1. INTRODUCTION

1.1. Statement of problem

Sorghum (*Sorghum bicolor* (L.) Moench) is an indigenous cereal crop to Africa, where it is grown in the semi-arid and sub-tropical zone, which includes the large belt in northern Africa spreading from the Atlantic to Ethiopia and Somalia (Dendy 1995). Due to its drought tolerance and adaptation to semi-arid, sub-tropical and tropical conditions, sorghum can still be produced where agricultural and environmental conditions are unfavorable for the production of other cereal crops. This is of particular importance as Global Warming and the growth of the world's population will require that more marginal lands be used for food production (Taylor and Dewar 2001).

World annual sorghum production in 2002 was 54.5 million tons, of which Ethiopia produced about 1.82 million tons (FAO 2003). Nearly all the sorghum grain produced in Ethiopia is used for human consumption. About 80% is used for making leavened bread (*injera)* and 10% is used to make home brewed beer (*tella)* (Gebrekidan and GebreHiwot 1982). The remainder goes into making stiff porridge (*genfo*), unleavened bread (*kitta),* boiled whole grain (*nifro*), popped grain (*kollo*) and animal feed.

The Ethiopian Sorghum Improvement Program (ESIP) conducts research on local landraces and accessions from the world sorghum collection for improvement of sorghum in Ethiopia. The factors requiring consideration in sorghum improvement include: yield increases, resistance to yield limiting biotic and abiotic factors and end use quality traits. Of late, end-use quality as a factor is receiving more attention than ever. The national cultivar release committee of Ethiopia has made it mandatory to include end-use quality data before a cultivar is proposed for release.

Injera is a fermented leavened, flat, Ethiopian traditional bread made from cereals such as tef and sorghum and is a staple food of Ethiopia (Gebrekidan and GebreHiwot 1982). *Injera* prepared from the flour of tef [*Eragrostis tef* (Zucc.) Trotter], a tiny millet-like grain, is preferred because it is soft and rollable and is less subject to staling. Because sorghum is less expensive in Ethiopia, there is great interest in improving the quality of sorghum *injera*. The major problem associated with *injera* from sorghum is its fast staling property leading to dry and friable texture upon storage.

Gebrekidan and GebreHiwot (1982) evaluated sorghum cultivars from Ethiopia and internationally for *injera* making qualities. They reported that sorghum cultivar differences existed for *injera* making and staling properties. Yetneberk and Adnew (1985) developed a standard procedure for sorghum *injera* preparation and used it to evaluate the *injera* making qualities of sorghum cultivars from the ESIP and a set from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). The existence of sorghum cultivar differences for *injera* making quality was reconfirmed, as reported by Subramanian and Jambunathan (1990). However, the sorghum grain quality factor(s), which affect *injera* making quality, are little researched and not well understood. Thus, by making use of the existing broad genetic diversity of sorghum (House et al. 1995), it should be possible to identify and select for sorghum grain characteristics responsible for good *injera* making quality. If successful, the characteristics identified will be used as objective breeding selection criteria in the ESIP.

1.2. Hypotheses

Studies of some Ethiopian sorghum cultivars have shown differences in their *injera* making quality. These differences are probably due to specific genetically controlled physico-chemical characteristics of the grain. It should therefore be possible to develop objective breeding selection criteria for sorghum cultivars of improved *injera* making quality.

1.3. Objectives

- To confirm the role of grain quality in sorghum *injera* making
- To determine the sorghum grain physico-chemical factors involved in *injera* making quality.
- To establish objective indicators for rapid evaluation of sorghum cultivars in terms of *injera* making quality.

- To develop a simple, objective system for selecting sorghum cultivars with good *injera* making quality in the Ethiopian sorghum improvement program.

2. LITERATURE REVIEW

This review discusses and compares the origin, distribution and importance of sorghum and tef and what is known about both cereals in terms of structural components of the grains, chemical composition, pasting and gelling properties, decortication and milling, fermentation, bread making, *injera* preparation and its evaluation methods.

2.1. Sorghum and tef: Origin distribution and importance

Sorghum (*Sorghum bicolor* (L.) Moench) is a tropical grass, which originated in North Africa, cultivated extensively for human consumption in Africa and India, particularly in arid and semi-arid regions of the world. Tef [*Eragrostis tef* (Zucc.) Trotter] is also a tropical grass, believed to have been domesticated in the northern highlands of Ethiopia (House et al 1995). It is a significant food crop in only one country in the world, Ethiopia (Seyfu 1993, National Research Council 1996). Ethiopia is also considered as the major world center for the genetic diversity of tef (Seyfu 1993).

It is estimated that more than 70 percent of the world sorghum crop is consumed as food in the main production areas of Africa and Asia (ICRISAT/FAO 1996). In Ethiopia, both sorghum and tef are consumed as staples and are important sources of carbohydrate in the diet, which is cereal-based, specifically in *injera*. Next to tef, sorghum is the second preferred cereal for making *injera* (Gebrekidan and GebreHiwot 1982). Of note is the fact that the cultivation productivity of tef is low and therefore it commands a higher market price than other cereals in Ethiopia (Seyfu 1993).

2.2. Anatomy of sorghum and tef grains

Sorghum and tef are remarkably different in grain size and shape but the grains are anatomically very similar. The sorghum grain (Fig 2.1) is essentially spherical, approximately 4 mm long, 2 mm wide, and 2.5 mm thick with an individual kernel weight of 25-35 mg (Serna-Saldivar and Rooney 1995). The tef grain (Fig 2.2) is oval, tiny in size, 1.0 to 1.2 mm with a mean weight of 0.62 ±0.05 and 0.83 ±0.02 mg for white and red cultivars, respectively (Umeta and Parker 1996). The size and shape of the tef grain lends itself to compact packing, which reduces storage space compared to sorghum grain.

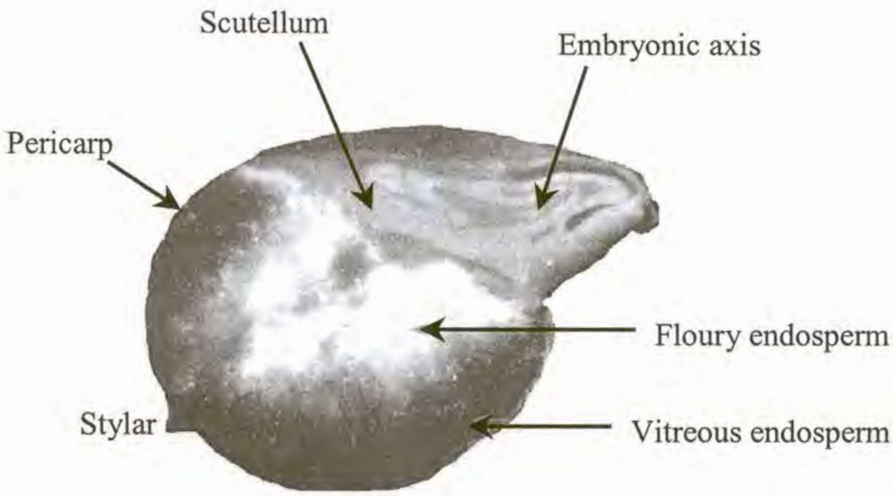

Figure 2.1. Micrograph of longitudinal section of sorghum grain (Taylor and Belton 2002).

Structurally, both sorghum and tef grains are composed of three main parts: the pericarp (outer covering), the endosperm (storage organ) and the germ (embryo) (Rooney and Miller 1982, Umeta and Parker 1996). Genetically, sorghum pericarp color is red, white or lemon yellow (Rooney et al 1986). Tef grain color varies from milky white to almost dark brown (Seyfu 1993).

In sorghum, the pericarp is arranged in distinct sub-layers, namely the epicarp, mesocarp and endocarp (Rooney and Miller 1982). The mesocarp appears to be the thickest layer of the pericarp consisting of several layers of elongated, thin walled cells. The pericarp of the sorghum grain varies in thickness and its thickness is controlled genetically (Rooney and Miller 1982, Scheuring et al 1983). These authors stated that thin pericarp (pearly) is manifested by the presence of a single dominant Z allele, whereas the thick pericarp (chalky) is determined by two recessive alleles, zz. Thick pericarp sorghums have abundant starch granules held in a loose mesocarp network (Rooney and Miller 1982, Earp and Rooney 1982, Scheuring et al 1983). Tef pericarp is comparatively thin and forms the bran envelope that protects the seed (Umeta and Parker 1996). Although the mesocarp and endocarp of tef are reported to be fused, some starch granules were found in the mesocarp (Umeta and Parker 1996).

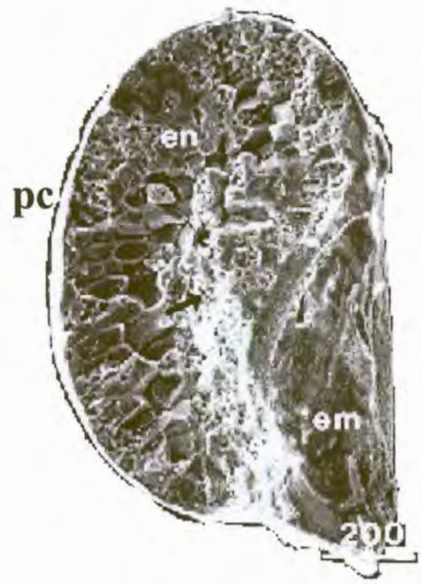

Figure 2.2. Micrograph of longitudinal section of tef grain (Parker et al 1989). Pericarp (pc), starchy endosperm (en) with outer vitreous region and floury center (arrowed) and relatively large embryo (em).

In sorghum, the presence or absence of a testa layer beneath the pericarp is controlled by the complementary B_1 and B_2 genes with the testa present when both the B_1 and B_2 genes are dominant (Rooney and Miller 1982). Tannins are concentrated in the outer layers of the grain of some types of sorghum, the tannin (high-tannin) cultivars, mainly in the testa and to a lesser extent the pericarp and aleurone (Hahn et al 1984). Red tef grain is reported to contain a tannin-rich pigmented material deposited in the lumen of the testa cells that gave the seed its red color (Umeta and Parker 1996). However, it is doubtful if tef actually contains tannins (Bultosa and Taylor 2004). In both tef and sorghum, attached to the testa is the aleurone layer a one-cell thick single layer of blocky cells rich in protein and spherosomes (Serna-Saldivar and Rooney 1995, Umeta and Parker 1996).

Both the germ of sorghum (Rooney and Miller 1982) and tef (Umeta and Parker 1996) are large in proportion to the rest of the kernel. The anatomical parts of the germ are the scutellum and embryonic axis (Fig 2.1). The function of the scutellum is to supply most of the hydrolytic enzymes, which modify the grain components during germination

(Briggs 1998) the embryonic axis consists of the shoot and the root initials, that eventually give rise to a mature plant (Briggs 1998). The germ tissue is rich in lipids, protein and minerals (FAO 1995). Most of the lipids of sorghum are located in the scutellum and lipid contents are reduced when kernels are decorticated and/or degermed (Serna-Saldivar and Rooney, 1995), due to removal of all or part of the germ. The germ of some sorghum cultivars is deeply embedded inside the endosperm and is extremely difficult to remove, while in others protrudes from the kernel and is more easier to remove (Rooney and Miller 1982).

The starchy endosperm is the largest component of both sorghum and tef grains. In sorghum from one-half to three-fourths of grain weight is starch (Serna-Saldivar and Rooney, 1995). The predominant structures in sorghum starchy endosperm cells are starch granules, protein bodies, and protein matrix (Shull et al 1990). The starchy endosperm of sorghum grains is comprised of two visually and physically distinct regions, a hard vitreous outer area and a floury soft inner area (Fig 2.3). The relative proportion of vitreous to floury endosperm varies among cultivars (Rooney and Miller 1982). The outer most region of the starchy endosperm just beneath the aleurone layer has been described as the peripheral endosperm (Serna-Saldivar and Rooney 1995). The combination of large, simple polygonal-shaped starch granules, numerous protein bodies and protein matrix in the outer endosperm forms a continuous structure (Shull et al 1990). In sorghum, the central endosperm (floury), on the other hand, has less densely packed, more spherical starch granules. Within the sorghum endosperm, the starch granules and protein bodies are contained within cell walls (Rooney and Miller 1982, Shull et al 1990). Similarly, tef endosperm also has a vitreous outer area and a floury inner area (Parker et al 1989) (Fig 2.2). As with sorghum the peripheral endosperm of tef contains most of the protein reserves of the endosperm (Parker et al 1989). In tef, protein bodies are located outside compound starch granules (Umeta and Parker 1996, Bultosa et al 2002).

2.2.1. Starch granules

Starch is unique among carbohydrates because it occurs naturally as discrete particles, called granules and is the predominant food reserve substance in plants. There is diversity in the structure and characteristics of native starch granules among different plant sources

(Whistler and BeMiller 1999). Sorghum starch exists as large simple granules, about 20 μm in diameter (Hoseney 1994). The starch granules of sorghum are compact and polygonal in the vitreous endosperm, but are spherical in the floury endosperm (Rooney and Miller 1982) (Fig 2.3A). Some granules, such as those in oats and rice, have a higher level of structure in which many small individual granules are cohesively bound together in an organized manner (Thomas and Atwell 1999). These are called compound starch granules. Tef starch granules are also polygonal in shape and aggregated into compound grains, each complex of granules representing the contents of an amyloplast (Umeta and Parker 1996, Bultosa et al 2002) (Fig 2.3B). There is no evidence of strong attachment between adjacent tef starch granules within the compound starch (Bultosa et al 2002). Individual starch granules of size 2 to 6 μm in diameter are released on milling (Umeta and Parker 1996). The size of small starch granules in barley and rice 2 to 6 μm and 3 to 5 μm, respectively (Pomeranz et al 1984), is similar to tef starch granules. It has been found

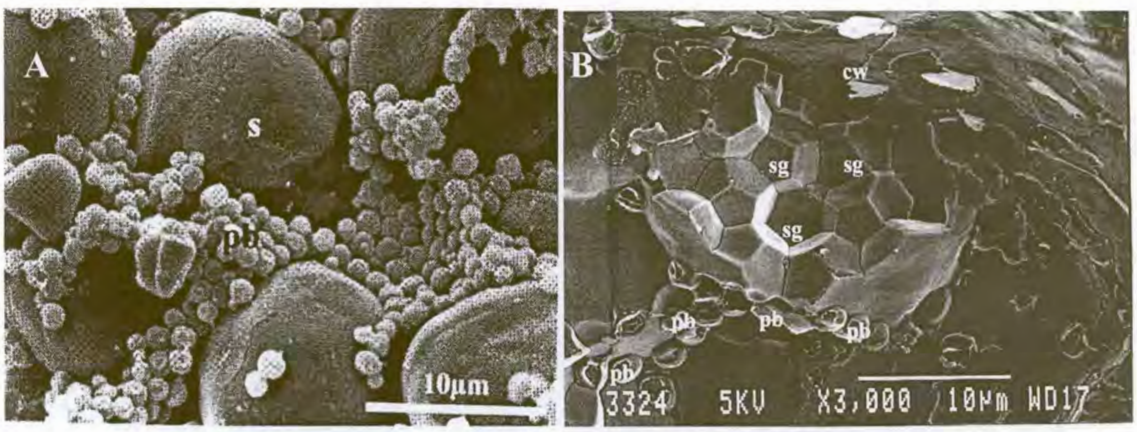

Figure 2.3. Micrographs of starch granules and protein bodies in sorghum and tef. **A**, Floury endosperm of sorghum. s = starch granule, pb = protein bodies (Duodu et al 2002). **B**, Tef compound starch granule. sg = single granule, pb = protein bodies, cw = cell wall (Bultosa et al 2002).

that small starch granule size within a population is positively correlated with resistance to swelling and peak viscosity in wheat, potato and maize starches (Fortuna et al 2000, Li and Yeh 2001).

2.2.2. Significance of endosperm texture

Endosperm texture has been identified as a factor that most consistently affects the processing and food making properties of sorghum (Rooney et al 1986). Ease of mechanical decortication of the sorghum grain depends on the hardness (related to vitreouness) of the grain (Shepherd 1979, Reichert et al 1982, Lawton and Faubion 1989). With hard grain, the bran is removed with minimum loss of endosperm material. Finer flour is normally achieved from more vitreous endosperm, but more energy and time are required (Rooney et al 1986). However, flours from the vitreous endosperm typically contain closely-packed, polygonal starch granules with protein bodies, while starch granules released from the floury endosperm, that are loosely-packed, tend to be released as individuals, as they are not held together by matrix material (Duodu et al 2002). Furthermore, during pasting the association of the protein bodies around the starch granules appears to act as a barrier to starch gelatinization (Chandrashekar and Kirleis 1988). Almeida-Dominguez et al (1997) also demonstrated that floury maize samples developed higher viscosities more rapidly. The authors ascribed this phenomenon to loosely packed starch granules with reduced protein-to-starch bonds in floury maize which hydrated and swelled more rapidly in the presence of heat. This may also apply to sorghum, because a negative correlation was reported between grain hardness and peak paste viscosity (Taylor et al 1997). As stated by Chandrashekar and Mazhar (1999), higher peak temperature was also positively correlated with grain hardness. A recent study by Zhan et al (2003) indicated that sorghum cultivars with low kernel hardness gave higher ethanol and lactic acid yields. They ascribed this to the low starch protein packing of the floury endosperm. A similar effect might possibly be imparted on the fermentation of sorghum dough in *injera* making. Thus, the endosperm matrix protein and protein associated with starch which affects endosperm texture also influences the milling, pasting and fermentation properties of the grain. Generally the expression of vitreousness is influenced by the growing environment (Rooney and Miller 1982), but in any one environment it is possible to distinguish between genotypes differing in vitreousness.

2.3. Chemical components of sorghum and tef

2.3.1. Starch

Starch is a major component of many food plants where it occurs as water-insoluble granules (Miles et al 1985). Worldwide, starch provides 70-80% of the calories consumed by people (Whistler and BeMiller 1999). Starch comprises two main polysaccharides amylose, an essentially linear polymer composed of α-1,4 linked D-glucopyranose molecules (Fig 2.4), and amylopectin a very large, branched, D-glucopyranose polymer containing both α-1,4 and α-1,6 linkages (Thomas and Atwell 1999) (Fig 2.5). Recent evidence, suggests that some branches are present on the amylose polymer (Curá et al 1995). Amylose chains are helical with hydrophobic, lipophilic interiors capable of forming complexes with linear hydrophobic portions of molecules that can fit within the lumen of the helix (Whistler and BeMiller 1999). The structure and molecular weight range of amylopectin molecules vary with the source of the starch (Myers et al 2000) and thereby determine its crystallinity and branching patterns (Hizukuri et al. 1997).

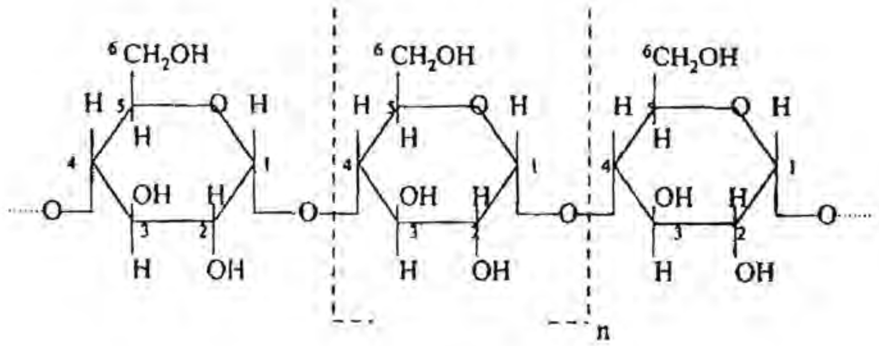

Figure 2.4. α-1,4 linkages of amylose (Thomas and Atwell 1999).

The starch in normal (non waxy) cereals is approximately 25% amylose and 75% amylopectin. Taylor et al (1997) reported mean amylose contents of 32.0% and 23.5% for starches from sorghum cultivars grown under rainfed and supplementary irrigation, respectively. For normal starch sorghums, environmental effects may exert more influence on amylose than genetic differences (Ring et al 1989). Starches from sorghum cultivars differing in polyphenol level had an amylose content ranging from 21.5 to

29.9% (Beta et al 2000a). A similar range of amylose contents for normal sorghum starches of 21.2 to 30.2% was reported by Subramanian and Jambunathan (1982). According to Ring et al (1989), pericarp and testa pigments significantly lower the measurable amylose in sorghum. In tef, amylose content of starches from different cultivars ranged from 24.9% to 31.7% (Bultosa et al 2002). Tef starches seemed to have higher amylose content compared to sorghum starches. There are indications that amylose enables starch to form a gel after the starch granule has been cooked (Thomas and Atwell 1999). However, because of the amylopectin in starch, its properties differ from that of pure amylose, retrogradation is slowed and gel formation is delayed.

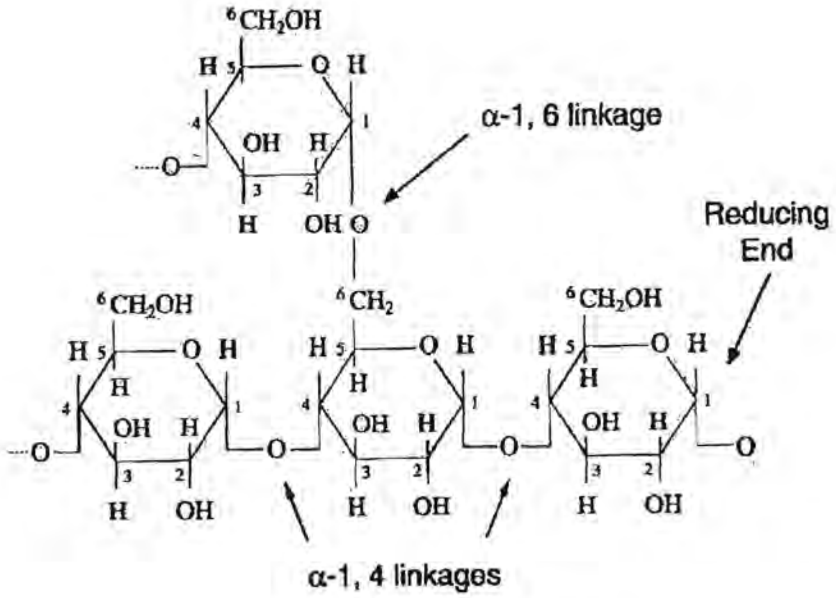

Figure 2.5. α-1,4 and α-1,6 glycosidic bonds of starch (Thomas and Atwell 1999).

2.3.1.1. Starch functional properties

Water solubility and water absorption

Water solubility index (WSI), a measure of how much of the flour component is soluble in water, is useful as it is a reflection of the strength of the network within the starch granules (Qian et al 1998). These authors further explained that the leaching of small molecular weight polysaccharides increases as the network of the starch granules become weak. In general, polysaccharides become more soluble in proportion to the degree of chain irregularity (Whistler and BeMiller 1999). Kavitha and Chandrashekar, (1992) reported that soft endosperm sorghum cultivars had significantly higher water-soluble non-starch polysaccharide content than did hard endosperm cultivars, probably due to differences in cell wall composition. Cultivar differences for WSI of tef starches were reported by Bultosa et al (2002).

Polysaccharides modify and control the mobility of water in food systems, which may affect many functional properties of food including texture (Whistler and BeMiller 1999). These authors further explained that water in excess of that involved in hydration is entrapped in capillaries and cavities of various sizes in the gel or tissue. Water absorption index (WAI), a measure of the amount of water absorbed by the flour, is related to the amount and swelling degree of the starch gel phase (French 1984). The endosperm cell wall, non-starch polysaccharides of sorghum are rich in water-inextractable glucuronoarabinoxylans (Verbruggen et al 1993), which might be involved in water absorption in whole sorghum flour. Additionally, undamaged starch granules are not soluble in cold water but can imbibe water reversibly. This reversible range varies with the type of starch and increases with granule diameter (Whistler and BeMiller 1999).

Starch gelatinization

Starch gelatinization is an irreversible, non-equilibrium process (Deffenbaugh and Walker 1989) during which granule birefringence (Maltese cross) and crystallinity disappear (Miles et al 1985). These authors pointed out, however, that at temperatures below 100°C and in the absence of mechanical shear, granule integrity is maintained. Gelatinization occurs over a temperature range, with larger granules generally gelatinizing first and smaller granules later (Whistler and BeMiller 1999). The point of initial gelatinization and the range over which it occurs is governed by starch concentration, method of observation, granule type and heterogeneities of the granule under observation (Atwell et al 1988). The gelatinization temperature of starch also varies with the amount of added water and the species from which the starch was obtained (Subramanian et al 1994). The gelatinization temperature range of sorghum starch (68-78 °C) is slightly higher than that of maize (62-72°C), very much higher than that of wheat (58-64 °C) and barley (51-60

°C) (Hoseney 1994), but similar to that of tef (68-80°C) (Bultosa et al 2002). The high gelatinization temperature of sorghum has been considered an undesirable property because it prolongs the cooking time of sorghum during food processing (Ali and Wills 1980). It is noteworthy that the involvement of endosperm protein in limiting starch gelatinization in hard sorghum flour has been reported (Chandrashekar and Kirleis 1988).

Starch pasting

Starch pasting is the phenomenon following gelatinization. It involves granule swelling, exudation of molecular components from the granule and eventually total disruption of the granule (Atwell et al 1988). Pasting is related to the development of viscosity (Thomas and Atwell 1999). The pasting property of starch is a key to understanding flour and starch physical characteristics and potential utilization (Lee et al 2002). The changes in viscosity of starch paste can be followed by viscograph type instruments such as the Rapid Visco Analyser (RVA). The RVA is a heating and cooling viscometer configured especially for testing starch-based and other products requiring precise control of temperature and shear (Newport Scientific 1995).

At its paste peak viscosity (PV), starch is regarded as fully pasted due to granule swelling and starch leaching (Whistler and BeMiller 1999). Peak viscosity indicates the water holding capacity of the starch (Newport Scientific 1995). The mean peak viscosity of the sorghum starches was found to be markedly higher than that of maize starch (Beta et al 2000a), indicating that swollen sorghum starch granules are more resistant to shear breakdown. Bultosa et al (2002) reported that the PV of tef starch was considerably lower than that of maize starch. Although the comparisons hold true, the value for the PV of maize was different as reported by the two authors. This is probably due to differences in the samples and conditions of measurement used. PV can be affected by granule size. Small granule size was positively correlated with resistance to swelling in wheat, potato and maize native starches (Fortuna et al 2000, Li and Yeh 2001). It has been reported that the PV of sorghum starches is affected by growing environment (Beta and Corke 2001). Also, an inverse relationship between sorghum grain hardness and PV was reported by Taylor et al (1997). With regard to the time taken to reach PV, tef starch took a longer time (mean 4.2 min) (Bultosa et al 2002) compared to sorghum starch (2.4 min) (Beta et al 2000a). This could also be related to the small starch granule size of tef.

At breakdown viscosity (BV) (peak viscosity minus hot paste viscosity), the swollen granules have been disrupted further and amylose molecules have generally leached out into the solution and aligned in the direction of the shear (Whistler and BeMiller 1999). Low BV indicates the stability of the swollen granules against disintegration during cooking (Agunbiade and Longe 1999). As Zobel (1984) states, generally, starches with greater shear thinning are more soluble. The BV of sorghum starch paste was found to be twice that of maize starch (Beta et al 2000a), indicating that sorghum starch paste was less stable than maize starch. The BV of tef starch pastes was found to be considerably lower than that of maize starch paste (Bultosa et al 2002).

Cold paste viscosity (CPV) is related to the ability of the starch paste to form a gel after cooling (Whistler and BeMiller 1999), due to a decrease of energy in the system and subsequent hydrogen bond formation between starch chains (Hoseney 1994). Bultosa et al (2002) reported small cultivar differences in CPV of tef starches. These authors showed that the CPV of tef starches was considerably lower than that of maize starch. For sorghum cultivars differing in polyphenol content, Beta et al (2000a) reported lower starch CPV than for maize starch. CPV can vary with botanical source of the starches, amylose content and formation of amylose-lipid complexes (Whistler and BeMiller 1999). The wide range of reported values appears to indicate a genetic basis for CPV.

Setback, the increase in paste viscosity on cooling is generally due to the reassociation of solubilized starch polymers and insoluble granular fragments during the cooling phase of pasting (Thomas and Atwell 1999). Setback is used in different ways by different authors to mean either (CPV – PV) or (CPV – hot paste viscosity), the latter sometimes being referred to as total setback (Dengate 1984). In any case, setback values are indicative of the retrogradation tendency of starch (Abd Karim et al 2000) and high setback values are associated with more syneresis (Newport Scientific 1995). Syneresis, a process that excludes water from the gel phase (weeping), is a consequence of the continuous reassociation and eventual recrystallization or retrogradation of gelatinized starch polymers during cooling and storing (Whistler and Daniel 1985, Thomas and Atwell

1999). According to Bultosa et al (2002), the setback viscosity of tef starches was low compared to maize starch. These authors reported cultivar differences for setback viscosities of tef starches. The setback values for maize and sorghum starch pastes were found to be similar (Beta et al 2000a). These authors also reported a low setback value for starch from tannin sorghum.

With regard to the effect of setback on food quality, high setback viscosity of sorghum starch and flour was associated with acceptable thick porridge making quality and a low setback viscosity with acceptable *roti* making quality (Rooney and Murty 1982). This finding indicates the potential of setback viscosity to be used as selection index for food quality in sorghum breeding. Moreover, a genetic basis for differences in setback viscosity among sorghum cultivars was suggested by Taylor et al (1997), which is advantageous for screening sorghum cultivars for this trait.

Starch retrogradation

Starch retrogradation is a process, which occurs when the molecules comprising gelatinized starch begin to reassociate in an ordered structure (Atwell et al 1988). Retrogradation of starch involves two separate processes, one involving the amylose solubilized during gelatinization and the other involving amylopectin within the gelatinized granule (Miles et al 1985). The rate of retrogradation depends on the molecular ratio of amylose to amylopectin and fine structure of the amylose and amylopectin molecules (Whistler and BeMiller 1999). High molecular weight polymers contribute to more solubilization (Jackson et al 1989) and retrogradation of starch (Cagampang and Kirleis 1985). Other factors such as botanical source of the starch, temperature and starch concentration are important determinants of retrogradation (Orford et al 1987, Whistler and BeMiller 1999). Amylose retrogrades quickly and is responsible for textural changes occurring in starch gels during the first few hours of cold storage (Morris 1990), which results from a phase separation into polymer-rich and polymer-deficient phases (Miles et al 1985). In the process of retrogradation, a gradual exudation of water (starch syneresis) from the gel also takes place (Gudmundsson 1994). Morris (1990) pointed out that the aggregation of amylopectin might have an influence on the paste physical properties over longer period. An interesting feature of the crystallization involving amylopectin, as compared to that of amylose, is its reversibility on heating to 100 °C (Morris 1990). This demonstrates the possibility that amylopectin alone could be responsible for the thermally reversible component of crystallinity in the starch gel.

Many quality defects in food products, such as bread staling and loss of viscosity and precipitation in soups and sauces, are due, at least in part, to starch retrogradation (Whistler and BeMiller 1999). The retrogradation tendency of tef starch is slower than maize starch (Bultosa et al 2002). This functional property is beneficial to reduce the staling of baked products from tef, such as *injera*. *Injera* from tef is known for its slow staling property compared to *injera* from sorghum, which is probably related to tef starch's slow retrogradation tendency.

Starch gelling

A gel is a continuous, three-dimensional network of connected molecules entrapping a large volume of a continuous liquid phase (Whistler and BeMiller 1999). Starch gelation occurs with junction zone formation through hydrogen bonding (Whistler and BeMiller 1999). Gelation behavior varies among normal starches, as evidenced by differences in final gel strength (Zobel 1984). This author states that at 5% or higher concentrations, starch pastes possess a certain amount of rigidity as a result of granule swelling, the binding of solubilized molecules and the formation of physical cross-links resulting from molecular reassociation. Textural properties of a gel are indicative of how a starch will perform under various cooking applications (Wu and Corke 1999).

Gelation of amylopectin is reported to be as a result of chain entanglement, which forms a network structure (Whistler and BeMiller 1999). Jane and Chen (1992) reported that amylopectin with long branched chain and amylose of intermediate molecular sizes produce the greatest synergistic effect on viscosity. Gel strength or rigidity of a gel results from the applied stress being stored in the paste, rather than being dissipated. Such a paste is said to be viscoelastic (Zobel 1984). Generally, gel softness is associated with release of water (starch syneresis) during storage (Wu and Corke 1999). In sorghum, gel spread was negatively associated with vitreousness and particle size index of the flour

(Murty et al 1982a), indicating that a gel from vitreous endosperm is stiffer, as was confirmed by Cagampang et al (1982). According to Beta and Corke (2001) starch gel hardness in sorghum is affected by genetic and environmental factors. Similarly, cultivar differences for tef starch gel texture were reported by Bultosa et al (2002). These authors found that the gel texture of tef starch is short and is generally firmer than maize starch.

2.3.2. Protein

The protein content of sorghum generally ranges from 7 to 14% (Taylor et al 1984b), while tef contains less protein, between 6 to 10% (Lester and Bekele 1981). Protein content is influenced by cultivar and the environment, with considerable environmental variation (House et al 1995). Seed proteins, in general, are composed of three groups, namely storage proteins, structural proteins and biologically active proteins (enzymes) (Fukushima 1991). The storage proteins have been described as a sink for surplus nitrogenous compounds required for physiological processes (Tsai et al 1978). The protein compositions of the vitreous and floury portion of the endosperm are reported to be different. Watterson et al (1993) found that the vitreous endosperm of sorghum contains 1.5-2 times more total protein than the floury endosperm. The sorghum germ contains about 16% of the grain nitrogen, most of which occurs as low molecular weight nitrogen and albumin and globulin proteins (Taylor and Schűssler 1986). Albumins and globulins are richer in most of the essential amino acids than other sorghum protein fractions (Youssef 1998).

The protein bodies of the sorghum starchy endosperm are primarily prolamins, whereas the matrix protein around the protein bodies is primarily glutelin (Taylor et al 1984a). The prolamins, which are storage proteins, are given different names in different cereals, e.g. gliadin of wheat, hordein of barley, secalin of rye, zein of maize, pennesetin of pearl millet and kafirin of sorghum (Hulse et al 1980). Kafirins make up about 80% of the total starchy endosperm protein (Taylor et al 1984a). Kafirin may be classified into three main classes: α-kafirins, β-kafirins and γ-kafirins (Shull et al 1991). These authors stated that these kafirin classes are analogous to the α-, β- and γ-zeins of maize. The major prolamins of tef have also been characterized and found similar to the α-prolamins of maize, sorghum and *coix* (Tatham et al 1996).

The digestibility of sorghum protein unusually decreases somewhat on simple cooking in water (Eggum et al 1983, Mitaru et al 1985). Processing can improve sorghum protein digestibility. Extruded decorticated sorghum protein was 81% digestible (MacLean et al 1983) and fermented sorghum protein was 79% digestible (Graham et al 1986). Natural fermentation of African porridge improved the protein digestibility of cooked sorghum (Taylor and Taylor 2002). As *injera* is a fermented food, the fermentation process could enhance its protein and energy digestibility. However, if *injera* is made from tannin sorghum digestibility could be much reduced as the tannins in tannin sorghum are well known to interact with sorghum proteins and digestive enzymes (Duodu et al 2003).

Through screening many sorghum cultivars over several years, two sorghum lines (P851171 and P850029) with substantially higher protein digestibility than normal sorghums, both in the cooked and uncooked form, have been found by Hamaker and Axtell (1997). These lines were found in the high lysine populations developed by Axtell and co-workers at Purdue University (Hamaker and Axtell 1997). Thus, screening of sorghum lines for protein digestibility could possibly alleviate the adverse effect of wet cooking. However, invariably, sorghum cultivars that have high digestibility according to *in vitro* tests also have a soft, floury endosperm that can adversely affect processing characteristics (Rooney et al 1997).

2.3.2.1. Lysine

Generally, a protein may be considered of good nutritional value if it is a good source of essential amino acids. Lysine is the limiting essential amino acid in most cereals including sorghum and tef. However, a naturally occurring Ethiopian mutant sorghum has a lysine content of 3.1 g/100 g protein and a high total crude protein content of 15-17% (Axtell et al 1974), and consequently sustained better rat growth (Protein Efficiency Ratio) than normal sorghum (Serna-Saldivar et al 1994). As mentioned, the germs of both sorghum and tef occupy a relatively large proportion of the kernel. The proteins of the germ and pericarp of sorghum are 3-4 times richer in lysine than the endosperm (Taylor and Schüssler 1986). Unfortunately, in sorghum, the germ is largely removed during decortication, resulting in a product with reduced lysine content. This is of particular importance for infant feeding on sorghum as infants have a higher essential amino acid requirement (Serna-Saldivar and Rooney 1995). In the case of tef, the whole grain is milled and utilized, producing a more lysine-rich flour (Parker et al 1989).

2.3.3. Lipids

The lipids of sorghum, like those of other cereals, are located mainly in the germ, although there are smaller amounts present in the endosperm (Taylor and Belton 2002). Lipids are mainly stored in spherosomes, lipid-containing organelles, in the germ and aleurone (Morrison 1988). The oil in the germ of cereals is rich in polyunsaturated fatty acids (FAO 1995) with a large number of chemical classes and a much larger number of individual compounds (Hoseney 1994). Fatty acid profiles of sorghum grain lipids revealed that the major acids are palmitic (C16:0) (15.1-24.8%), oleic (C18:1) (29.9-41.8%) and linoleic (C18:2) (35.9-51.3%) (Maestri et al 1996), indicating a high level of unsaturation. The total lipid content of sorghum ranges from 0.5 to 5.2%, but normally in the higher range (Serna-Saldivar and Rooney 1995), while that of tef is in the range of 2.0-3.1 % (National Research Council 1996), which is strange as the germ of tef is also relatively large. For maize, Hoseney (1994) attributed the difference in lipid content between cultivars to differences in germ size and amount of oil in the germ. This might also apply to sorghum. The proportionally large germ in sorghum results in a high fat content flour when sorghum is milled without decortication. The fat component of whole sorghum flour may also cause rancidity due to oxidation of unsaturated fatty acids. This becomes more important, for example when, as is traditionally the case, households keep enough flour for a few weeks at ambient temperature. In relation to the pasting properties of starches, lipids are reported to cause a higher pasting temperature and a lower starch paste viscosity (Fortuna et al 2000). Free fatty acids, however, increase starch paste viscosity (Nelles et al 2000).

2.3.4. Non-starch polysaccharides

Non-starch polysaccharides of cereal grains generally consist of the cell wall components: cellulose arabinoxylans and β-glucans (Fincher and Stone 1986). Sorghum grain contains about 7.9% non-starch polysaccharides, of which about 4.1% are pentosans (Serna-Saldivar and Rooney 1995), mainly arabinoxylans. The arabinoxylans in sorghum are highly substituted (arabinose:xylose = 0.9:1) and contain uronic acids, acetyl and feruloyl substituents (Verbruggen et al 1993). Arabinoxylans can have the capacity to retain water. Flat breads made of doughs containing high levels of arabinoxylans consequently have better palatability and pliability (Nandini and Salimath 2001). The β-glucans of sorghum account for only about 0.06% of the endosperm weight (Serna-Saldivar and Rooney 1995), which is very low, compared to cereals such as barley. The arabinoxylan in the cell walls of the so-called coarse cereals (maize, sorghum and millets) is much less hydrophilic and does not result in the viscous, slimy mixtures that are common with rye and oats (Hoseney 1994). According to Nandini and Salimath (2001), *roti* (*chapatti*) made from sorghum flour are crispier than *chapatti* made from wheat flour. These authors attributed this difference to the highly branched nature of sorghum arabinoxylans, which form an inflexible matrix. Lack of arabinoxylan functionality in sorghum appears to negatively influence its dough rheology. The type and composition of non-starch polysaccharides present in tef is not documented. Knowledge about the non-starch polysaccharides of tef might help explain the textural differences between *injera* from sorghum and tef.

2.3.5. Tannins

Some sorghum cultivars contain polymeric phenolic compounds known as condensed tannins. These are secondary plant metabolites (Hahn et al 1984). Condensed tannins have been recognized as one of the mechanisms by which ripening sorghum grain is protected from bird damage (Bullard and York 1996). Although the term condensed tannins is still widely used to describe these flavonoid-based polyphenolics, the chemically more descriptive term "procyanidins" is gaining acceptance (Hagerman 2002). The monomers of the best characterized condensed tannins are known to be linked via a carbon-carbon bond between the C8 of the terminal unit and the C4 of the extender

(Hagerman 2002) (Fig 2.6). The presence of condensed tannins in some sorghum cultivars has important nutritional and processing implications in foods and feeds.

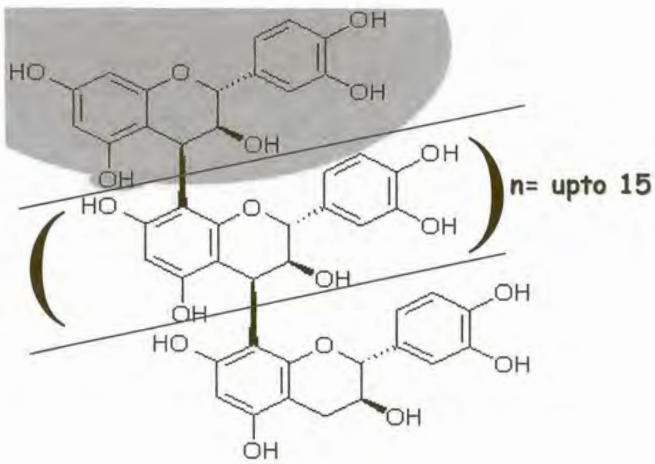

Figure 2.6. Structure of sorghum procyanidin (adapted from Hagerman 2002). The shaded area indicates the structure of a monomer.

Tannins are believed to have an inhibitory effect on enzymes, for example during malting, by forming protein-tannin complexes (Daiber 1975). Tannins are also known to cause dark color and astringent bitterness in foods prepared from whole tannin sorghum (Bacon and Rhodes 2000). Yetneberk and Haile (1992) reported that *injera* prepared from whole sorghum with a pigmented testa had a brownish color, astringent taste and was unacceptable to consumers. The latter are due in part to the fact that the proline-rich protein in saliva associates with the tannins (Lu and Bennick 1998). Protein binding causes antinutritional effects through inhibition of the digestion and assimilation processes (Butler 1989) and formation of indigestible protein-tannin complexes (Chibber et al 1980). Electrophoretic analysis indicated that the indigestible residue of tannin sorghum consisted mainly of prolamins (Butler et al 1984), indicating the binding power of tannins with prolamins. Kafirin binding of tannins has recently been confirmed (Emmambux and Taylor 2003). Tannins have also been associated with some anti-microbial (Ebi et al 1999) and enzyme-inhibitory activity (Scalbert 1991). This probably also accounts for the poor quality of *injera* made from tannin sorghum, resulting from inhibition of the fermenting microorganisms in the dough.

Traditionally the negative effects of tannins have been reduced by treating with wood ash (alkali) and by malting (Mukuru 1990). Decortication is also known to improve tannin sorghum biological value substantially (Reichert et al 1988, House et al 1995) by removal of the tannin or testa layer. To improve the quality of *injera* from tannin sorghum, Yetneberk and Haile (1992) decorticated the grain. However, cultivars with high tannin contents require considerably longer decortication times to reduce the tannin content substantially (Mwasaru et al 1988).

A further problem is that tannin sorghums generally tend to be soft, resulting in low extraction rate (Chibber et al 1978). Nevertheless, Beta et al (2000b) obtained a marked reduction (71-81%) in tannin content with abrasive decortication of Zimbabwean tannin sorghums. Treatment of tannin sorghums with dilute alkali or formaldehyde prior to roller milling also substantially reduced the quantity of tannins (Beta et al 2000b). Household processing through natural fermentation of tef flour dough was reported to reduce the tannin content by about 55%, presumably through the action of polyphenol oxidase generated during fermentation (Urga et al 1997). However, if tef does not contain tannins this cannot be so. Hassan and El Tinay (1995) reported 63.1% and 61.4% tannin reduction from two tannin Sudanese sorghums after 14 hr of fermentation. This was probably due to tannin-protein interaction.

2.6. Decortication and milling

To make *injera*, the cereal grain must be milled into flour. The term "milling" can refer to both decortication of the grain and reduction of the grain into flour (Anglani 1998). Decortication followed by size reduction is the most common industrial sorghum milling process. Sorghum industrial milling technology is still evolving, unlike the situation with wheat, rice and maize where specialized milling technologies have been developed. The decortication principle applied to rice and barley dehullers, decorticators and polishers is widely applied in sorghum milling (Hulse et al 1980, Reichert et al 1982). For sorghum, the primary objective of decortication is to remove the pericarp and associated pigments and tannins (if present) and the germ. As stated, an important milling difference between sorghum and tef is that sorghum is decorticated prior to size reduction, while tef is not, owing to the small size of tef grain.

Hand pounding was generally the process of traditional sorghum milling. It is a manual operation using wooden mortar and a pestle and is aided by addition of water to the grain. Pounding provides impact and abrasion actions to remove the bran layers from the endosperm (Reichert et al 1982). Thickness of the pericarp is important in traditional milling, since there is an inverse relationship of pericarp thickness with the time required for mortar and pestle decortication (Scheuring et al 1983). Considerable effort is required to decorticate sorghum kernels with thin pericarps by pounding. This is because the detachment point of the sorghum pericarp is in the starch-containing mesocarp (DeFrancisco et al 1982). Sorghum with a thin, tightly packed pericarp has practically no mesocarp (Rooney and Miller 1982, Scheuring et al 1983).

Mechanical decortication operates on the principle of progressively rubbing off the outer layers of the dry kernel (Oomah et al 1981). The type of abrasive surface used significantly affects the dehulling rate, efficiency and reproducibility (Reichert et al 1982). According to Schmidt (1992) the most widely used decortication machine for removal of bran from sorghum grain is the PRL (Prairie Research Laboratory) dehuller. Its simplicity and robustness are the two characteristics that make it ideal for use in developing countries (Taylor and Dewar 2001). However, by the virtue of its abrasive decortication action, not all the germ is removed and the endosperm meal has high fat content, between 2 and 4 % (Gomez 1993). The PRL sorghum dehuller was under test in Ethiopia in the early 1980s and was found to be very effective and efficient (Gebrekidan and GebreHiwot 1982). Sorghum decortication is not commercialized in Ethiopia and there appears to be growing interest for such ventures, if value-added sorghum products can be promoted.

Decortication generally starts with breakage in the mechanically weak mesocarp and loosening of the pericarp exterior to that tissue (Shepherd, 1981). Genotypic differences for sorghum milling yield were reported by (Setimela and Andrews 2002). In relation to sorghum grain size, an increase in milling yield with smaller grains was reported by Wills and Ali (1983). With respect to endosperm texture, Lawton and Faubion (1989) observed that sorghums with softer endosperm had higher rates of loss than did harder sorghums, because, soft floury grains disintegrate during decortication and cannot be milled efficiently (Rooney et al 1997). Structurally, sorghum grain hardness is related to the distribution density of protein bodies and matrix in the endosperm (Shull et al 1990). Good milling cultivars retain their integrity and allow the pericarp to be removed to produce high yields of decorticated kernels (Rooney et al 1997). Milling properties of sorghum grains can be improved by breeding and selection (Anglani 1998). However, good milling quality may not be compatible with good or desired agronomic properties of sorghum (Scheuring et al 1983). With respect to *injera* quality, decortication of sorghum improves the color and other quality attributes of *injera* (Gebrekidan and GebreHiot 1982, Yetneberk and Adnew 1985, Subramanian and Jambunathan 1990, Yetneberk and Haile 1992).

Finer sorghum flour makes a more cohesive dough during mixing (Murty and Kumar 1995). This might be important to form a more cohesive continuous matrix during the baking of the *injera*. A milling technology that can produce a finer and more refined flour is important to improve the quality specifically color and texture of *injera* from sorghum. In South Africa, small roller mills with two or three pairs of rollers, plus a vibrating sieving device have been developed (Taylor and Dewar 2001). The mills comprise top pair of rollers which are coarse fluted "break" rolls, the second pair are finer break rolls and a third pair (if present) are smooth "reduction" rolls. Working with sorghum of a wide range of hardness, Gomez (1993) reported that, with preconditioning, milling with a roller mill can produce sorghum meal with higher extraction and slightly lower ash and fat content compared to decortication followed by hammer milling. Thus, such small-scale roller mills, which simultaneously remove the bran fraction and reduce particle size are applicable to developing countries like Ethiopia, where large-scale industrial sorghum roller milling is not yet practiced.

2.7. Fermentation

Sorghum flours are used for production of naturally fermented traditional flat or semi-leavened breads such as *kisra* of the Sudan (Ejeta, 1982), *kisar* of Chad (Murty and Kumar 1995), *injera* of Ethiopia (Gebrekidan and GebreHiwot 1982) and *dosa* of India (Rooney et al 1986) and in Sri Lanka known as *thosai* (Murty and Kumar 1995). *Kisra*, a thin pancake baked from fermented batter like *injera*, differs from *injera* in that it is soft and moist but not spongy and porous on the top surface. *Dosa* is usually made from a mixture of rice and black gram flour, but sorghum is used instead of rice in some areas (Rooney et al 1986).

Fermentation to produce foods such as *injera* involves the controlled souring by naturally occurring lactic acid bacteria (Chavan and Kadam 1989). Like many other traditional fermented foods, the fermentation in *injera* making is originally spontaneous and dependant upon the load and flora of microorganisms naturally present in the flour, mixing water and air borne contaminants. However, households are generally able to carry out consistently successful fermentations through practising a system of back-slopping, whereby a portion of liquid from a successful fermentation is used to inoculate freshly prepared dough of sorghum flour. Over a number of such cycles, rapidly fermenting lactic acid bacteria with a high acid tolerance are probably selected, as reported by Mosala and Taylor (1996) for *ting* a lactic acid fermented firm sorghum porridge. Nout et al (1989) showed that by back-slopping each day, the normally slow fermentation process (2-3 days) was accelerated by enrichment with acid producing strains of lactic acid bacteria. This simple method of carrying out predictable lactic acid fermentation is also practiced in Ethiopian households for *injera* production. Due to destruction and reduction of antinutrients such as phytic acid and tannins during fermentation, the bioavailability of micronutrients in fermented foods is higher than those of unfermented foods (Urga et al 1997). Fermentation also improves *in vitro* carbohydrate availability (Kazanas and Fields 1981), starch digestibility (Hassan and El Tinay 1995) and protein digestibility (Taylor and Taylor 2002). Additionally, the low pH generated protects fermented foods against the growth of pathogenic microorganisms (Svanberg et al 1992).

The fermentation of tef dough for *injera* making involves several groups of microorganisms, viz: Gram-negative rods, lactic acid bacteria and yeasts, growing in succession (Gashe et al 1982). The dominating yeast flora at the peak of the fermentation consist of Torulopsis and Saccharomyces species (Gifawesen and Bisrat 1982). An amylase-producing bacteria (Bacillus sp. A-001) has been isolated from fermenting tef dough (Lealem and Gashe 1994), which might be involved in the breakdown of the starch in the dough. Lealem and Gashe (1994) reported that about 9% of the tef dough starch was utilized after fermenting the dough for 72 hr. In tef *injera* fermentation there was a reduction in the pH of the dough from about pH 5.8 to pH 3.8 (Umeta and Faulks 1989). These authors observed that lactic acid and acetic acid were the major organic acids produced during dough fermentation. The carbon dioxide produced during fermentation plays a fundamental role in the formation of the cellular structure of leavened breads (Bloksma 1990), including is *injera*.

2.8. Dough making and baking

The flour of wheat when mixed with water forms a cohesive, viscoelastic dough (Hoseney 1994). During mixing, the soluble components of the flour dissolve and the insoluble components hydrate. Hoseney (1994) further pointed out that an important factor during mixing to form a leavened dough is the incorporation of air into the dough. 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 (Kharkar and Schofield 1977). Such proteins are not present in sorghum (Taylor et al 1984a). Sorghum dough, unlike wheat dough, is poorly cohesive and not elastic. Consequently it does not produce high specific volume bread. In the production of wheatless sorghum bread there are two possibilities of creating cohesive dough: adding water binding substances such as gums as gluten substitutes to improve dough cohesiveness, and modification to the bread making procedure through pregelatinizing some of the starch, as in the "custard process", to make the dough more viscous so that it will hold gas during fermentation (Taylor and Dewar 2001).

Similarly the cake mix industry often uses extra-moist cake formulas, where pregelatinized starch softens the cake crumb and retains moisture in the baked product (Moore et al 1984). A similar effect is achieved with the traditional *injera* making procedure. By cooking part of the fermented dough to gelatinize the starch, the carbon dioxide produced by the fermentation is trapped and leavens the *injera* on baking. Hence, starch and flour properties probably play a major role in *injera* quality. Starch is an ingredient that can affect the texture, body and appearance of a product (Thomas and Atwell 1999). On baking *injera*, the batter with partially gelatinized starch is poured on a very hot clay griddle and cooked covered. This generates steam essential for cooking *injera*, completely gelatinizes most of the starch within the batter. The starch granules fuse into a continuous amorphous matrix in which bubbles of gas are trapped (Parker et al 1989). These authors report that the protein bodies play no role in the formation of the matrix-gas bubble interface.

2.9. Staling

Staling is a common problem to almost all baked products and it commences as soon as baking is complete and cooling begins (Thomas and Atwell 1999). Staling of baked products is due, at least in part, to the gradual transition of amorphous starch, formed on baking, to a partially crystalline, retrograded state (Whistler and BeMiller 1999). Unlike *injera* from tef, an important problem with *injera* from sorghum is that it firms rapidly and becomes friable in texture upon storage (Gebrekidan and GebreHiwot 1982). The change in starch crystalline structure during post-baking storage is known to lead to rigidity of crumb, as reported by Lineback and Rasper (1988) with regard to wheat bread. Martin and Hoseney (1991) suggested that bread firming is also a result of cross-links between starch granule remnants and protein fibrils. It has been found that compositing sorghum flour with tef flour improves stored *injera* texture compared to 100% sorghum flour (Gebrekidan and GebreHiwot 1982). However, the tef flour components responsible for retarding the staling of *injera* are not known.

Alternatively, the addition of emulsifiers (surfactants), known to improve the bread making of sorghum and wheat composite breads (Bushuk and Hulse 1974), might be applicable in sorghum *injera*. Emulsifiers are lipid substances, possessing both lipophilic and hydrophilic properties, with the ability to reduce the surface tension between two normally immiscible phases (Stampfli and Nersten 1995). In wheat flour dough, surfactants act as dough strengtheners, helping the dough withstand mechanical abuse during processing, and as anti-staling agents, i.e. reducing the degree of starch retrogradation (Hoseney 1994). Other properties include improved crumb structure, finer and closer grain, increased uniformity in cell size (Stampfli and Nersten 1995). Emulsifiers are known to improve the tearing quality of pita bread (Farvili et al 1995). The emulsifiers used in the bread making industry include calcium stearoyl lactylate (CSL), sodium stearoyl lactylate (SSL) and glycerol monostearate (GMS) (Stampfli and Nersten 1995).

2.10. Standardized *injera* making procedures

The traditional method of *injera* preparation varies from household to household and from region to region. However, in general *injera* preparation involves two fermentation stages. The first takes 24-48 hr (depending on the sourness desired) from mixing the flour with water and adding the back-slopped culture. Then a portion of the fermented dough is cooked and added back to the fermented dough to initiate the second fermentation. The mixture is brought to a batter consistency and allowed to ferment for about 2-3 hr. After gas bubbles have formed and subsided the batter is poured on a hot clay griddle and baked covered. By cooking part of the dough to gelatinize the starch, the carbon dioxide produced by the fermentation is trapped and leavens the *injera* on baking.

Various researchers have developed different standardized laboratory procedures in order to evaluate sorghum cultivars for *injera* making quality. The approach taken by Gebrekidan and GebreHiwot (1982) involved the use of dry flour to initiate the second stage fermentation. Gelatinization of the starch was performed by adding boiling water to the flour and mixing it with a wooden spoon, as opposed to adding a portion of the fermented dough in boiling water and cooking with continuous stirring, which is the normal practice. Further, the time and temperature employed does not seem to be sufficient to allow the starch to completely hydrate, fully swell and solubilize, because the gelatinizatoin temperature range of sorghum starch is high (68-78 °C) (Hoseney 1994). Also, an objective of cooking part of the dough is to increase the amount of gluey material between the dough particles to form more cohesive starch matrix in the *injera* (Umeta and Parker 1996). For a similar application, the use of gelatinized cassava starch to increase gas cell wall strength in sorghum wheatless bread was reported by Satin (1988). Addition of pregelatinized starch to sorghum flour also increases water absorption capacity and the rolling quality of dough and eating quality of *roti* (Desikachar and Chandrashekar 1982). This is as a result of gelatinization, starch becomes a flexible material (Kent and Evers 1994).

A different approach was taken by Yetneberk and Adnew (1985). Their procedure involved: milling decorticated sorghum to flour, preparation of a dough (kneading for about 5 min) and then fermentation of the dough for about 48 hr after adding starter culture (5% flour weight basis). After the first stage fermentation, about 25% of the fermented dough was thinned with 30 mL water and cooked in 200 mL boiling water for 1 min. The gelatinized batter was cooled to about 45 °C at room temperature and added back to the fermenting dough. After thorough mixing, 100 mL of water was added and the batter was fermented at room temperature for 2-3 hr. At this stage of fermentation, considerable gas evolution takes place. To make the *injera*, 500 g of the fermented batter was poured in a circular manner onto a 50 cm diameter hot clay griddle (called a *mitad*), covered and then baked for about 2 min. This procedure is in use to evaluate sorghum cultivars in the Ethiopian Sorghum Improvement Program (ESIP).

The merit of the latter standard procedure is that complete starch gelatinization is achieved, as a result of direct cooking of a portion of the dough. Gelatinization time, temperature of gelatinized dough at the time of mixing and the time to bake the *injera* are controlled, leading to greater consistency, which probably helps to reveal differences between sorghum cultivars. However, variation in ambient temperature will affect microbial growth, fermentation rate, rate and amount of lactic acid and carbon dioxide gas production, and the viscosity of the batter. Fermenting in a thermostatically controlled chamber such as water bath or an incubator would control these better and remains as recommendation.

Other drawbacks associated with both methods include the fact that during baking the batter is manually poured and spread on the *mitad*. Thus, the thickness of the *injera* depends on the consistency of the operator. The electrically heated *mitad* used for baking is not thermostatically controlled. Hence, the time which elapses between applications of batter on the hot clay griddle needs to be kept as constant as possible to limit variations in batter cooking temperature, which might cause differences in the *injera* texture. This in turn might contribute to variation in *injera* quality not attributable to sorghum cultivar.

2.11. Sensory evaluation

The best way of determining the quality of a food product is through sensory analysis. In sensory analysis, human beings are used as they have both critical faculties and emotion (Jellinek 1985). However, a limitation to the use of untrained sensory judges is that they do not have a common language with which to communicate sensations and an agreed system of categorization (Ishii and O'Mahony 1991). For example, a reddish-orange colour could be categorized as 'red' by one judge and 'orange' by another. Similarly, the sensory concept of sourness for one judge could not exactly aligned with that of the other judge. This is analogous to using a set of instruments that are not calibrated in the same way (Ishii and O'Mahony 1991).

Generally, two main groups of methods of sensory evaluation are identified: 1) Analytical or objective methods (difference, ranking and quality tests), and 2) Hedonic or subjective methods (preference, consumer and market tests) (Jellinek 1985). For analytical methods, a trained panel is required and the panel members have to act like an analytical instrument. For the hedonic methods, a large number of untrained persons have to be used and their evaluation should come spontaneously, based on emotion (Jellinek 1985).

In sorghum cultivar evaluation for *injera* making quality, Gebrekidan and GebreHiwot (1982) used a trained panel of only 5 people and evaluated *injera* attributes in terms of appearance, texture and taste. Other researchers, Yetneberk and Adnew (1985) and Yetneberk and Haile (1992) used a semi-trained panel of 6 people who were also *injera* consumers for the purpose of sorghum cultivar evaluation for *injera* making quality.

Zegeye (1997) used a consumer panel to assess consumer acceptance of *injera* from tef sorghum, maize and barley with Ethiopian traditional chicken stew. The types of tests he conducted were difference and preference tests with 75 and 102 panelists, respectively. The method he employed for the difference test was the triangle test and the hedonic scale for rating the degree of like or dislike. The objective of this work was to assess the taste reaction of a traditionally tef consuming community when sorghum, maize and barley are used for *injera* making. This author concluded that sorghum can be the most promising tef substitute for *injera* making and suggested selection of good *injera* making sorghum cultivars and development of proper processing technologies.

The use of descriptive sensory evaluation techniques to produce objective descriptions and evaluation of *injera* in terms of perceived sensory attributes remains as a gap in application. Descriptive analysis is a sensory method by which the attributes of a food product are identified and quantified using human subjects who have been specifically trained for this purpose (Stone and Sidel 1985, Lawless and Heymann 1999). It is a flexible and useful sensory method, providing detailed information on all of a products' sensory properties (Murray et al 2001). The data are easily analyzed statistically and can be represented in graph form. Descriptive techniques can be used when there is a need to define sensory-instrumental relationships (Lawless and Heymann 1999).

2.12. Sorghum grain characteristics as related to flat bread quality

Sorghum improvement programs in the sorghum growing countries of the world have generated a range of segregating materials by crossing between lines possessing good agronomic characters, disease and pest resistance. However, there is often no clear-cut direction to assist sorghum breeders to select for grain quality for a particular end-use. Researchers have taken different approaches to generate relationships between sorghum grain characteristics and quality attribute of food products. Those related to flat breads from sorghum will be discussed, as they are relevant to *injera*.

Concerning *injera*, in collaborative research between the International Crops Research Institute for the Semi Arid Tropics (ICRISAT) and Ethiopia, Subramanian and Jambunthan (1990) evaluated the grain characteristics of 16 sorghum cultivars grown at ICRISAT in Patancheru, India. The standard *injera* making procedure developed by Yetneberk and Adnew (1985) was used for *injera* making. A panel of 6 people evaluated *injera,* as stated above. Attributes considered were: top and bottom surface color of *injera*, description of the eyes (honeycomb structure), texture, taste, aftertaste and overall rating. Sorghum physico-chemical properties and sensory attributes of *injera* were correlated. Texture of *injera* was positively correlated with flour paste total setback ($r = 0.62$, $p < 0.05$), and *injera* eye quality was positively correlated with starch content ($r = 0.70$, $p < 0.01$) and negatively with protein content ($r = -0.63$, $p < 0.05$). Subramanian and Jambunthan (1990) pointed out the need for detailed work on starch and protein quality of sorghum grain to understand more about these relationships.

With regard to sorghum *roti*, this product should be smooth, soft, and slightly sweet with a characteristic sorghum aroma (Murty et al 1979). Murty and Subramanian (1982) studied 15 sorghum cultivars for *roti* making quality. Parameters measured were: endosperm texture and water absorption of the grain, color (grain, dough and *roti*), kneading quality and rolling quality of the dough and *roti* sensory quality. A trained panel of 5 people evaluated the *roti* for taste, texture, aroma and keeping quality. Taste (1 = good, 5 = very bad), texture (1 = very soft, 5 = very hard), aroma (1 = pleasant, 3 = unpleasant) and keeping quality (1 = good, 5 = very bad). Note the mixture of hedonic and non-hedonic terms. The scores obtained from the panelists were used for the evaluation of sorghum cultivars. The authors suggested basic studies of *roti* dough properties were required for rapid screening in sorghum breeding.

Using the method described by Murty and Subramanian (1982), Murty et al (1982b) evaluated *roti* quality of 422 sorghum genotypes of differing pericarp color and endosperm texture. These authors suggested that good *roti* producing sorghum types should possess a colorless thin pericarp, 60-70% corneous (vitreous) endosperm, a flour particle size index (PSI) value around 65, and less than 24% water absorption. White grains with 100% corneous endosperm produced *rotis* with relatively hard texture and less desirable keeping quality, while floury grain produced a poor dough and *rotis* with poor flavor and keeping quality. These authors reported that although the measured physical parameters were statistically significant, none of the characters was correlated strongly enough with *roti* quality to be used for indirect selection criteria. This could in part be attributed to the problem of the sensory techniques employed. As described, a trained panel cannot be used for hedonic methods and untrained consumer panel for analytical methods.

Subramaninan and Jambunathan (1982), evaluated 45 sorghum genotypes for *roti* quality. They evaluated the samples for physical properties (grain hardness, flour swelling capacity, solute content of the water extract of the flour) and chemical characteristics (protein, water soluble protein, amino acid, starch, amylose, fat, ash and total sugars) and gel filtration chromatography of the soluble protein. Relationships between *roti* quality and certain physico-chemical characteristics were obtained. They concluded that the quantity of water soluble protein, amylose and sugars jointly influenced *roti* quality. These findings indicate the importance of studying all aspects of the grain and flour in order to obtain useful selection criteria.

Tortilla, an unfermented flat bread usually prepared from alkali-cooked, steeped maize, is a staple in Mexico and Central America (Rooney et al 1986). Sorghum is used alone or in combination with maize for tortillas in some areas of Honduras (Futrell et al 1982). A good sorghum *tortilla* should be light in color with a less grainy texture. Iruegas, et al (1982) evaluated sorghum lines for their processing and *tortilla* quality. The selection strategy they used was in two phases. The first phase was a predictive test, designed as simple routine test to evaluate large number of different genotypes from small samples. A 10 g sample of each individual plant selection was evaluated for tannins, phenol content and alkali-cooked to select for acceptable *tortilla* color. Selected genotypes were further tested for visual kernel vitreousness. Vitreousness is important during alkali-cooking sorghum with maize in the same batch. Genotypes with medium and high degree of vitreousness were selected.

In the second phase, the selected genotypes were tested for further physical kernel characteristics (hardness, hectoliter weight), processing (pilot cooking, lime cooking, milling and evaluation of cooking liquid and cooked kernel) and product evaluation (*tortilla* making, physical and sensorial). The authors concluded that sorghum genotypes with very low tannin and phenol contents generally produce acceptable *tortillas.*

2.13. Conclusions

With regard to sorghum grain quality evaluation, this review has revealed that identifying sorghum grain selection criteria involves a complete analysis of the grain and flour. Establishing relationships between the measured parameters and product quality attributes is equally important to identify the relevant criteria. As traditional sorghum foods are diverse, no single criterion of quality can be identified. Thus, the challenge to improve sorghum for better utilization is great. A strategy whereby breeders and food scientists can work together must carefully developed. Furthermore, if sorghum has to compete with other cereals as a source for value-added products, use of improved cultivars and improved technologies are absolutely necessary.

This review shows that information on sorghum grain characteristics and flour components in relation to *injera* quality is scanty. Therefore, the physico-chemical properties of sorghum cultivars with varying endosperm texture and their relationship to the sensory attributes of *injera* need to be addressed. This approach should lead to identification of specific grain or flour quality parameter(s) that are related to good sorghum *injera* quality, which can be used as selection criteria in the ESIP.

Concerning selection of sorghum cultivars on the basis of *injera* making quality, this review indicates that previous researchers generally made use of trained panels as consumer panels. Additionally, the attributes measured were too few and did not completely describe the product. The use of more objective methods, such as descriptive sensory and instrumental texture measurement, which more completely describe and quantify the quality attributes of the product, is desirable.

The review also shows that there has been very little research into technologies for improving sorghum *injera* making quality. Thus, the effect of decorticating sorghum grain or compositing sorghum flour with tef flour needs further investigation.