–25 kg) is fed into the barrel by means of a hopper fitted with a flow regulator. The bran and germ are progressively abraded off and removed by means of a cyclone fan. Decortication may be carried out on a batch basis using a single machine, or on a continuous basis using several dehullers in series.

PRL-type dehullers are now manufactured commercially in Botswana (Mmapatsi and Maleke, 1996) and Zimbabwe (Dendy, 1995a) and more than 200 are in use in southern Africa for milling sorghum, maize and

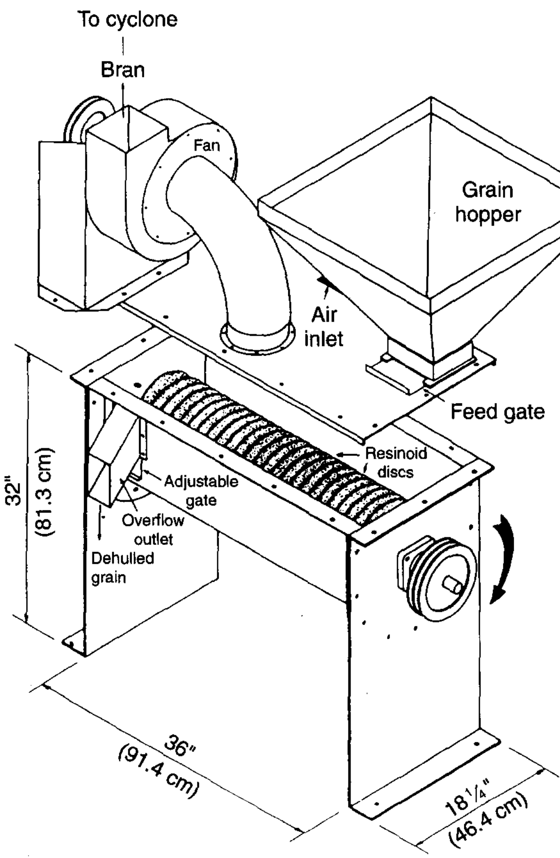

FIG. 2. Schematic diagram of a PRL-type dehuller. Source Reichert (1982). Used with permission.

pearl millet. In Botswana in particular, rural sorghum mills have contributed greatly to improving food security by enabling small farmers to mill meal for porridge making, from their own sorghum crop (Morei, 1988; Mmapatsi and Maleke, 1996). What has contributed to the success of the PRL-type dehuller is its simplicity and robustness, two characteristics that make it ideal for use in developing countries. However, one drawback is that by virtue of its action of abrasive decortication, not all the germ is removed and thus the endosperm meal still has a high fat content, between 2 and 4% (Gomez, 1993). Also, kernel breakage can be a problem. Young *et al.* (1990) found that parboiling sorghum prior to decortication using a boil-soak-boil process was a way of significantly reducing kernel breakage and increasing endosperm meal yield, particularly with soft endosperm grain.

To reduce losses during decortication and improve the efficiency of germ removal, researchers have also carefully studied the traditional hand-pounding milling process used for sorghum (Munck *et al.*, 1982). When sorghum is hand-pounded using a pestle and mortar, the pestle generates interactive forces between the grains. In conjunction with conditioning with water this causes large flakes of bran to be removed rather than a fine bran flour in the case of abrasive decortication. Applying the attrition principle of hand-pounding, United Milling Systems in Denmark developed a decorticator (the DVA sorghum decorticator) which employs a steel rotor to squeeze the pre-conditioned sorghum kernels against each other and against a cylindrical screen. The "hulls" and endosperm fragments from the cracked kernels are then discharged through the screen by a high-pressure air current (Munck *et al.*, 1982). If the grain is properly conditioned first, this decorticator apparently removes the germ completely and very cleanly from the endosperm due to its mode of operation. However, despite the effectiveness of this attrition decorticator it has not been widely adopted for milling sorghum.

Because equipment for decortication was not then generally available and because of the problem to the baker of mixing sorghum flour with wheat flour to produce composite flour, research was carried out in the early 1980s into co-milling of sorghum and wheat (Meppelink and De Ruiter, 1984). Using a conventional wheat roller milling process, flour of acceptable quality for bread and cookie making was produced from a 25% sorghum grain, 75% wheat grist. A major problem was, however, that flour yield was significantly reduced compared to that from whole wheat, from 71.2% to 63.6%.

More recently, research efforts have again focused on applying wheat roller milling technology to sorghum. Cecil (1992) described a semi-wet milling process, whereby sorghum grain was conditioned at elevated temperature (60°C), over six hours to 26% moisture. It was then milled using a pilot-scale wheat roller mill without modification. The process resulted in effective separation of the bran and germ. The process is claimed to be particularly suitable for high-tannin sorghums as the tannins are removed with the bran. However, major drawbacks of the semi-wet milling process are that the flour yield is rather poor and that the flour must be dried after milling if it is to be stored.

A recent development in South Africa is that of small roller mills with two or three pairs of rollers, plus a vibrating screen sieving device (Fig. 3). Typically such mills have a capacity of 500 kg/hour. The top pair of rollers are coarse fluted "break" rolls, the second pair are finer break rolls and the third pair (if present) are smooth "reduction" rolls. Research has shown that with moderate pre-conditioning (to 16% moisture), milling with such a roller mill can consistently produce sorghum meal of higher extraction, and slightly lower ash and fat content compared to decortication and hammer milling, using sorghums of a wide range of hardness (Gomez, 1993). A similar study concluded that flour produced from sorghum in the single-stage roller milling process was finer and more refined, containing less fat, fiber, ash and tannin than the products of decortication followed by hammer milling (Hammond, 1996).

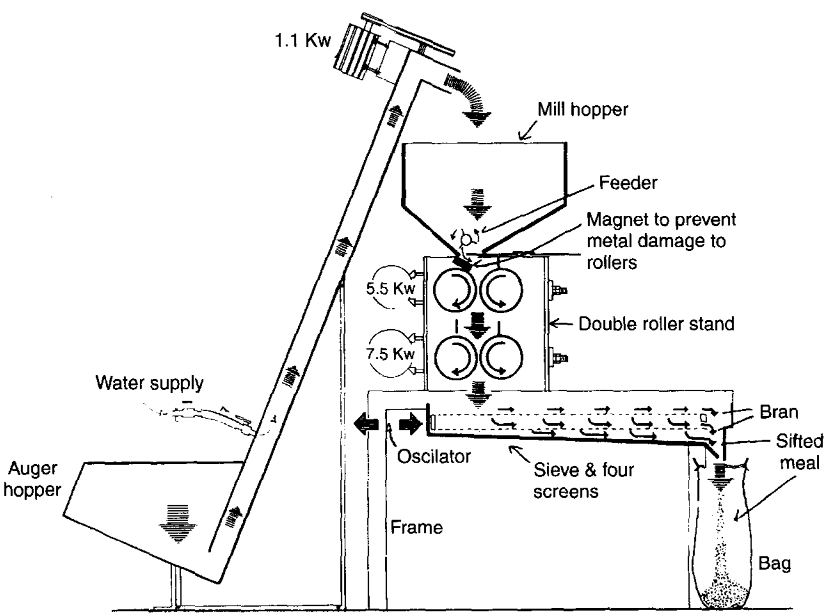

FIG. 3. Schematic diagram of small roller mill with double roller stand. Courtesy of Maximill, Kroonstad, South Africa.

Apart from producing a somewhat more bran- and germ-free product, the major advance of this roller milling technology is the incorporation of reduction rolls. This appears to provide a simple means of producing fine flour from sorghum suitable for use in baking.

B. WET MILLING

Wet milling, as the name implies, involves milling the grain in water. The objective differs from dry milling in that separation and isolation of the chemical components in the grain – starch, protein, oil and fiber – is sought. The chemical components have very wide food, feed and non-food applications, and world-wide maize and wheat wet milling are very large industries. For example, in the USA more than 10% of the maize crop is wet milled (Kent and Evers, 1994). Currently, commercial sorghum wet milling is not practiced to any significant extent (Rooney and Serna-Saldivar, 1991). According to these authors sorghum wet milling is slightly economically disadvantageous in comparison to maize wet milling. The reasons for this apparently include the fact that the pericarp is more fragile and hence tends to break up into small pieces rather than being cleanly separated. The pieces inhibit the separation of starch and protein, and the polyphenols in the pericarp pigment the starch and oil. These pigments then have to be removed.

To help improve the viability of sorghum wet milling, recent research by Buffo *et al.* (1998) attempted to identify sorghum grain quality factors associated with wet milling attributes. It was found that the initial rate of water uptake by the sorghum grain was significantly correlated with the recovery of both starch and protein. This, according to the authors, indicates a need to understand fully the process of breakdown of the matrix of protein that surrounds the starch granules.

IV. BREAD, CAKES AND COOKIES

A. WHEAT FLOUR DOUGHS

When mixed with water, the flour of wheat will form a cohesive, visco-elastic dough, which will hold bubbles of gas, normally produced by yeast fermentation or chemical leavening. On baking, the expanded foam will set to form a sponge-like structure characteristic of leavened bread or cake. Wheat is the only cereal which will form a visco-elastic, gas-holding dough of this character, and it is generally accepted that it is the gluten proteins of wheat which are responsible (Hoseney, 1994). Specifically, it is believed that it is the high molecular weight glutenin proteins of wheat which are critical in visco-elastic dough formation, as they impart elasticity (Khatkar and Schofield, 1997). Such proteins are not present in sorghum (Taylor *et al.,* 1984).

B. SORGHUM-WHEAT COMPOSITE BREAD

Traditionally, fermented flat breads such as *injera* (Ethiopia), *kisra* (Sudan) and *dosa* (southern India) have been produced using sorghum flour (Murty and Kumar, 1995). The cohesiveness of these products appears to be related to the fact that flour of very fine particle size may be used, in the case of *roti* 43% < 75 μm diameter, which increases water absorption (Murty *et al.*, 1984). Additionally, cooking of some of the flour, as in the case of *injera* production (Murty and Kumar, 1995), presumably helps bind the dough or batter together.

Since the 1960s much research has been undertaken into using sorghum to produce conventional-type expanded bread. In 1964 the FAO launched a program to use composite flours in bread production. A composite flour is simply a mixture of two or more flours from different sources (cereals, legumes, tubers). The objective of the "Composite Flour Program" was to seek new possibilities for the use of raw materials other than wheat in the production of bread, biscuits (cookies), pastas, and similar flour-based foods (De Ruiter, 1978). The Program spawned a huge research effort. By 1980 there were no fewer than 129 programs world-wide; 72 on bread, 36 on cookies and 21 on pasta, of which 7 in developed countries and 17 in developing countries involved sorghum and millets (Faure, 1992). Between 1970 and 1991 there were more than 1200 publications on composite flours and bread technology (Munck, 1995).

The most common approach has been to make bread using wheat flour plus one or more other flours. There have been a number of important technological developments. With composites containing 30% sorghum and millet, or maize, it was shown that the mechanical dough development process (the so-called Chorleywood process) produced a stronger dough and higher loaf volumes than the traditional bulk fermentation process (Pringle *et al.*, 1969). The mechanical dough development process was specially developed to enable weak (poor quality gluten) wheat flours to be used to bake pan bread. It applies intense mechanical energy to develop the flour into dough in 3–4 minutes, but requires the presence of oxidizing agents to strengthen the gluten after mixing (Kent and Evers, 1994). A problem with the Chorleywood process for developing countries is that specialized high-speed mixers have to be used. However, it has been shown that good results with sorghum, millet and maize composite flours can be achieved through mechanical dough development using sheeting rollers

(Bushuk and Hulse, 1974). The process involved passing the dough several times between rollers of progressively narrower gap size (4.9, 4.8 and 4.0 mm) before the first short proof and then between rolls of 9, 5 and 3 mm prior to molding, panning and second proofing and baking.

Chemical additives, so-called dough improvers, seem to be of great importance for making good quality bread with composite flours. The role of oxidizing agents has already been mentioned. Early research in this area showed that through the addition of potassium bromate and ascorbic acid as oxidizing agents (each at 50 mg/kg flour) it was possible to make good quality bread with flour containing at least 25% maize (Ballschmieter and Vlietstra, 1963). Bushuk and Hulse (1974), using a variety of different composite flours, including sorghum and millet, made similar findings. The specific role of oxidizing agents appears to be to reduce disulfide bond-sulfhydryl group interchange and to increase disulfide bonding between the gluten proteins (Hoseney, 1994).

Several workers have clearly demonstrated the improving effect of adding emulsifiers in composite flour bread making. Pringle *et al.* (1969) found that complete replacement of shortening (baking fat) with 1% (flour basis) of 20% glycerol monostearate (a monoglyceride) substantially improved the quality of composite breads. Bushuk and Hulse (1974) found that with sorghum and maize composite flours addition of 0.5% sodium stearoyl-2-lactylate (SSL) gave increased loaf volumes, particularly at high levels (30–40%) of sorghum flour incorporation. The type of emulsifier also appears to be important. It has been found that sucrose fatty acid esters, emulsifiers of high hydrophilicity, were generally more effective at improving loaf volume and crumb tenderness of sorghum and other non-wheat–wheat composite breads than mono- and diglycerides or SSL (Breyer and Walker, 1983).

Emulsifiers are a type of surfactant (surface active agent). They are amphiphilic in nature, having both a hydrophilic and lipophilic (hydrophobic) component and have the effect of lowering surface tension at interfaces. The specific dough improving effect of emulsifiers appears to be due to them reducing repulsion charges between gluten molecules, causing them to aggregate (Stauffer, 1996). Improved aggregation between gluten molecules would appear to be of particular importance in composite flours as the wheat gluten has been diluted.

According to Dendy (1992a) research world-wide into sorghum–wheat composites has shown that with a wheat flour of reasonable strength, preferably over 12% protein (N × 5.7) it is possible to make bread of reasonable quality with up to 30% sorghum flour. This is provided that the sorghum flour is clean, fine, free from specks of colored bran, compatible in color with wheat flour and of as low fiber content as possible.

Notwithstanding the clear technical feasibility of making good quality bread using sorghum or other non-wheat flour composites, the practical implementation of composite flour technology has been very limited indeed. Dendy (1992b), in a review of composite and alternative flour products, remarked "there must be few technologies that have been so thoroughly researched and so little applied". The reasons for this are many. It is often a matter of economics. Due to subsidies, imported wheat in developing countries has invariably been cheaper than locally produced sorghum. Perhaps not surprisingly, as sorghum or non-wheat grains have not traditionally been used for bread making, adequate supplies of these grains are invariably not immediately available. There have also been technical problems in the production of clean sorghum endosperm meal, as discussed above. Additionally, some of the research into composite flour technology has been unrealistic. High levels of incorporation of non-wheat flour can be achieved when strong wheat flour of high protein content plus dough improvers are used in well-controlled laboratory bakeries. However, in the developing world, for example central and southern Africa, the wheat used is frequently the soft type with low protein content, dough improvers are not available and the baking process is poorly controlled (Randall *et al.*, 1995).

To solve these problems, Dendy (1992a) gave a 10-point strategy for setting up a successful composite flour program. The strategy comprises: a technical survey to determine the attainable level of non-wheat substitution, an economic study, a government national implementation program, assurance of seed multiplication and supply, increased grain production, selection and installation of milling and blending equipment, training of bakers in composite flour technology, market surveys of consumer acceptability plus consumer education, and formulation of grain and flour quality standards.

C. WHEATLESS BREAD

A more radical, and perhaps ultimately more successful approach, has been to try to produce bread without the use of wheat flour at all, so-called "wheatless" bread. Jongh (1961) showed that through the addition of glycerol monostearate it was actually possible, contrary to general belief, to produce a yeast-leavened bread-like product with just starch. The emulsifier appears to cause the starch granules to aggregate so that they will hold gas bubbles. Following this pioneering discovery, researchers have investigated various additives to help improve the gas-holding capacity of sorghum flour doughs. Hart *et al.* (1970) examined a wide range of gums, pectins and surfactants. It was found that of the thickening substances only

4000 centipoise methyl cellulose at an addition rate of 4% was really effective. It increased gas retention, prevented the loaf from collapsing and gave a larger loaf volume. Glycerol monostearate in addition to methyl cellulose gave a finer, but weaker crumb structure. Casier *et al.* (1977) reported that rye pentosans at an addition rate of 3–4% improved the loaf volume and staling resistance of breads made from sorghum and millet flours. The pentosans of rye increase the viscosity and flexibility of the dough gas cell walls enabling greater expansion. These effects are apparently due to the glue-like nature of the pentosans and interactions between the pentosans and the swollen starch granules in the dough (Kubiczek and Olugbemi, 1988). Although technically successful, the obvious drawback for developing countries of such an approach is that the methyl cellulose or rye pentosans would have to be imported.

Satin (1988) avoided this problem by the use of gelatinized cassava starch to increase gas cell wall strength. Cassava starch seems uniquely effective for this purpose as on gelatinization it produces a gel with far greater cohesion than the starches of other cereals and tubers (De Ruiter, 1978). The probable reason that cassava starch is particularly effective is that it has a higher ratio of amylopectin to amylose (5:1) than most cereal starches (Wheatley and Chuzel, 1993). As cassava is a staple food product in much of Africa and south-east Asia its use would not constitute an expensive import in most sorghum-producing countries.

This process of making bread with the aid of gelatinized starch, the so-called "custard" or "batter" process, has become well developed. As first described by Satin (1988) cassava starch is cooked in water at a 1:8 ratio and then raw flour, egg white, salt, oil, yeast and sugar are mixed into the custard to make a dough. Olatunji *et al.* (1992b) reported excellent success in making bread in a similar way, but making a batter rather than a dough. Sorghum flour, pre-gelatinized cassava flour, raw cassava flour and other ingredients (Table III) are mixed at low speed with water for 5 minutes to form a dough. On mixing the dough at medium speed for 5 minutes it breaks down to form a sticky batter. The batter is then allowed to rest for 15 minutes and is mixed again at medium speed for 5 minutes. The batter is weighed into pans and proofed at 40–50°C, 80% RH for 20–30 minutes then baked at 200–230°C for 20–25 minutes. More recently, Hugo *et al.* (1997) showed that with such a sorghum flour–cassava starch system, the inclusion of 1% shortening plus 1% succinylated monoglycerides gave the largest loaf volume and softest crumb, and slowed down the rate of staling slightly.

Much progress has been made with sorghum wheatless breads and it has been suggested that countries with little or no wheat production should direct both breeding and processing to wheatless products (Dendy, 1992b).

TABLE III

INGREDIENTS FOR SORGHUM BREAD MAKING USING THE BATTER PROCESS

Flour	Other ingredients (on a total flour basis)
Raw sorghum flour (70%)	Instant dried yeast (1.0%)
Raw cassava starch (10%)	Granulated sugar (10.0%)
Pre-gelatinized cassava starch (20%)	Salt (1.5%)
	Margarine (1.0%)
	Monoglycerol palmitate (0.6%)
	Total water (100–110%)

Reference: Olatunji *et al.* (1992b). Used with permission.

Outstanding technical problems are that these sorghum breads stale more than twice as fast as wheaten bread (Hugo *et al.*, 1997) and have a rigid consistency more similar to cake than bread.

D. WHEATLESS CAKES AND COOKIES

The rigid crumb structure formed in leavened sorghum products is actually advantageous if sorghum flour is used to make cakes. Olatunji *et al.* (1992a) describe a batter process for wheatless flour cake-making using finely milled sorghum flour (particle size < 150 μm) (70%) and cassava starch (30%). Sugar, fat and eggs are creamed in the normal way. Then the sorghum–cassava flour, baking powder and water (60–80% flour basis) are slowly mixed in to form a batter. The batter is baked at 180°C for approximately 30 minutes.

In cookie manufacture, soft wheat flours with a low protein content, and low percentage starch damage are generally considered most suitable (Hoseney, 1994). A too-strong flour gives cookies a tough texture and too much damaged starch results in the cookies becoming very hard as excessive baking is required. Since sorghum and other non-wheat grains do not contain gluten they would appear to be more suitable for manufacturing cookies, than bread or cakes. However, Badi and Hoseney (1976) found that cookies made from sorghum did not spread, had no top surface cracks, were fragile and had a gritty texture. A combination of hydrating the flour and drying it before use, and adding unrefined soy lecithin (an emulsifier), improved cookie surface character and greatly increased cookie spread. Grittiness was somewhat reduced by increasing the pH of the dough. Breyer and Walker (1983) found that sucrose fatty-acid ester emulsifiers of high hydrophilicity were the most effective in increasing the spreadability of sorghum wheat composite cookies. They also appeared to strengthen the cookies somewhat.

Concerning the issue of cookie fragility, Dendy (1993) reported successful pilot trial production of Nigerian "cabin bread" type biscuits made from 100% sorghum flour using a "custard" process. A portion of the flour was boiled in water and the remaining flour and other ingredients (salt, coloring and chemical leavening agent) were added. The gelatinized starch bound the dough together so that it could be rolled and cut.

Regarding cookie texture, Grøndal (1988), according to Munck (1995), compared the sensory qualities of high-fat sorghum cookies with a corresponding wheat recipe. The sorghum cookies were significantly less acceptable in terms of sandiness and mouthfeel, although their overall acceptability did not differ. It is the vitreous endosperm of sorghum which adversely affects product texture (Munck, 1995), probably because the kafirin complex (the prolamin storage protein of sorghum) which encapsulates the starch granules is highly cross-linked and hydrophobic and retards starch granule water uptake and gelatinization (Chandrashekar and Kirleis, 1988). Grøndal found a significant improvement in cookie texture if extruded sorghum flour replaced 25% of the sorghum flour in the cookies, presumably because extrusion disrupted the structure of the vitreous endosperm material. It has been suggested that separation of the hard and soft endosperm of sorghum should be carried out during milling (Munck, 1995). The hard endosperm material is optimal for brewer's grits and the soft endosperm ideal for baking, particularly for cookie manufacture because of its low protein content and low level of damaged starch. Hallgren (1984) separated the hard and soft endosperm in two sorghum varieties. The hard endosperm flours had protein contents ($N \times 6.25$) of 11.9 and 11.2%, and 10.2 and 14.8% damaged starch, whereas the soft endosperm flours had only 5.8 and 8.3% protein, and 4.1 and 8.2% damaged starch.

E. FUTURE DIRECTIONS

Although sorghum, as with other non-wheat grains, can be used in leavened breads, cakes and cookies, up until now it has almost invariably been considered as a non-functional diluent or filler. This approach may not be entirely correct. Hugo *et al.* (1997) found that with sorghum–cassava bread, loaf volume was correlated with increased amylose-amylopectin ratio. Concerning the functionality of the protein, Lawton (1992) pointed out that zein, the prolamin storage protein of maize, has long been known to be able to form fibers, films and plastics. He then went on to show that zein and maize starch will form a visco-elastic dough when mixed at elevated temperature (25–35°C). Kafirin is very similar to zein and recently it has been reported that isolated kafirin also has film-forming properties (Buffo *et al.*, 1997). It remains to be seen whether kafirin will also form a dough when mixed with starch under similar conditions.

Enzymes such as amylase, proteinase, xylanase and glucose oxidase are increasingly being used to modify the components of wheat flour, in order to improve their functional baking qualities (Si, 1997). It appears that enzymatic modification of sorghum flour can also improve its baking quality. Recent work in our laboratories has shown that enzymatic modification of sorghum flour through malting gives a flour that produces a composite bread with a softer crumb structure and much improved resistance to staling (Hugo and Taylor, unpublished data).

V. OTHER FOOD PRODUCTS

A. RICE SUBSTITUTES

Traditionally, in some parts of India and Africa, whole grain or decorticated sorghum is consumed as a rice-like product (Rooney, 1986). Abrasive decorticators have been applied to manufacture sorghum rice-type foods in several African countries: in the Sudan called pearl dura or "dessert rice" (Perten, 1983), in Kenya called "Supa Mtama" (Dendy, 1993), and South Africa, rather perversely called "corn rice". However, a problem with sorghum rice is its long cooking time (Perten, 1983). For example, the South African product must be rinsed, then cooked for 10–15 minutes, rinsed again and then cooked for a further 25–35 minutes. This cooking problem appears not to have been resolved.

B. PASTA AND NOODLES

Faure (1992) reviewed the limited amount of research that has been carried out into using sorghum to produce pasta. The major problems encountered related to a lack of cohesiveness due to the absence of gluten. Addition of pre-gelatinized maize starch (25%) to untreated sorghum flour improved final product firmness and greatly reduced losses during cooking (Miche *et al.*, 1977). However, such a process is clearly uneconomical, especially for developing countries. Heat treatment at 90°C of sorghum pasta during drying appears to be a potentially much better way of reducing cooking losses (Faure, 1992). Other factors such as the white, or reddish color of sorghum severely limit its potential use in pasta where a yellow color is preferred, which could be imparted by yellow maize.

The white color of some sorghums is advantageous in noodles. Recent work has shown that using a white sorghum of normal amylose-amylopectin ratio with medium to hard endosperm, good quality noodles can be produced by microwave pre-cooking of the flour, water and salt mixture, prior to dough extrusion (Kunetz *et al.*, 1997).

C. TORTILLAS

Tortillas and similar maize-based flat breads, which are traditional to Latin America, are becoming increasingly popular foods in the USA and worldwide (Rooney, 1993). The key manufacturing step is that maize kernels are cooked and steeped in lime to prepare the dough, a process known as nixtamalization. The lime cooking weakens cell walls, causes the starch granules to swell and in some cases partially destroys them, and modifies the physical appearance of the protein bodies (Gomez *et al.,* 1989). These effects on cellular structure are intensified when the kernels are subsequently ground into *masa* (dough). The modification of cellular structure brought about by lime cooking, steeping and grinding enable the formation of a cohesive, pliable semi-plastic product following baking.

In parts of central America and Mexico, sorghum is being used successfully as a complete or partial replacement for maize in tortilla production (Murty and Kumar, 1995). The use of sorghum necessitates relatively minor changes in processing. As the proportion of whole sorghum in the *masa* is increased, cooking and steeping times have to be reduced (Choto *et al.*, 1985). Whole sorghum may impart a greenish yellow to the tortillas due to polyphenols in the outer part of the grain (Bedolla *et al.*, 1983). If the sorghum is decorticated this color is reduced or eliminated. However, it is necessary to reduce cooking time and lime concentration when decorticated sorghum is used, in order to prevent the *masa* from becoming too sticky. In general, the use of white sorghum improves the color of tortillas in comparison to yellow maize (Choto *et al.*, 1985), which may be even further improved if white tan plant sorghum hybrids are used (Almeida-Dominguez *et al.*, 1991). A nutritional advantage of processing sorghum by lime cooking is that it frees much of the niacin, which as in maize, is in a chemically bound, largely unavailable form (Magboul and Bender, 1982).

D. INSTANT AND READY-TO-EAT PRODUCTS

By pre-gelatinizing the starch, cereal foods can be converted into an instant or even ready-to-eat (RTE) form. Apart from saving preparation time, instant products are advantageous in developing communities where fuel for cooking is often scarce and expensive. Several technologies can be used to pre-cook cereals, including: micronization (infra-red heating), gun puffing, oven puffing, roller cooking and extrusion cooking (Hoseney, 1994). The technique of extrusion cooking is probably the most versatile (Linko *et al.*, 1981). An extrusion cooker comprises a screw turning in a barrel, which has a narrow orifice or die at the end. The screw transports and mixes the material. Importantly, it generates pressure, sheer and frictional heat (external heat is also generally applied) which melts the starch granules. As the product emerges from the die it is shaped, the pressure is instantly dissipated and moisture vaporizes. This causes the product to expand. It then sets on cooling into a rigid "cellular" structure.

Anderson *et al.* (1969) showed that endosperm grits from sorghum could be roller cooked or extrusion cooked to produce pre-cooked materials with similar water-absorption properties and viscosity characteristics to those from maize grits. Extrusion cooking with a simple single screw extruder has been used in Zimbabwe to prepare an instant *mahewu* from ground sorghum, maize meal and soya (Chigumira, 1992). *Mahewu* (also known as *magou*) is a traditional southern African lactic acid fermented cereal gruel. In this instant product, sugar and malic acid were used to simulate the natural sour taste. In South Africa, there is a similar instant *mahewu*-type product called "Morvite", where sorghum grain has been pre-cooked by gun puffing.

Because of widespread infant malnutrition in the developing world, there is great interest in producing safe, nutritious weaning porridges (Ngoddy *et al.*, 1994). Malleshi *et al.* (1989) produced instant weaning porridge from a composite of sorghum and cowpeas. Almeida-Dominguez *et al.* (1993a,b) produced a similar product from mixtures of pearl millet, cowpeas and sorghum malt using extrusion cooking. Compositing with legumes such as cowpea or soya improves the protein quality of sorghum foods, as sorghum, like almost all cereals, is very deficient in the essential amino acid lysine and its protein in particular is poorly digestible when cooked (reviewed by Klopfenstein and Hoseney, 1995).

Extrusion cooking has also been used to produce expanded savory-flavored snack foods from sorghum (red and white varieties) on its own (Dendy, 1993), and in combination with cowpeas (Falcone and Phillips, 1988). "Corn" flakes have also been produced experimentally from sorghum flour either on its own or composited with soya flour using cold extrusion, followed by steaming, rolling and toasting (Lu and Walker, 1988). Perhaps not surprisingly, consumer panellists preferred the sorghum products to bran flakes. More recently, whole and decorticated sorghum grain has been used to prepare granola type breakfast cereal and bars (Cruz y Celis *et al.*, 1996). The grain was subjected to micronization, then flaked between corrugated rollers. The granolas were prepared by mixing the sorghum flakes with wheat bran, sesame and sunflower seeds, raisins, sorghum molasses, oil, fructose and water, then baking. Of the sorghum types examined, a waxy (high amylopectin) type, which had a puffed texture after micronization, was most preferred. Clearly sorghum can be used with complete success in place of maize in the production of instant and RTE products.

VI. MALTING

A. APPLICATIONS

Throughout sub-Saharan Africa, by far the highest usage of the cereal sorghum is that of malting for its use in the brewing of traditional "opaque" fermented beverages (Novellie and De Schaepdrijver, 1986; Haggblade and Holzapfel, 1989; Daiber and Taylor, 1995). It is estimated that in Southern Africa alone, approximately 200,000 tonnes of sorghum are malted annually and some 3000 million liters of sorghum beer are brewed each year.

Attention has also been drawn to the possibility of substituting barley malt, traditionally the material of choice, with malted sorghum for the production of European "clear" lager type beers (Skinner, 1976; Okafor and Aniche, 1980; Dufour *et al.*, 1992; Ajerio *et al.*, 1993; Owuama, 1997). The reason for this is that barley does not grow well in the semi-arid areas of Africa and in many cases has to be imported. In fact, in 1988, when the government of Nigeria placed a total ban on the importation of cereals, the clear lager beer brewing industry in that country was forced to utilize locally available sorghum and maize grains plus industrial enzymes, as a replacement for the previously imported barley malt (Koleoso and Olatunji, 1992; Ajerio *et al.*, 1993; Agu *et al.*, 1995; Ilori *et al.*, 1996).

Although sorghum malt is most commonly used for brewing, another application (somewhat under-utilized) of this material is in the formulation of weaning foods. Inadequate energy intake during a child's weaning period is a major cause of malnutrition among the developing world's young children (Lorri and Svanberg, 1995). The most problematic age of child weaning is about 9–12 months, when an already considerable nutritional demand, about 40 g/kg body weight, coincides with a still limited stomach capacity (Malleshi and Amla, 1988). In rural communities the first weaning foods are generally gruels made from cereal staples with low energy and nutritional density. Conventional starchy weaning foods absorb large quantities of water, become bulky when prepared and the child generally cannot consume sufficient quantities to meet its calorific requirements. Simple means are available to enhance the caloric density of weaning foods. When a small amount of malted sorghum flour ("power flour") is added to thick porridge, it is thinned fairly quickly (Nout *et al.*, 1988). The amylase enzymes in the malt break down the complex carbohydrates and liquefy the starch in the porridge. This reduces the viscosity of the porridge whilst maintaining the energy density. In addition, the porridge is also, to some extent, predigested and the malt enzymes somewhat reduce the anti-nutritional and flatus factors, enhance the vitamin content and improve the mineral availability. The malt also bestows flavor and sweetness to the porridge.

To maximize the potential of using "power flour" in weaning foods, technological innovation is required to bring together the science and technology of malting with that of porridge-making quality. Preliminary work conducted in the laboratories of the CSIR (South Africa) (unpublished) has indicated that the decrease in viscosity as occasioned by the addition of malted sorghum to the porridge is directly related to the malting time and, consequently, the activity of the amylase enzymes in the malt.

As mentioned earlier, when cooked, the protein of sorghum is apparently uniquely indigestible amongst cereal proteins (Axtell *et al.*, 1981; Mertz *et al.*, 1984; Rom *et al.*, 1992). The technology of malting has been shown to improve the nutritional value of sorghum by improving the *in vitro* digestibility of the sorghum protein (Wang and Fields, 1978). Although the mechanism by which the digestibility is improved remains unresolved, the technology of malting offers a simple means of improving the value of sorghum-based food.

B. MALTING TECHNOLOGIES

Malting involves the limited germination of cereal grain in moist air under controlled conditions. The general purpose of the malting process is to mobilize the grain's endogenous hydrolytic enzymes, particularly the amylases for the breakdown of starch into fermentable sugars.

The malting process consists of three distinct operations, *viz.* steeping, germination and drying. The metabolic processes of germination are initiated during steeping by immersing the grain in water and allowing it to imbibe a suitable amount of water. During the germination phase, the moist grain is allowed to grow in a humid atmosphere under controlled conditions. When the degradation of the endosperm, which naturally sustains the development of the growing embryo (germ) during germination, has progressed to only a limited extent, the maltster terminates both its degradation and the growth of the germ to produce a shelf-stable product, by drying the grain (Briggs *et al.*, 1981; Taylor and Dewar, 1992).

Although steeping is widely acknowledged as the most critical stage of the malting process for the major malting cereal, barley (Briggs *et al.*, 1981; French and McRuer, 1990), for many years it has been considered to be relatively unimportant for sorghum. This is perhaps because in sorghum malting it is necessary to water the grain during the germination step, whereas in barley malting the grain must receive all the water it requires for germination during steeping (Novellie, 1962). The assumption that steeping is relatively unimportant is reflected in commercial sorghum malting practice in South Africa, where there is no standard prescribed steeping procedure. Sorghum is steeped commercially from anything between approximately 4–6 hours to a maximum of 24 hours, under non-controlled temperature conditions. Only in a very few cases does the moisture content of the grain at the end of steeping reach the 33–35% (wet weight basis) which was recommended by Hofmeyr (1970) 30 years ago.

Recent studies have established that, as is the case for barley, the steeping stage is a critical stage of the malting process for sorghum and that the conditions of steep should be controlled in order to optimize the quality of the resulting malt (Dewar *et al.,* 1997a). The quality of malt, in terms of diastatic power (DP) (amylase activity), free amino nitrogen (FAN) and hot water extract (HWE) were found to be significantly affected by steeping time and temperature. In addition, aeration during steeping has been found to further improve the quality of the malt produced (Ezeogu and Okolo, 1995; Okolo and Ezeogu, 1995; Dewar *et al.*, 1997a).

The optimum conditions for the germination stage of sorghum malting have been well established (Novellie, 1962; Morrall *et* al., 1986; Dewar *et al.*, 1997b). In terms of both steeping (Dewar *et al.*, 1997a) and germination (Morrall *et al.*, 1986; Dewar *et al.*, 1997b), it would appear that the optimum temperature for sorghum, at least for subsequent malt quality, is in the range 24–30°C. A temperature of 18°C (and possibly lower), reported as optimal for barley malting (Briggs *et al.*, 1981), is suboptimal for sorghum (Dewar *et al.*, 1997a), as are temperatures of 32°C and higher (Morrall *et al.*, 1986).

The moisture content of sorghum, both at the end of steeping (Dewar *et al.*, 1997a) and of the green malt (i.e. prior to the drying process) (Dewar *et al.*, 1997b) has been found to be significantly positively correlated with malt quality in terms of DP, FAN and HWE. It would appear, therefore, that the moisture content of sorghum during the malting process is an important indicator of malt quality, at least for brewing purposes.

Recent publications have indicated that steeping sorghum in a dilute solution of NaOH improves the DP (Okolo and Ezeogu, 1996a) and FAN (Okolo and Ezeogu, 1996b) content of the malt. This finding has been supported by the work of Dewar *et al.* (1997c) who offered an explanation as to the mechanism by which alkali steeping affects sorghum malt quality. For condensed-tannin-free sorghum, the improvement in malt DP and FAN occasioned by steeping the grain in dilute NaOH was accompanied by an increased water uptake during steeping. Alkali is known to disrupt the molecular structure of the non-starch polysaccharides, which make up the cell walls (Verbruggen *et al.,* 1995). It was suggested that the NaOH disrupts the sorghum pericarp cell wall structure and, consequently allows water to enter the grain more rapidly during steeping, but not at a rate causing any significant imbibitional damage. Enhanced imbibitional hydration of the grain, brought about by steeping in dilute NaOH, could facilitate the onset of the stage of active metabolic activity more rapidly, thereby producing the malt quality required more quickly.

Concerning the malting of high-tannin sorghums, to produce good quality malt from this type of grain, it is essential that the tannins be inactivated (Daiber, 1975a). Otherwise when the malt is milled and mixed with water during brewing, the tannins will bind with the malt enzymes, adversely affecting hydrolysis of starch, proteins and other components of the brewing mash. A process of inactivating the tannins, which involves soaking the grain for a matter of hours in a very dilute solution of formaldehyde, was patented by Daiber (1975b). Although this process is still in use in southern Africa, the use of formaldehyde is becoming viewed less than favorably. Alternative methods of inactivating tannins are therefore being sought. One such approach which has yielded promising results is that of treating the grain with a dilute solution of alkali (Price *et al.*, 1979; Dewar *et al.*, 1997c).

FAN content is an important component of malt quality, as it is required during the fermentation stage of the brewing process as a source of yeast nutrition (Baxter, 1981; Pickerell, 1986). Adequate FAN levels are especially important in lager beer brewing processes which use unmalted grain (sorghum or maize) with only a small amount of sorghum malt (Muts, 1991). The roots and shoots of sorghum malt are known to be rich in nitrogenous compounds (Taylor, 1983). Although the roots and shoots of sorghum together represent only a small proportion of the total mass of the malt (generally less than 20%) they have been found to contribute as much as 61% to the FAN content of the whole malt (Dewar *et al.*, 1997b).

One of the problems encountered during malting is that of fungal and bacterial contamination, the hot, humid conditions being ideal for their proliferation. Although several chemical treatments are currently available, none are totally ideal and the minimization of fungal and bacterial proliferation during malting is still largely based on good housekeeping practices. Recently, anti-fungal proteins have been isolated from sorghum endosperm (Kumari and Chandrashekar, 1994a). Hard grains have also been shown to be more resistant to fungal attack (Sunitha *et al.*, 1992) and according to Kumari and Chandrashekar (1994b) resistant grains have more anti-fungal proteins. These authors also provide evidence that the anti-fungal proteins are linked to both the level and location of the kafirins (prolamins) in the sorghum grain.

In addition to time and exogenous factors such as temperature, aeration and moisture affecting the germination and malting quality of the grain, there is a great deal of evidence that plant hormones or plant growth regulators (PGRs) play a role in controlling germination (reviewed by Bewley and Black, 1978; Fincher and Stone, 1993; Kermode, 1995). The PGR gibberellic acid (GA_3) is used in the barley malting industry to improve the malting quality of the grain, particularly the production of the critically important hydrolytic enzyme, α-amylase (Paleg, 1960; MacLeod *et al.*; 1964; Briggs *et al.*, 1981). Exogenous GA_3, however, is not used in the sorghum malting industry, largely because it has been shown over many years that its application does not significantly improve the amylase activity of this grain (Daiber and Novellie, 1968; Aisien and Palmer, 1983; Aisien *et al.*, 1983). In this context, it has been shown that throughout sorghum germination the combined level of the endogenous gibberellins$_{1+3}$ is low and fluctuates erratically, apparently unrelated to the time of germination (Dewar *et al.*, 1998). A challenge therefore exists to understand the endogenous mechanisms involved in sorghum germination and, by utilizing this information, to exogenously affect germination and consequently sorghum malt quality.

In South Africa, commercial sorghum malting is carried out in one of two ways: either by "floor malting" or by "pneumatic malting". In floor malting, the steeped grain is germinated on a flat concrete floor outdoors. Pneumatic sorghum malting involves blowing air through a perforated floor on top of which is the bed of germinating grain. This is invariably carried out indoors. Pneumatic malting offers more control over the conditions of malting than floor malting which is affected by the prevailing weather conditions. Hence, the quality of malt produced from a floor malting system tends to be lower and of inconsistent quality.

Although pneumatic maltings have a distinct advantage over floor maltings in producing better quality malt, they do, however, have major drawbacks for developing countries. Firstly, pneumatic maltings are very expensive. Furthermore, the equipment, particularly the fans and turners, require regular and fairly sophisticated maintenance. In addition, electricity, coal, oil or gas is required. In contrast, floor maltings are inexpensive to construct, require no sophisticated maintenance and do not need electricity or a fossil fuel source. In developing countries a strong need exists for sorghum malting technology which combines the simplicity and relative

FIG. 4. CSIR outdoor sorghum malting system. Foreground – germination box. Background – steeping tank.

inexpense of floor maltings with the environmental control that is obtainable in the pneumatic type maltings.

The CSIR has developed a novel, outdoor sorghum malting system, which addresses these problems (Taylor and Dewar, 1992). The malting system is manually operated, utilizes solar energy and the only utility required is potable water. It is of modular construction, consisting of three components: a steeping vessel, a germination box and a solar dryer (Fig. 4). This novel, outdoor malting system successfully combines the simplicity and relative low cost of floor maltings with the malt quality obtainable from pneumatic-type maltings. It is different from the existing outdoor maltings in Africa, in that it allows control over the environmental conditions of malting. It also offers potential for the entrepreneur farmer to convert grain into a value-added, shelf-stable product.

VII. BREWING

A. SORGHUM BEER

Opaque sorghum beers are brewed throughout southern, central and eastern Africa. These beers have many different names, including *joala*, *oruramba*, *chibuku*, shake-shake, sorghum beer and opaque beer (see reviews by Novellie and De Schaepdrijver, 1986; Haggblade and Holzapfel, 1989; Daiber and Taylor, 1995; Mwesigye and Okia Okurut, 1995).

Unlike clear lager-type European beers, many of these beers are brewed with sorghum malt. They are characterized by being opaque and often quite viscous, due to the occurrence of semi-suspended particles of cereal, starch and yeast. Their alcohol content tends to be relatively low (approx. 3% w/w). They are not hopped, but sour in taste due to lactic acid fermentation (or the addition of commercially produced lactic acid). Generally, they are not pasteurized and are consumed in an active state of fermentation. Their shelf-life is consequently rather short, around one week.

Various different methods of brewing, for both sorghum and clear lager-type beers, exist. Generally, however, the aims of the brewing processes are the same; physically and enzymatically to solubilize starch, protein and other constituents of the malt, and often also an unmalted cereal adjunct, and then to ferment this wort using yeast. The basic sorghum beer process involves souring (lactic acid fermentation of sugars by lactobacilli), cooking (starch gelatinization), mashing (thinning and conversion of gelatinized starches to sugars), straining (spent grain separation), and alcoholic fermentation (conversion of the sugars by yeasts to ethanol and carbon dioxide). For more detail on the sorghum beer brewing process, see the above-mentioned reviews.

Traditional small-scale brewing of sorghum beer is still very widely practiced with varying degrees of innovation. Probably because of the lack of control over the conditions of brewing, there is generally no clear distinction between the various steps in the brewing process. Indeed, several different steps take place at once, and there tends to be repetition of various steps (Mwesigye and Okia Okurut, 1995) and in many cases, the process is exceedingly long (up to 14 days).

Over the years the home-brewing process has changed somewhat with the introduction of commercially produced sorghum malt, commercially produced maize meal or sugar as adjunct, and the addition of commercially brewed sorghum beer as inoculum in the process (reviewed by Novellie and De Schaepdrijver, 1986). Another significant advance at the small-brewing scale has been the use of commercial "beer powders". Beer powder comprises finely milled sorghum malt, pre-cooked maize meal adjunct, active dried yeast, and mineral salts. To make beer, the correct quantity of water is added, and then beer ferments rapidly, being ready for consumption within 24 hours. Very recently, commercial brewers have introduced a new product for small-scale brewing operations, concentrated wort syrup produced by evaporation. The product simply requires reconstitution and fermentation, and produces a beer of comparable quality to conventional, industrially brewed sorghum beer. For the small-scale brewer, the use of beer powders or wort concentrate constitutes significant savings in terms of the time and brewing equipment (no need for expensive cooking and mashing vessels) required to produce a consistent product.

This type of initiative is opening up small business opportunities to rural communities. In addition, the commercial brewer now has potential to reach remote markets that previously were not feasible due to the limited shelf-life of the actively fermenting liquid sorghum beer product (De Schaepdrijver, 1987). Recently, in Mozambique and the Democratic Republic of the Congo, successful commercial sorghum brewing operations have been initiated using beer powder (Von Ascheraden R & D Manager, Nola, South Africa, pers. comm.).

In terms of commercial sorghum beer brewing, the process has been optimized over the years. Unlike the traditional home-brewing operation, commercial industrial brewers, largely from the implementation of successful research efforts, are able to control the conditions of brewing much more effectively and consequently split the key brewing steps into separate unit operations and conduct them under optimal conditions of temperature. An example of an efficient brewing process used in South Africa is the so-called "split-sour, double-cook process" (Daiber and Taylor, 1995; Harris, 1997) (Fig. 5). The original brewing process was developed in the gold-mining region of South Africa, referred to as the "Reef", and comprised a single mashing period, followed by addition of yeast to the wort directly after. As the temperature of sorghum malt starch gelatinization (64–68°C) (Taylor, 1992) is higher than the mashing temperature (60°C), this starch would normally have been mostly lost from the beer during wort separation. The process was modified to include a second cooking stage and double (split) addition of sour from the lactic acid fermentation. Its efficiency has been increased substantially by the introduction of the reheating stage after mashing, which effectively gelatinizes and hence recovers the sorghum malt starch. After the second cooking period, a small amount of malt or industrial amylase is added to solubilize the malt starch. The process also has an additional benefit as it pasteurizes the mash. The efficiency of the process has been further improved by adding the sour in two parts, the first during adjunct cooking and the second at the end of the mashing period. This ensures that the pH of the mash is optimal for the action of the malt amylase enzymes (Taylor, 1992).

One area that requires further development is that of packaging. Currently, polythene-lined, cardboard, milk-type cartons are widely used in the retail liquid sorghum beer market. The cartons have been specially

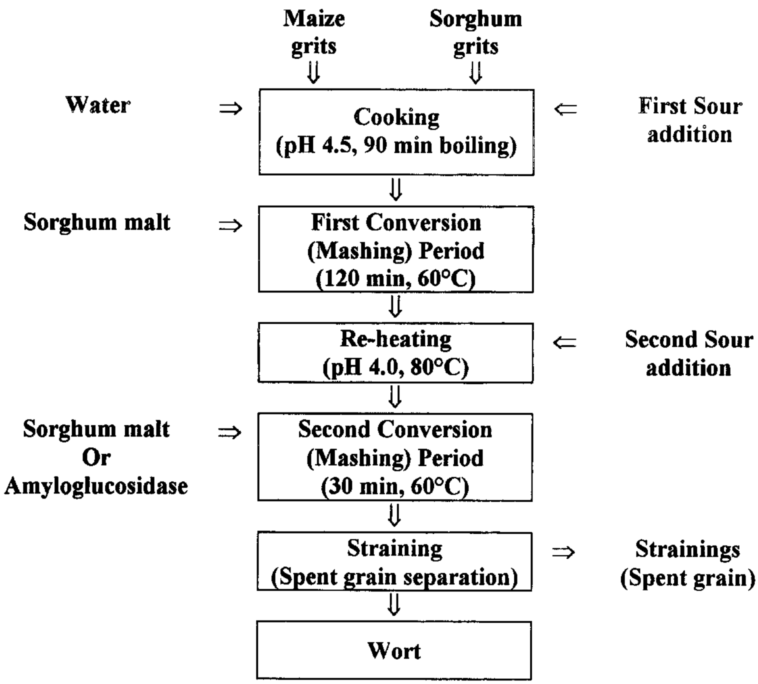

FIG. 5. Outline of "Split-Sour, Double-Cook" industrial sorghum beer brewing process.

designed with a small vent at the top to deal with the problem of the actively fermenting sorghum beer (approximately 17 liters of carbon dioxide is produced per liter of beer). Notwithstanding this innovative adaptation, the packaging is far from ideal. The high cost of the carton largely outweighs the cost of the product it contains. It is also messy due to the escape of foam and spilling of beer, and generally does not raise the image of the product in the marketplace.

A related challenge for the industry is to produce an acceptable, shelf-stable sorghum beer at a relatively low cost. There have been attempts to extend the shelf-life of sorghum beer through pasteurization after alcoholic fermentation (Novellie and De Schaepdrijver, 1986). However, to date, such developments have been only moderately successful and further innovation is required. The cost of glass bottles or cans appears to be outside the reach of the market. One development has been an aseptically packed "Long-life" beer in Tetra Pak® UHT milk-type cartons (De Schaepdrijver and Joustra, 1985). A drawback of this product is that it is non-carbonated. To compensate for the lack of bubble mouthfeel, fruit and ginger-flavored beers have been marketed. The alternative, as mentioned above, is through the use of beer powders and wort concentrates to bring sorghum beer of consistent quality to the consumer.

Although great strides have been made in the development of the technology for opaque sorghum beer, probably because of its origins in the developing world, industrial opaque beer brewing is largely still in its infancy compared with European-type beer brewing. A major requirement for successful industrialization and product development is trained skilled personnel. In this regard, from 1993, the CSIR and the University of Pretoria in South Africa have been offering training courses in sorghum malting and sorghum brewing technology. Both courses have been well received by the sorghum malting and brewing industries throughout sub-Saharan Africa. Indeed, the sorghum brewing technology course is rapidly becoming a required qualification within the industry.

B. CONVENTIONAL BEER

Interest in using sorghum to brew conventional clear beers (lager, ale and stout) goes back to the early 1900s. Beer brewed with sorghum malt was exhibited at the Madras Exhibition in India in 1917 (Viswanath *et al.*, 1918). Three different brewing technologies using sorghum can be distinguished: sorghum grain adjunct with barley malt, sorghum grain adjunct with industrial enzymes, and sorghum malt.

Sorghum grits have been used as an adjunct in conventional beer brewing for many years, notably in Mexico (Canales and Sierra, 1976). Cultivars high in tannins or other polyphenols are avoided as they adversely affect the acceptability of the beer, presumably due to the polyphenols reacting with proteins during the brewing process. It has been reported that sorghum varieties rich in amylopectin (waxy and heterowaxy types) produce worts high in complex carbohydrates but low in fermentable sugars and hence may be suitable for brewing low-alcohol beer (Figueroa *et al.*, 1995). Sorghum grits are produced by dry milling, as described above, and as used commercially apparently should have a fat content of around only 0.5% (Canales and Sierra, 1976). The brewing process is identical to that when maize or rice grits are used as adjunct. The grits must be first cooked in order to gelatinize the starch, so that it can be hydrolyzed by the malt amylase enzymes. The major problem with using sorghum as adjunct is the high losses incurred in producing grits of acceptable quality, i.e. low in color and fat. Reportedly, in Mexico the breweries offset these losses by using the sorghum bran in their own cattle feedlots (Joustra, brewing consultant, South Africa, pers. comm.).

Brewing using sorghum adjunct (or other grain adjuncts) and industrial enzymes, instead of malt, is a much more recent development. Nigeria is a major brewer of lager beer and stout, but up until the late 1980s the only local raw material used was water. As described above, in 1988 the Nigerian government banned the importation of cereals. This resulted in a frantic effort by the breweries of that country and brewing research laboratories around the world to devise processes to use locally produced grain, mainly sorghum, to brew conventional beer without barley malt (Aisien, 1988).

These efforts have been remarkably successful. For several years, a number of beers have been brewed in Nigeria using sorghum grain and maize grits plus a cocktail of industrial hydrolytic enzymes and little or no barley malt (Little, 1994; Lamidi and Burke, 1995). Figure 6 shows a generalized adjunct-enzyme brewing process to the sweet wort stage. The precise nature and quantities of enzymes used in commercial processes do not appear in the public domain. However, various sources (MacFadden and Clayton, 1989; Bajomo and Young, 1993; Little, 1994; Lamidi and Burke, 1995) indicate the types of enzymes used and their purpose. Thermostable α-amylase is added before cooking the adjunct to hydrolyze the starch into dextrins. Then, during mashing, maltogenic amylase or amyloglucosidase (glucoamylase) hydrolyzes the dextrins into fermentable sugars, proteinase hydrolyzes proteins to peptides and amino acids to

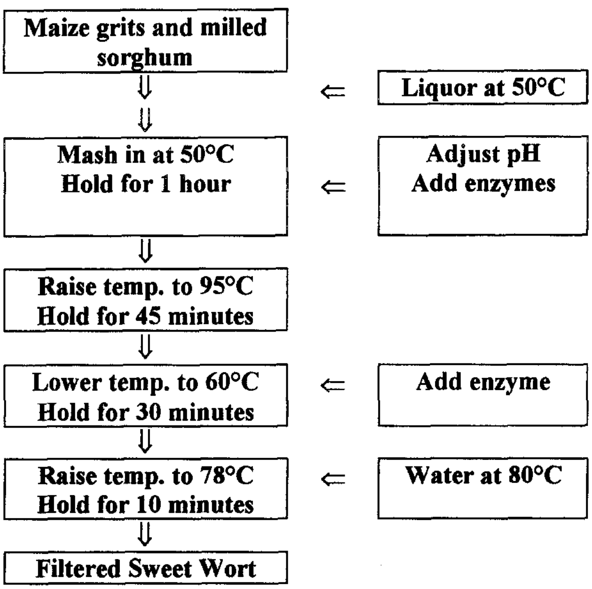

FIG. 6. Outline of a typical commercial process for mashing sorghum lager beer. Source Lamidi and Burke (1995). Used with permission.

improve extract and increase the FAN content of the wort, and pentosanase or ß-glucanase hydrolyze non-starch cell wall material to improve wort separation.

Brewing with sorghum has necessitated a change in the technology of separating the wort from the spent (insoluble) grain. Normally, the husks of the barley malt act as a filter bed in the wort separation vessel, known as a lauter tun (Briggs *et al.*, 1981). However, sorghum is a huskless grain. Thus an alternative technology of mash filters has had to be adopted (Little, 1994). A mash filter comprises a number of cloth sieves of varying pore size, mounted together in series. The traditional problem with mash filters was that they rapidly fouled up and had to be dismantled to be cleaned. A recent development has been tangential-flow filters with automatic discharge of spent grain material (Hermia and Rahier, 1992).

Brewing conventional beer with sorghum malt is technically more difficult and does not appear to have been commercialized. Extrinsic problems concern the production of sorghum malt of consistent quality and freedom from molds, as discussed above. There are also intrinsic differences in the properties of sorghum and barley malt, notably the high gelatinization temperature of sorghum starch. This makes the simultaneous gelatinization and enzymatic hydrolysis that take place when mashing with barley malt problematic due to enzyme inactivation (Taylor, 1992). A number of workers have shown, however, that high levels of extract (starch solubilization) can be achieved with sorghum malt by using decoction mashing (process where portions of the mash are removed, cooked and returned to the mash vessel) (Palmer, 1989; Ilori, *et al.*, 1991; Taylor, 1992). A typical decoction mashing process will comprise four periods of mashing at different temperatures, for example 45°C, 60°C, 70°C and 75°C. After each of the first three periods, one third of the mash is removed and boiled to gelatinize the starch and then returned to the whole mash, which raises the mash temperature. This process ensures that all starch is fully gelatinized and helps ensure that some of the malt amylase enzymes remain active. Alternatively, an enzyme-active extract may be made from the malt at low temperature (e.g. 45°C). The insoluble material containing the starch is cooked, then cooled and the enzyme extract added back to perform the mashing. The extract yield from sorghum malt is also improved by the addition of calcium ions to the mash (200 ppm) (Taylor and Daiber, 1988; Taylor, 1992), since the activity of α-amylase is calcium dependent.

Sorghum malt differs from barley malt in its amylase complement. Although the level of α-amylase is similar, sorghum malt has much lower ß-amylase activity, five to six time less (Dufour *et al.*, 1992). Since ß-amylase is the enzyme responsible for hydrolyzing dextrins into the fermentable sugar, maltose, the low ß-amylase activity of sorghum malt may result in dextrinous worts with poor fermentability (Taylor, 1992). This problem can in part be solved by mashing with an enzyme-active extract (Palmer, 1989), as described above. Additionally, ß-amylase levels in sorghum can be increased through manipulation of malting conditions (Taylor and Robbins, 1993), cultivar selection (Dufour *et al.*, 1992) and possibly recombinant DNA technology.

Poor wort filtration, caused in part by dextrinous worts, is another problem encountered when brewing with sorghum malt (Aisien and Muts, 1987). Additionally, this problem is clearly related to differences in the cell walls of sorghum and barley, such as the fact that in sorghum the endosperm cell walls are not substantially degraded during malting (Glennie, 1984) and that the endosperm cell walls are rich in water-unextractable glucuronoarabinoxylans (Verbruggen, 1996). Further, sorghum malt appears to be deficient in a certain non-starch polysaccharide degrading enzyme, (1,3)(1,4)-ß-glucanase, resulting in high levels of ß-glucan in the wort (Etokakpan, 1992).

For these reasons, it appears that sorghum malt on its own cannot satisfactorily replace barley malt, and in practice, best results are obtained using sorghum malt in combination with industrial enzymes, with the resulting beer comparing favorably with commercial beer produced with 100% barley malt (Olatunji *et al.*, 1993). However, whether it is economical to brew with sorghum malt and industrial enzymes when a satisfactory product can be produced using sorghum grain and enzymes is doubtful. Stout is one beer product where the use of sorghum malt rather than grain is desirable. The characteristic dark color and rich flavor of stout are obtained by roasting the malt at high temperature. It has been shown that an acceptable stout in terms of flavor, color and foam head retention can be produced using sorghum malt roasted at 200°C for 4 hours, plus appropriate levels of sugar and caramel (Ogundiwin and Ilori, 1991).

VIII. FERMENTATION

A. ALCOHOLIC FERMENTATIONS

If sorghum grain is used to brew conventional beer the level of FAN in the wort may be less than half from conventional barley malt mashes (Bajomo and Young, 1994). This affects yeast metabolism, resulting in beer with a different profile of volatiles. All sorghum grain beers contain lower levels of the esters ethyl acetate and iso-amyl acetate, but higher levels of the fusel oils iso-butanol and 3-methyl butanol, and low levels of diacetyl (butanedione) (Little, 1994). The differences in the levels of these compounds are, however, not sufficient to produce any abnormalities in beer aroma or flavor (Bajoma and Young, 1994). Notwithstanding this, it appears to be common practice to add a so-called "yeast food" in these all grain beers to ensure proper fermentation (Little, 1994). It appears that a small amount of sorghum malt may be used for this purpose, as it is rich in FAN (Dewar *et al.*, 1997b).

If sorghum malt is used to brew conventional beer, the wort may contain a much higher proportion of glucose relative to other fermentable sugars than barley malt worts (Palmer, 1989; Dufour *et al.*, 1992; Taylor 1992). The high proportion of glucose can pose a problem during fermentation as a result of the "Crabtree effect" that produces changes in yeast enzymic composition and cell structure (Hough *et al.*, 1982). Sorghum malt worts with a higher proportion of maltose, similar to that of barley malt worts, can be obtained through using a decoction-type mashing process, with an amylase extract of sorghum malt (Taylor and Dewar, 1994). It appears that the high proportion of glucose in sorghum malt worts is due to the enzyme α-glucosidase (Byrne *et al.*, 1993; Taylor and Dewar, 1994), which hydrolyzes maltotriose and maltose to glucose. Sorghum α-glucosidase is highly insoluble in aqueous solution (Watson and Novellie, 1974). If an extract is made from sorghum malt and the residue cooked, the α-glucosidase which is in the residue will be inactivated, but the supernatant will contain the malt α- and ß-amylase enzymes which will produce a maltose-rich wort (Taylor and Dewar, 1994).

Another problem with sorghum malt worts is that they may have a very high content of amino acids that are taken up immediately by yeasts during fermentation (threonine and glutamine) and somewhat lower levels of amino acids which are taken up slowly during fermentation ((Dufour *et al.*, 1992). These differences in wort amino acid composition are probably due to differences between the prolamin proteins of barley and sorghum (Taylor, 1983). The consequence of the differences in wort amino acid compositions is that beer made from sorghum malt may contain higher levels of the undesirable flavor compound, diacetyl (Dufour *et al.*, 1992). The problem can be avoided by adjusting the temperature profile during fermentation.

A related problem concerning yeast amino acid metabolism may occur in sorghum beer fermentations. Sorghum beer can contain several times the level of fusel oils (long chain alcohols) as lager beer (O'Donovan and Novellie, 1966). Fusels oils are responsible for causing hangovers and more seriously, are potential carcinogens. Fusel oil levels in sorghum beer can be controlled by reducing fermentation temperature (Pickerell, 1987).

The level of amino acids (FAN) in sorghum beer worts has also been found to directly influence the rate and extent of fermentation (Pickerell, 1986). As the sorghum beer grist contains a relatively low proportion of malt to unmalted cereal adjunct, the level of FAN in sorghum beer worts is invariably low (Taylor and Boyd, 1986). In severe cases where wort FAN is very low, this can pose a problem by resulting in incomplete fermentation (Pickerell, 1986). To obviate this problem a minimum wort FAN content has been recommended (Pickerell, 1986). As the malt is the major source of FAN in the wort (Taylor and Boyd, 1986), wort FAN can be manipulated through adjusting sorghum malting conditions, as described by Dewar *et al.* (1997b).

The effect of FAN on sorghum beer fermentation rate can be used to advantage. In summer when the ambient temperature is high, fermentation rate can be slowed down and hence beer shelf-life extended, by reducing wort FAN (Mathiba *et al.*, 1997), and conversely in winter, fermentation rate could be accelerated by increasing wort FAN.

B. LACTIC ACID FERMENTATIONS

In Africa, many traditional sorghum foods have undergone a lactic acid fermentation. These foods include alcoholic beverages such as sorghum beer, gruels like *motoho oa mabela* of Lesotho, porridges such as *ting* of Botswana and flat breads like *injera* of Ethiopia. The lactic acid fermentation performs a number of important functions. Apart from the refreshing taste imparted by the lactic acid, which consumers enjoy, the low pH of the food (usually < pH 4.0) can render it safe from pathogens (Nout *et al.*, 1988; Svanberg *et al.*, 1992) and slow down its rate of microbial spoilage; hence extending the product's shelf life (World Health Organization, 1996). The fact that lactic acid fermented foods can be microbiologically safe is of crucial importance in Africa, as regrettably even today many people do not have access to safe water, let alone refrigeration. As a consequence, annually there are some 1500 million episodes of diarrhea in children under the age of five and over three million children die as a direct result.

Numerous other benefits have been claimed for the lactic acid fermentation of cereals, particularly sorghum, including: reduction in mycotoxin content (Adegoke *et al.*, 1994), reduction in porridge viscosity (Lorri and Svanberg, 1993), improvement in starch availability and digestibility (Kazanas and Fields, 1981; Hassan and El Tinay, 1995), improvement in protein digestibility (Kazanas and Fields, 1981; Chavan *et al.*, 1988; Moneim *et al.*, 1995), reduction in tannin content (Hassen and El Tinay, 1995) and improvement in mineral availability (Marfo *et al.*, 1990). On account of these benefits, several authorities are actively promoting the use of lactic acid fermentation in developing countries (Tomkins *et al.*, 1988; World Health Organization, 1996), especially for feeding the at risk in the community, i.e. weaning age children, the elderly and those who are immuno-compromised.

Surprisingly, however, relatively little attention has been given to the development of simple and safe methods of lactic acid fermentation, especially ones that can be applied in the home, where the use of pure cultures is impractical. Van der Walt (1956) showed that by carrying out the souring process in sorghum beer brewing at elevated temperature (45–50°C), essentially only the thermophilic, homofermentative (lactic acid only producing) bacteria (*Lactobacillus delbrueckii*) grow. In contrast, at lower temperatures a very mixed microflora flourish, including heterofermentative types which can produce off-flavors such as acetic and formic acids. As a result of this work, souring in industrial sorghum beer brewing is almost universally carried out at a strictly controlled temperature of 48–49°C.

Obviously such a level of temperature control is impractical in the home environment. However, households are generally able to carry out consistently successful fermentations through practicing a system of back-slopping, whereby a portion of liquid from a successful fermentation is used to inoculate a fresh slurry of sorghum meal (Mosala and Taylor, 1996). Over a number of such cycles, rapidly fermenting lactic acid bacteria with a high acid tolerance are selected. Nout *et al.* (1989) showed that by back-slopping each day, what they called accelerated fermentation, the normally slow fermentation process (2–3 days) was accelerated by enrichment with acid-producing strains of lactic acid bacteria. Further, consumption of fermentable carbohydrates by aerobes and enterobacteriaceae was inhibited, so that within five cycles no enterobacteriaceae were detectable. Thus by this simple method, safe and predictable lactic acid fermentation can be carried out without the complication of using pure cultures. These authors also showed that fermented sorghum meal produced by the accelerated fermentation process could be simply oven-dried into a shelf-stable product. The dried product, which had excellent microbiological stability, could be sold in packaged form and cooked into infant porridge as required.

Recently HACCP (hazard analysis critical control point) principles have been applied to help ensure the safety of fermented foods produced in the home (World Health Organization, 1996). Figure 7 shows the critical control points (CCPs) in the production of *uji*, an east African fermented sorghum, maize or millet porridge, frequently used as a weaning food. The cereal meal should be free of toxins produced by fungal contamination (mycotoxins). This can be ensured by storage under appropriate conditions. Water is a CCP, not so much for the reason that it may contain pathogens since the water should be boiled thoroughly during the dough cooking stage, but rather because it may contain chemical contaminants.

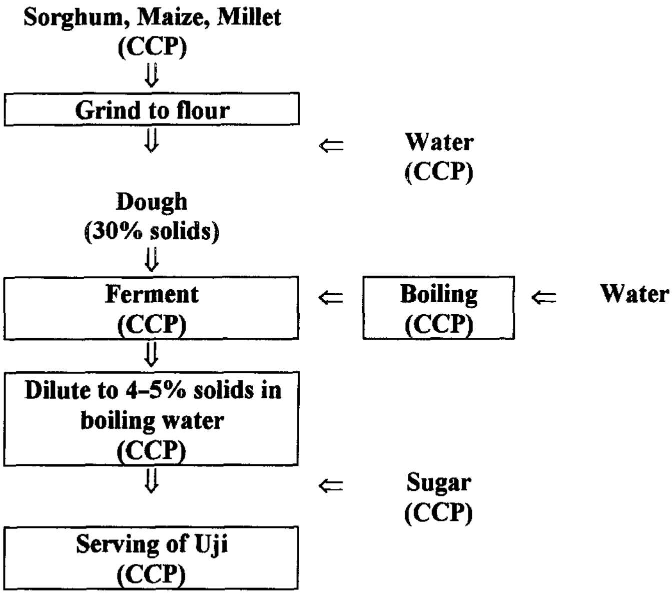

FIG. 7. Application of the HACCP system to preparation of *uji* fermented porridge in households, showing the critical control points (CCP). Source World Health Organization (1996). Used with permission.

The major hazard during fermentation is the production of thermostable toxins by for example *Staphylococcus aureus* and molds. Thus, the acidification process should be rapid, within 24 hours, as described above. Dilution in continuously boiling water is a CCP as pathogens must be killed during this step. The addition of sugar is also a CCP as it may be chemically or physically contaminated and microbiological contamination may be introduced via dirty utensils. Serving is a CCP as microbiological contamination, by for example *Shigella* sp., may occur from utensils or dirty hands. Additionally, spores from *Bacillus cereus,* which survived the previous steps, may germinate if the porridge is allowed to stand for some time. Thus, it is recommended that fermented porridges are consumed within four hours.

IX. CONCLUSIONS AND CHALLENGES

Over the past 20 or so years, tremendous strides have been made in developing sorghum food processing technologies. Two examples where the technologies have been successfully implemented are: the industrialization of sorghum brewing, taking it from a rural craft to a 20,000 liter batch scale, and brewing conventional beer with sorghum grain and enzymes. However, the implementation of other technologies, for example, composite breads, is notably lacking. One major factor limiting utilization of sorghum in Africa appears to be the unavailability of cost-efficient, reliable supplies of sorghum grain of acceptable quality for making high quality flour (Rooney, 1997).

The challenge, therefore, appears to revolve around an holistic approach to implementation, involving: economic studies, government programs, seed supply, grain production, selection of appropriate technologies, training of operators, consumer awareness, and grain and product quality standards; such as that described by Dendy (1992a) for composite flours.

It is encouraging that the focus of the current phase (1998–2003) of the Sorghum and Millet Improvement Program of SADC/ICRISAT (Anon., 1998) is to implement an integrated strategy for increasing sorghum utilization in southern Africa by creating "a strong regional network of public and private partners to promote a sustainable process of higher productivity, utilization, regional trade and income growth through increased commercialization of sorghum and millet".

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