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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.

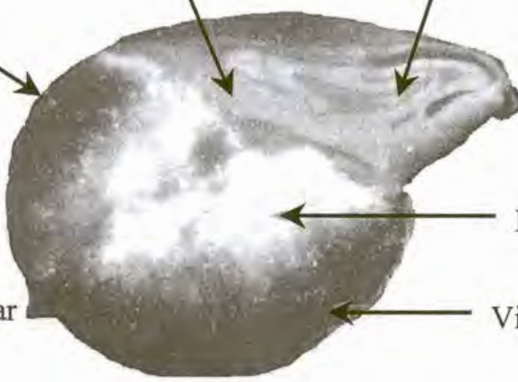

Figure 2.1. Micrograph of longitudinal section of sorghum grain (Taylor and Belton 2002).

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).

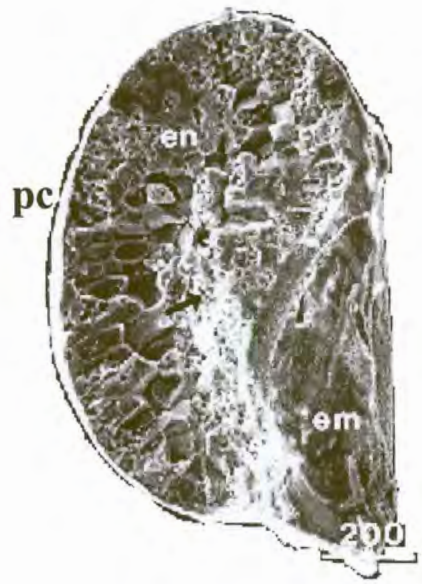

Figure 2.2. Micrograph of longitudinal section of tef grain (Parker et al 1989). Pericarp (pc), starchy endosperm (en) with outer vitreous region and floury center (arrowed) and relatively large embryo (em).

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

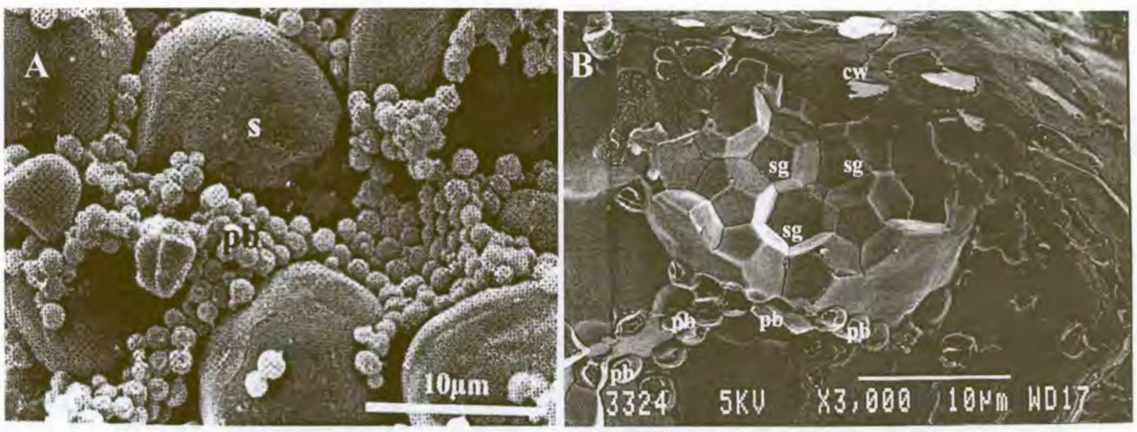

Figure 2.3. Micrographs of starch granules and protein bodies in sorghum and tef. **A**, Floury endosperm of sorghum. s = starch granule, pb = protein bodies (Duodu et al 2002). **B**, Tef compound starch granule. sg = single granule, pb = protein bodies, cw = cell wall (Bultosa et al 2002).

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).

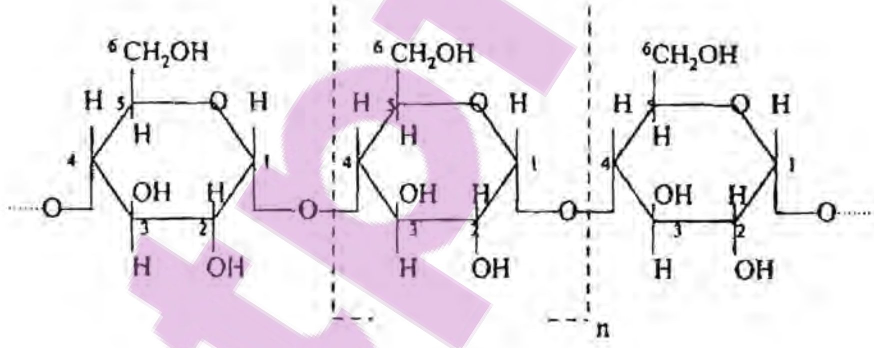

Figure 2.4. α-1,4 linkages of amylose (Thomas and Atwell 1999).

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.

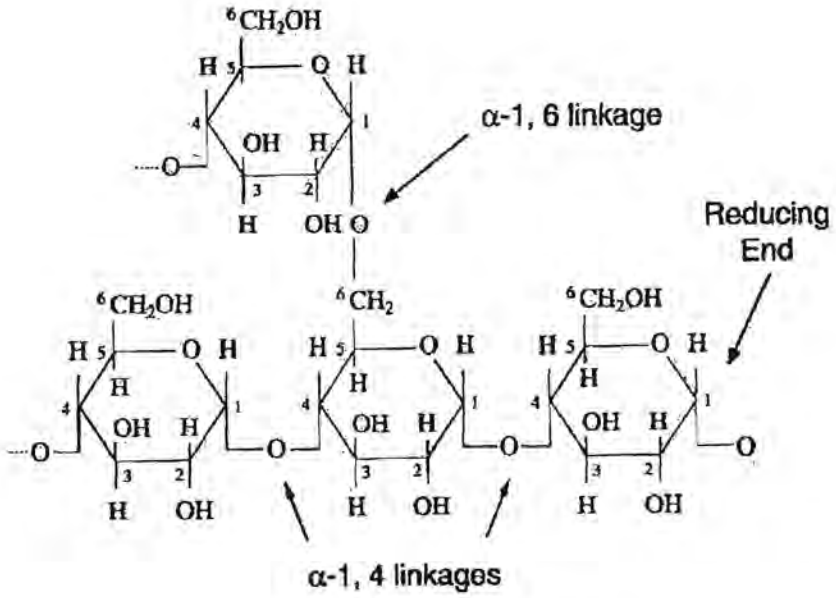

Figure 2.5. α-1,4 and α-1,6 glycosidic bonds of starch (Thomas and Atwell 1999).

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.

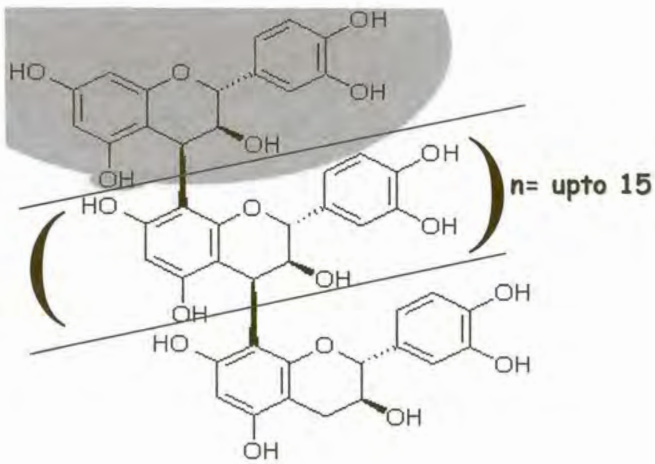

Figure 2.6. Structure of sorghum procyanidin (adapted from Hagerman 2002). The shaded area indicates the structure of a monomer.

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.

3. RESEARCH

3.1. Improving the quality of sorghum *injera* by decortication and compositing with tef

(Submitted for publication in the Journal of the Science of Food and Agriculture)

Abstract

Injera is an Ethiopian fermented leavened pancake-like bread made from cereals, with tef being preferred. Decortication and compositing with tef were evaluated as methods to improve the *injera* making quality of red tannin-free and tannin-containing sorghums. Both decortication and compositing improved sorghum *injera* quality. Concerning decortication, mechanical abrasion was found to be more effective than hand pounding because acceptable *injera* was obtained with lower milling loss. Good quality *injera* was produced at an extraction rate of 54% for tannin-containing and 83% for tannin-free sorghum. With compositing, good quality *injera* was produced with a 50:50 composite of whole tannin-containing sorghum and tef. Both processes reduced the tannin content of the flours, which appeared to relieve the inhibiting effects of tannins on the fermentation. Decortication also seemed to improve sorghum flour *injera* making quality by improving flour pasting, probably as a result of reducing the level of interfering substances such as lipids and proteins. In contrast, the improvement brought about by compositing with tef seemed to be due to inherit differences between tef and sorghum starch granules and an increase in the water solubility index of the flour. Compositing seems to be a more useful method of improving sorghum *injera* quality than decorticating as it avoids the grain loss associated with decortication.

3.1.1. Introduction

Injera, a staple food in Ethiopia, is a fermented, leavened pancake-like bread prepared from cereals such as tef and sorghum. It is characterized by having "eyes" (honeycomb-like holes) in its top surface. These are produced due to the production and escape of carbon dioxide during fermentation and baking, respectively. *Injera* prepared from flour of tef, a tiny millet-like grain, is preferred because it is soft and can be rolled. Notwithstanding this, nearly 80% of the sorghum produced in Ethiopia is used for the production of *injera* (Gebrekidan and GebreHiwot 1982). Both white and colored tannin-free sorghums are used. However, the white tannin-free sorghums are the most preferred because of the light *injera* color (Gebrekidan and GebreHiwot 1982). Tannin-containing sorghums are predominantly used for local beer production.

Since colored tannin-free and tannin-containing sorghums are lower priced than white sorghum and tef, it would be most desirable to improve their *injera*-making potential through the use of simple, practical technologies. Such technologies include decortication (often incorrectly referred to as dehulling, since the sorghum grain does not have a hull) and the use of composite flours. In fact, compositing tef flour with sorghum flour has been found to improve *injera* texture (Gebrekidan and GebreHiwot 1982, Yetneberk and Haile 1992). However, these studies were very limited in scope. The objectives of the work reported here were to evaluate grain decortication and compositing with tef flour as methods to improve the quality of *injera* made from tannin-containing sorghum and decortication for tannin-free red colored sorghum.

3.1.2. Materials and Methods

3.1.2.1. Materials

A red pericarp tannin-containing cultivar (Seredo) and a red tannin-free cultivar (IS 2284) were obtained from the Ethiopian Sorghum Improvement Program (ESIP) at Melkassa Agricultural Research Center. White tef was purchased from a local market.

3.1.2.2. Grain characterization

Thousand kernel weight (TKW) was measured by weighing 1000 randomly selected unbroken kernels. Glume color was determined by examining the inside of the glume after removing the kernel (Rooney and Miller 1982). The presence of a pigmented testa was determined by the Chlorox Bleach Test method (Waniska et al 1992) The vanillin-HCl method of Burns (1971) with sample blank subtraction was used to determine the level of condensed tannins. Pericarp thickness was determined by viewing longitudinally sectioned grains using a scanning electron microscope. Endosperm texture was viewed using a stereomicroscope and images were captured with a camera. Total endosperm and floury endosperm areas and pericarp thickness were measured using the UTHSCSA, Image Tool Software, version 2.0 (University of Texas Health Science Center, San Antonio, USA). The vitreous area was expressed as a percentage of the total endosperm area. Grain color was measured in L, a b units using a Hunter Lab Color Quest 45/0 (Hunter Associates, Reston, USA).

3.1.2.3. Decortication and milling

Decortication was performed by hand pounding and mechanical abrasion. For hand pounding, one kg of sorghum kernels was washed and placed in a wooden mortar and pounded with a wooden pestle. Samples were removed after 3, 6 and 10 min of pounding. The number of pounding strokes was recorded for each time interval. Decorticated kernels were spread on a clean cloth and dried in the sun. The bran and decorticated grains were separated by winnowing.

Mechanical abrasion was performed using a Tangential Abrasive Dehulling Device (TADD) according to Reichert et al (1982). One hundred g of sorghum grain was decorticated for 1, 2, 3, 4, and 5 min using a TADD fitted with sand paper of 60 grit (Norton type R284 metalite) (Norton Abrasives, Worcester, USA). Extraction rate in terms of percentage decorticated grain recovered was calculated for both methods. Samples were milled to flours using an Udy cyclone mill (Seedburo, Chicago, USA) fitted with a 200 μm opening screen size. Tef was not decorticated prior to milling.

3.1.2.4. Composite flours

Whole grain flour of the tannin-containing sorghum (Seredo) was composited with tef flour at five levels: 83.3%, 66.7%, 50%, 33.3% and 16.7%. 100% Seredo flour and 100% tef flour were also included.

3.1.2.5. Flour characterization

The effects of compositing sorghum flour with tef flour on flour water absorption index (WAI) and water solubility index (WSI) were determined according to Anderson et al (1969). Pasting properties of flours from the sequentially decorticated tannin-containing sorghum (Seredo) and composite flours of tef and Seredo were determined using a Rapid Visco Analyser (RVA) Model 3D (Newport Scientific, Warriewood, Australia). Flour (4 g, 14% moisture basis) was mixed with 25 ml distilled water in the RVA sample canister. A programmed heating and cooling cycle was used, where the suspension was held at 50°C for 1 min, heated at 93°C for 8 min at a rate of 6 °C/min and then held at 93°C for 5 min before cooling to 50°C within 8 min, and finally held at 50°C for 1 min. The RVA parameters measured were: peak viscosity (PV), the maximum hot paste viscosity at 93°C; hot paste viscosity (HPV), the trough at minimum hot paste viscosity; and cold paste viscosity (CPV), viscosity after cooling to 50°C and holding at this temperature.

3.1.2.6. Preparation of injera

Injera was prepared from flours of hand pounded and mechanically abraded sorghum and the composite flours of Seredo and tef using the method described in Chapter 3.2.

3.1.2.7. Sensory evaluation of injera

A semi-trained panel (a panel briefed about scoring of *injera* sensory attributes) of 6 people, who were *injera* consumers, evaluated 3 replicate samples of *injera*. The attributes used, which were generated by the author, were *injera* top and bottom surface color, description of the eyes (honeycomb structure of the top surface of the *injera*), texture, taste, aftertaste and overall rating. Rolled pieces of *injera* (3 mm wide) were presented to the panelists on a tray at ambient temperature (about 25°C) within 2 h after baking.

3.1.2.8. Statistical analysis

Analysis of variance was performed on the data to establish significant ($p < 0.05$) differences between the samples. Linear regression analysis was done to establish relationships between extraction rate and flour pasting properties.

3.1.3. Results and discussion

3.1.3.1. Grain characterization

Seredo had a lower TKW (21.5 g) compared to IS 2284 (35.9 g) (Table 3.1.1). TKW of tef was only 0.3 g. Seredo and IS 2284 had purple glume color, while tef had tan glume color. The tef grain was much lighter (L value 64.8) compared to the sorghums, Seredo (L value 36.7) and IS 2284 (L value 33.2). Seredo contained a pigmented testa and had a tannin content of 7.3% catechin equivalents, while IS 2284 and tef were tannin-free. Seredo had a much thicker and loosely packed pericarp with starch granules in the mesocarp, while IS 2284 had a thin, tightly packed pericarp with practically no mesocarp (Fig 3.1.1). Seredo had a more floury endosperm compared to IS 2284.

3.1.3.2. Decortication

Two methods of decortication were evaluated: traditional hand pounding with a pestle and mortar and mechanical abrasion (simulating industrial mechanical decortication). The objectives of decorticating the sorghum grain were to remove the bran, germ and the testa (which contained tannins in Seredo), in order to improve the color, taste and appearance of the *injera*. With hand pounding an increase in the number of pounding strokes was directly related to a decrease in extraction rate for both sorghum cultivars (Fig 3.1.2A). The extraction rate of Seredo was significantly ($p < 0.05$) lower (64.3%) after 400 pounding strokes compared to IS 2284 (69%). The softer endosperm and thick pericarp

(Reichert et al 1982, Shepherd 1979, Lawton and Faubion 1989) explains the reduced milling yields from Seredo.

Similar results were obtained using mechanical abrasion (Fig 3.1.2B). After 4 min of abrasion, the extraction rate for Seredo was 66.8% compared to 71.2% for IS 2284. As stated, extraction rate depends on the hardness of the grain. For Seredo, as the time of abrasion was increased to 5 min decorticated grain recovered declined to only 54%. This is because soft floury grains have a tendency to disintegrate during decortication (Rooney et al 1997). Notwithstanding this, abrasion of Seredo for 5 min reduced the tannin content of the grain from 7.3% to 1.3% catechin equivalents (Fig 3.1.2B), a reduction of 82%. Beta et al (2000b) obtained a similar reduction in tannin content (71-81%) with abrasion of Zimbabwean tannin-containing sorghums, but with very much lower decortication losses (decorticated grain recovered 81-84%), due to the grains being harder.

Sensory responses for *injera* made from hand pounded Seredo and IS 2284 flours are presented in Table 3.1.2. *Injera* made from whole Seredo flour had brown top and bottom surfaces, without eyes. It had a sticky texture and a bitter taste. Hence it was rated as poor. The tannins in Seredo were responsible for the brown color and the bitter taste of the *injera*. Tannins are known to cause dark color and astringency or bitterness in foods prepared from whole sorghum (Bacon and Rhodes 2000). Carbon dioxide produced during fermentation is known to play a fundamental role in the formation of cellular structure of leavened breads (Bloksma 1990). Thus the absence of eyes in whole flour Seredo *injera* is indicative of very little carbon dioxide being produced during fermentation. Since condensed tannins are associated with anti-microbial (Ebi et al 1999) and enzyme-inhibitory activity (Scalbert 1991) it can be assumed that the tannins inhibited the fermentation process. *Injera* prepared from Seredo flour of the lowest extraction rate (64.3%) produced by hand pounding, had a slightly bitter taste and was sticky with small, scattered eyes. This was presumably because the flour still contained significant levels of tannins. The tannin-free cultivar IS 2284 made good *injera* from hand-pounded flour of higher extraction rate (76.7%). At 68.3% extraction, a similar rate to the lowest examined for the tannin-containing Seredo, the *injera* from IS 2284 was rated very good. The much better *injera* making quality of IS 2284 at similar extraction

Table 3.1.1. Grain characteristics of Seredo (tannin-containing) and IS 2284 (tannin-free) sorghum cultivars and tef

Cultivar	TKW[a] (g)	Glume color	Pigmented[b] testa	Tannins (mg/100g catechin equivalents)	Pericarp thickness (μm)	Endosperm vitreousness (% of total endosperm area)	Grain color		
							L	a	b
Seredo	21.5 ±0.3b[c]	Purple	Yes	7.30±0.27c	126.8 ±26.5b	36.3 ±3.8a	36.7 ±0.4b	9.5 ±0.2b	12.7 ±0.4a
IS 2284	35.9 ±1.7c	Purple	No	0.47±0.08b	0.6 ±0.1a	48.0 ±5.7b	33.2 ±0.5a	16.4 ±0.4c	13.0 ±0.2a
Tef	0.3 ±0.0a	Tan	No	0.05±0.00a	ND[d]	ND	64.8 ±0.7c	3.2 ±0.1a	14.4 ±0.1b

[a]TKW = Thousand kernel weight.
[b]Yes = pigmented testa present, No = pigmented testa absent.
[c]Values followed by the same letter in the same column are not significantly different ($p > 0.05$).
[d]ND = Not determined.

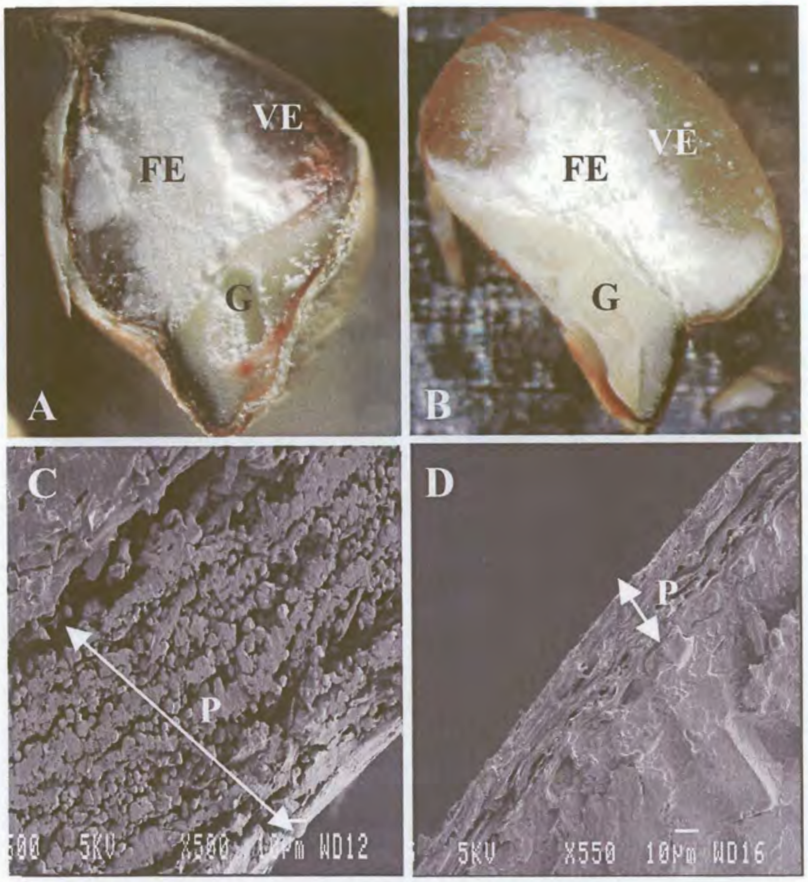

Figure 3.1.1. Micrographs of Seredo (tannin-containing) and IS 2284 (tannin-free) sorghum grains. **A**, Seredo endosperm; **B**, IS 2284 endosperm; **C**, Seredo pericarp; **D**, IS 2284 pericarp. P = pericarp; VE = vitreous endosperm; FE = floury endosperm; G = germ.

rates to Seredo was presumably due to the better milling characteristics of IS 2284 as a result of it being harder and the fact that it was tannin-free.

In contrast to hand pounding, mechanical abrasion of Seredo resulted in *injera* of good quality at an extraction rate of 66.8% (Table 3.1.2). This is presumably because at this extraction rate the tannin content of the flour had been reduced to only 2% (Fig 3.1.2B). Thus, mechanical abrasion, which works by polishing the grains against the abrasive surface and each other (Munck et al 1982), removed the tannin-containing testa layer more effectively compared to hand pounding. In hand pounding the pestle causes a

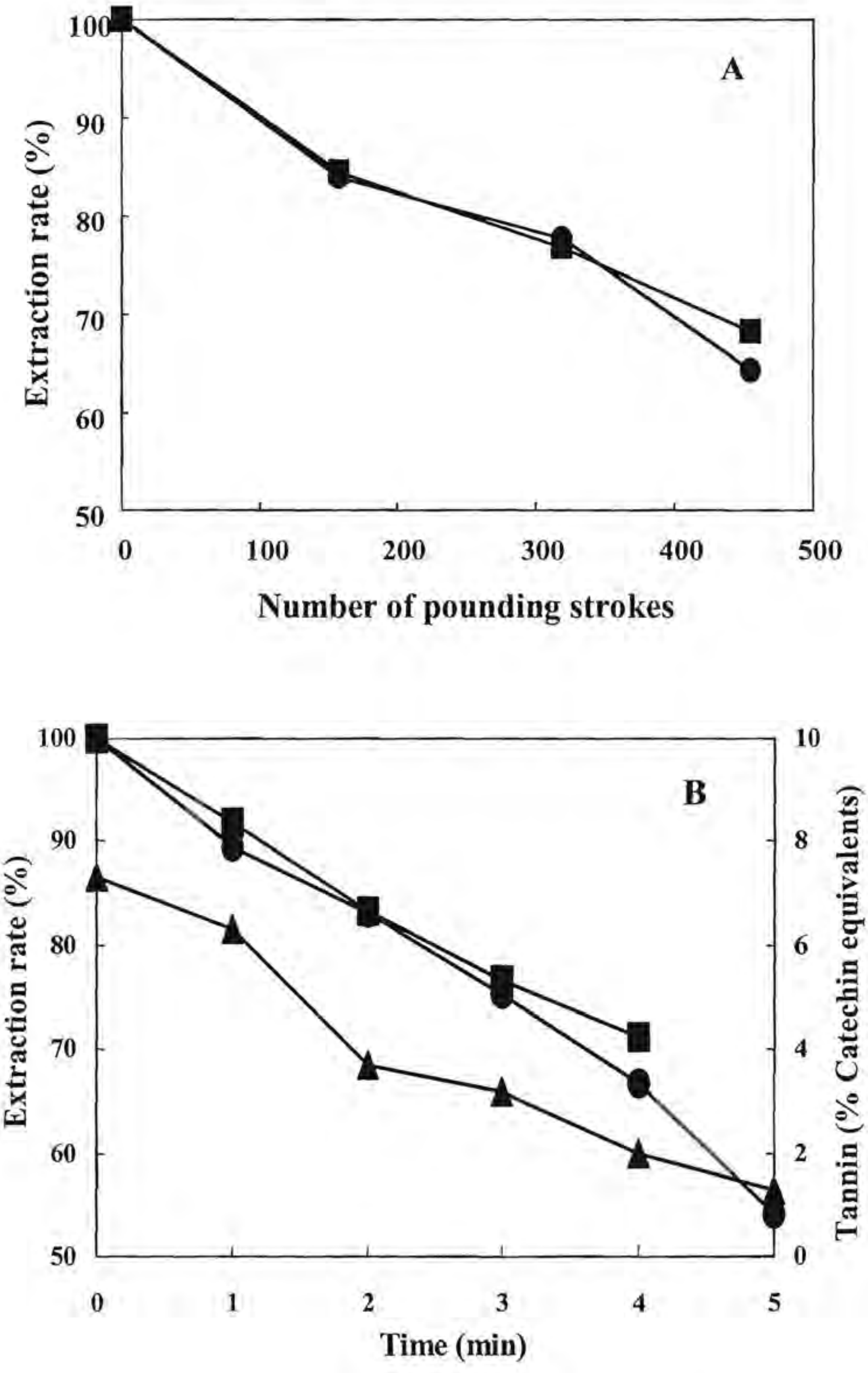

Figure 3.1.2. Effect of decortication on sorghum extraction rate. **A**, Hand pounding; **B**, Mechanical abrasion with TADD. Circles = Seredo (tannin-containing); Squares = IS2284 (tannin-free); Triangles = Tannin content of Seredo.

mechanical shock, generating strong interactive forces between the grains and between the grain and the equipment, which is said to result in the breaking off of large pieces of "hull" (Munck et al 1982). However, in the case of soft, tannin-containing sorghum grains such as Seredo considerable grain breakage appears to occur, as a result of these strong interactive forces. For the tannin-free red sorghum IS 2284, good quality *injera* was obtained by mechanical abrasion at an extraction rate of 83.3%, which was very much higher than for the tannin-containing Seredo and also higher than for hand pounded IS 2284.

To help explain the improvement in *injera* making quality with decortication, flours from sequentially TADD abraded tannin-containing sorghum (Seredo) were tested for their pasting properties. Whole Seredo flour had the lowest PV, HPV and CPV (Fig 3.1.3). With successive abrasion, PV, HPV and CPV increased markedly. Linear regression analyses of the relationships between extraction rate and PV, HPV and CPV gave r-values of –0.94, –0.98 and –0.98, respectively, indicating that the extent of decortication and these pasting parameters were closely related in an inverse manner. PV in particular indicates the water-holding capacity of starch and can be used as a measure of the resistance of starch granules to swelling (Fortuna et al 2000, Li and Yeh 2001). The relationship between PV and extent of decortication suggests that one or more of the grain components capable of inhibiting starch swelling were progressively removed with the bran.

Proteins and lipids are involved with resistance to starch swelling (Whistler and BeMiller 1999). Reductions in starch swelling and gelatinization rates in the presence of protein in sorghum have been associated with the tendency of endosperm protein to act as a physical barrier to starch swelling (Chandrashekar and Kirleis 1988). It is probably of significance that the highest concentration of endosperm protein in sorghum is in the peripheral endosperm (Shull et al 1990), and much of the lipid is in the germ (Wang et al 1997), both of which would be removed by decortication. Decortication would also enrich the starch content of the decorticated grain through the removal of grain components such as non-starch polysaccharides, proteins, and lipids, which are concentrated predominantly in the outer endosperm and the germ (Wang et al 1997). It is therefore additionally possible that the successive removal of those grain components in the bran may have led to a

Table 3.1.2. Sensory panel responses of *injera* prepared from sorghum flours of Seredo and IS 2284 decorticated by hand pounding and with TADD at different extraction rates

Cultivar	Extraction rate (%)	*Injera* quality attributes						
		Top surface color	Bottom surface color	Description of the eyes[a]	Texture	Taste	Aftertaste	Overall rating
Hand pounding								
Seredo (tannin-containing)	100.0[b]	Brown	Brown	None (flat *injera*)	Sticky	Bitter	Bitter	Poor
	84.0	Brown	Brown	None (flat *injera*)	Sticky	Bitter	Bitter	Poor
	77.6	Brown	Brown	Few, small, scattered	Sticky	Bitter	Bitter	Poor
	64.3	Light brown	Light brown	Few, small, scattered	Sticky	Slightly bitter	Slightly bitter	Poor
IS 2284 (tannin-free)	100.0[b]	Red	Light brown	Few, large, scattered	Crumbly	Slightly sweet	Slightly sweet	Poor
	84.5	Red	Red	Few, large, scattered	Slightly soft	Slightly sweet	Slightly sweet	Fair
	76.7	Red	Red	Many, small, evenly spread	Slightly soft	Sour	Slightly sour	Good
	68.3	Light red	Light red	Many, small, evenly spread	Soft	Sour	Slightly sour	V. good
Abrasion with a TADD								
Seredo (tannin-containing)	100.0[b]	Brown	Brown	None (flat *injera*)	Sticky	Bitter	Bitter	Poor
	89.5	Brown	Brown	None (flat *injera*)	Sticky	Bitter	Bitter	Poor
	83.0	Brown	Brown	Few, small, scattered	Sticky	Bitter	Slightly bitter	Poor
	75.3	Light brown	Light brown	Few, small, scattered	Sticky	Slightly bitter	Slightly bitter	Poor
	66.8	Red	Red	Few, small, scattered	Sticky	Slightly bitter	Slightly bitter	Fair
	54.0	Red	Red	Many, small, evenly spread	Soft	Slightly sour	Slightly sour	Good
IS 2284 (tannin-free)	100.0[b]	Light brown	Light brown	Few, large, scattered	Crumbly	Slightly sweet	Slightly sweet	Poor
	91.8	Red	Red	Few, large, scattered	Crumbly	Slightly sweet	Slightly sweet	Fair
	83.3	Red	Red	Many, small, evenly spread	Soft	Sour	Slightly sour	Good
	76.7	Light red	Light red	Many, small, evenly spread	Soft	Sour	Slightly sour	Good
	71.2	Light red	Light red	Many, small, evenly spread	Soft	Slightly sour	Bland	V. good

[a]Eyes (gas cells) refer to the honeycomb-like structure of the top surface of injera formed due to escaping gas bubbles during baking. [b]Whole flour (undecorticated).

progressive elimination of their diluting effects on the starch concentration, leading to increasingly higher PV, HPV and CPV values of the paste. Flours containing higher amounts of starches have been associated with generally higher paste viscosities (Whistler and BeMiller 1999).

Also, Parker et al (1989) showed that starch plays a major functional role in the formation of the continuous amorphous structural matrix of *injera* during baking. Further, Subramanian and Jambunathan (1990) reported a positive correlation between sorghum *injera* eye quality and the starch content of the flour.

3.1.3.3. Compositing

Sensory responses of *injera* made from composite flours of whole tannin-containing sorghum (Seredo) and tef are presented in Table 3.1.3. As stated, *injera* made from 100% Seredo flour had a brown top and bottom surfaces, was flat (without eyes) and had sticky texture, bitter taste and was rated as poor. In contrast, *injera* from 100% tef flour had a white top and white bottom surface, many small evenly spread eyes, very soft texture, a bland aftertaste and was rated excellent. As mentioned, the quality defects of *injera* from Seredo are probably due to a considerable extent to tannins inhibiting the fermentation process. At a low level of compositing with tef (16.7%), there were only a few small and scattered eyes on the surface of the *injera*. Also, other attributes of *injera* such as color, taste and texture were not improved. This can be attributed to minimal dilution of the tannin in the whole Seredo flour. *Injera* of good quality was produced with a 50:50 blend of whole Seredo and tef flour.

At this level of substitution, all the quality attributes of *injera* (color, eye number and distribution, texture, taste and aftertaste) were improved. It appears that as substantial tannin dilution had taken place, this enabled the yeast and lactic acid bacteria to ferment the dough. Additionally, tef appeared to impart its intrinsic flour quality to positively affect *injera* quality. The improvement in *injera* quality continued as the proportion of tef flour in the composite was increased beyond 50%.

Table 3.1.3 Sensory panel responses of *injera* prepared from composite flours of whole tannin-containing sorghum (Seredo) and tef flours composited at different proportions

Compositing proportion	*Injera* quality attributes						
	Top surface color	Bottom surface color	Description of the eyes[c]	Texture	Taste	Aftertaste	Overall rating
100% S[a]	Brown	Brown	Non (flat *injera*)	Sticky	Bitter	Slightly bitter	Poor
83.3% S + 16.7% T[b]	Brown	Brown	Few, small, scattered	Sticky	Bitter	Slightly bitter	Poor
66.7% S + 33.3% T	Brown	Brown	Few, small, scattered	Sticky	Slightly bitter	Slightly bitter	Fair
50.0% S + 50.0% T	Light brown	Light brown	Many, small, evenly spread	Soft	Slightly sour	Slightly sour	Good
33.3% S + 66.7% T	Light red	Light red	Many, small, evenly spread	Soft	Slightly sour	Slightly sour	V. good
16.7% S + 83.3% T	Light red	Light red	Many, small, evenly spread	Soft	Slightly sour	Bland	V. good
100% T	White	White	Many, small, evenly spread	V. soft	Slightly sour	Bland	Excellent

[a]S = Sorghum (Seredo) whole flour.
[b]T = Tef whole flour.
[c]Eyes (gas cells) refer to the honeycomb-like structure of the top surface of *injera* formed due to escaping gas bubbles during baking.

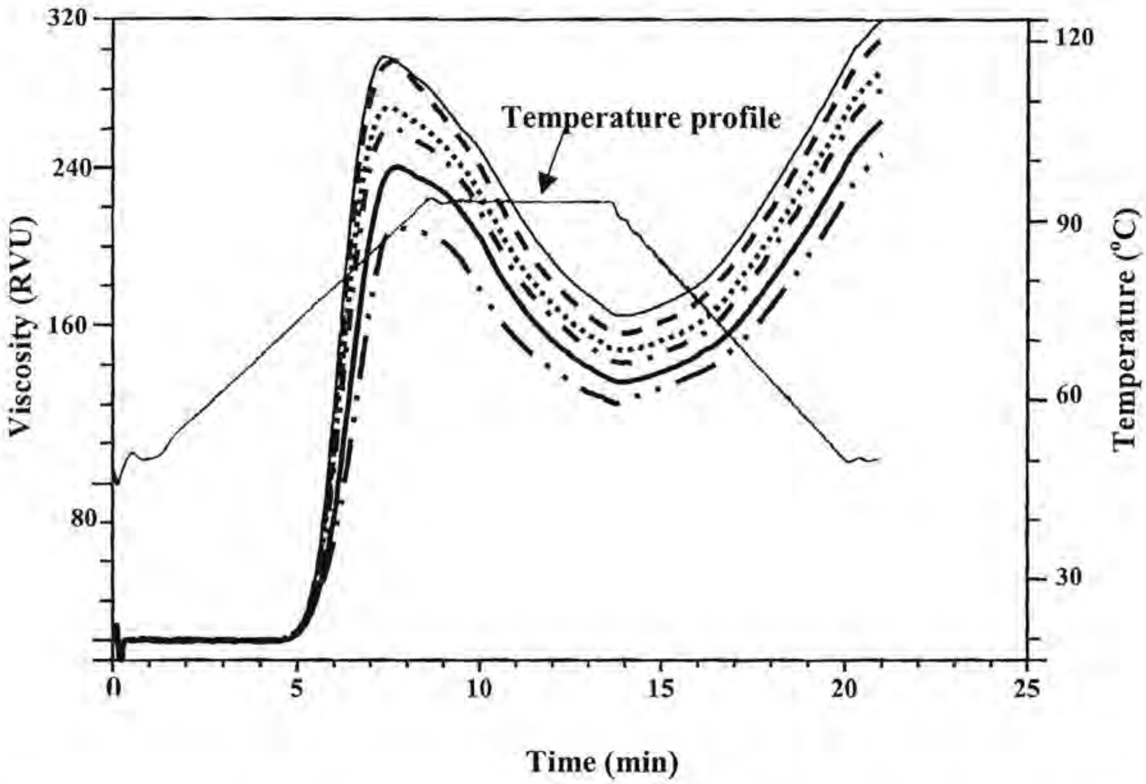

Figure 3.1.3. Effect of sequential decortication of the tannin sorghum (Seredo) on pasting properties of flours. 54% ——; 66.8% — — -; 75.3% ....; 83% — · —; 89% ——; 100% — · · ·

The changes in WAI and WSI when whole flour of Seredo and tef were composited are shown in Figure 3.1.4. As the proportion of tef flour in the composite increased, WSI increased progressively, while WAI declined somewhat. The increase in WSI agrees with the observation that during mixing, tef dough tended to be more sticky compared to sorghum. Water-soluble components in the tef flour could have modified the dough rheology and the texture of *injera* positively. This was manifested by the softer texture of *injera* as the proportion of tef was increased. The decrease in WAI can be attributed to a reduction in damaged starch as the proportion of tef flour increased. Tef starch exists as compound starch granules composed of many tiny granules of 2-6 μm diameter (Umeta and Parker 1996, Bultosa 2002), whereas sorghum starch exists as large single starch granules of about 20 μm diameter (Hoseney 1994). Tef starch granules, because they are so much smaller, are presumably much less prone to damage during milling than sorghum granules and hence would absorb less water.

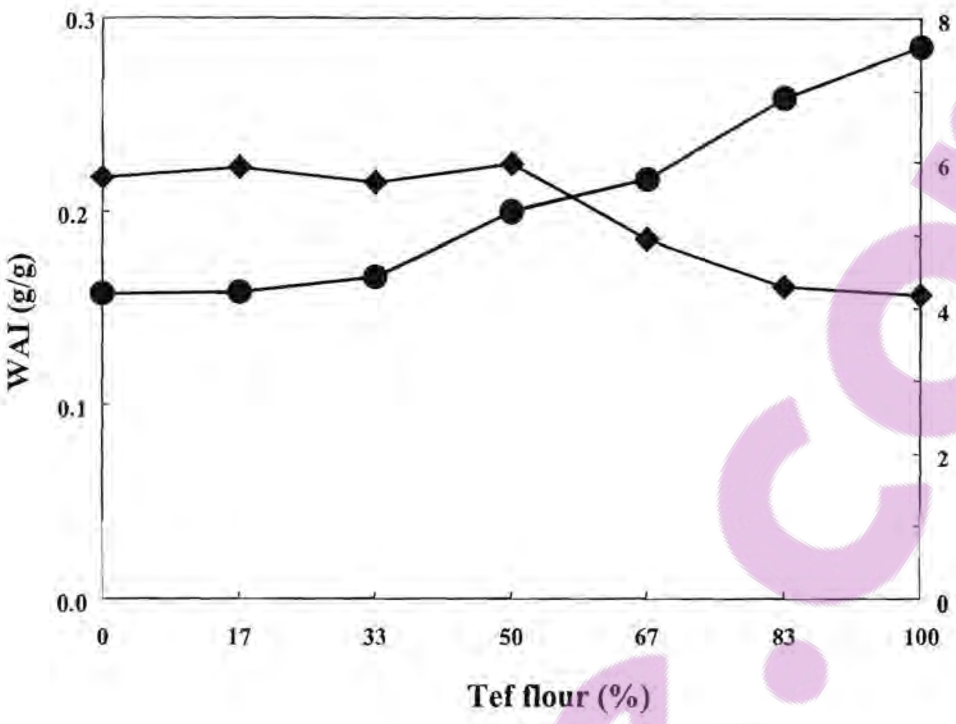

Figure 3.1.4. Changes in water solubility index and water absorption index of composite whole flours of a tannin-containing sorghum (Seredo) and tef composited in different proportions. Circles = WSI; Diamonds = WAI.

Figure 3.1.5 shows that whole Seredo sorghum flour exhibited significantly higher PV, HPV and CPV than whole tef flour. As the proportion of tef flour increased, the PV, HPV and CPV progressively decreased, in contrast to the effect of decorticating Seredo. For the sake of clarity only the 50:50 sorghum:tef curve is shown. The difference in pasting properties of sorghum and tef flours could also be related to inherent morphological differences in their starches. Working with potato, wheat and maize starches Fortuna et al (2000) concluded that the larger starch granules in a population have higher swelling capabilities, while smaller granules have higher resistance to swelling. This may apply to tef starch versus sorghum starch. CPV is related to the ability of the starch paste to form a gel after cooling (Whistler and BeMiller 1999). With high setback, more syneresis is

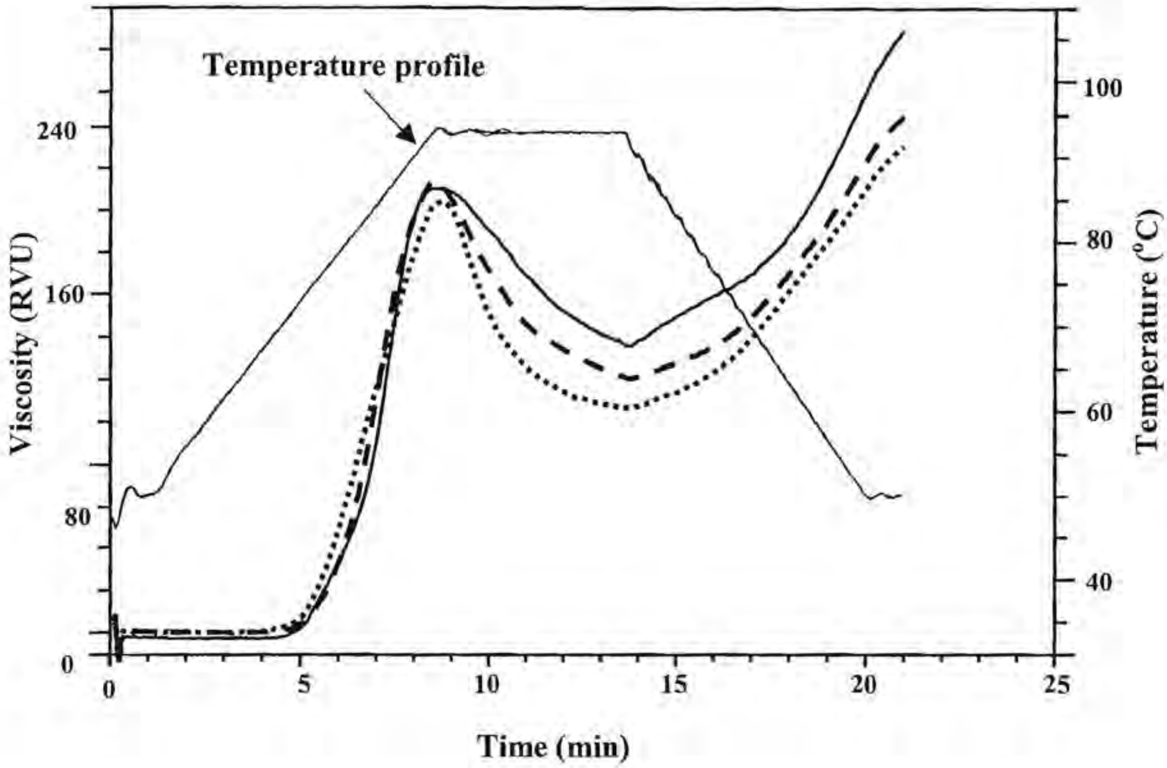

Figure 3.1.5. Effect of compositing the tannin sorghum (Seredo) with tef on pasting properties of the flours. 100% sorghum ——; 50% sorghum + 50% tef — — ; 100% tef ·····

likely to take place (Newport Scientific 1995). For tef starch, Bultosa et al (2002) reported a low setback viscosity and slow syneresis. This is probably related to the softer texture of tef *injera* compared to sorghum *injera*.

3.1.4. Conclusions

Decortication and compositing with tef are both effective ways of improving the *injera* making quality of tannin-containing and tannin-free red sorghum. Decortication improves the color and other quality attributes of *injera* through reduction in the level of non-starch components of the grain. In the case of tannin-containing sorghum decortication also removes some of the tannins, improving *injera* fermentation. Mechanical abrasion is a more effective method compared to hand pounding because acceptable *injera* can be obtained at higher flour extraction levels. Compositing of whole tannin-containing sorghum flour with tef flour improves *injera* quality primarily by diluting the tannins. Also differences in starch granule characteristics and the higher WSI of tef flour appear to positively influence the quality of *injera*. Compositing seems to be a more useful method of improving sorghum *injera* quality than decortication as it avoids the grain loss associated with decortication.

Acknowledgements

The Agricultural Research and Training Project (ARTP) of The Ethiopian Agricultural Research Organization (EARO) supported this research. Senayit Yetneberk gratefully acknowledges partial financial assistance from the International Sorghum and Millet (INTSORMIL) Collaborative Research Support Program.

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3.2. Effects of sorghum cultivar on *injera* quality

(in press, Cereal Chemistry, 2004)

Abstract

Injera is an Ethiopian fermented, leavened flat bread made from cereals, with tef preferred for the best quality *injera*. Because sorghum is less expensive in Ethiopia, there is great interest in improving the quality of sorghum *injera*. Effects of cultivar on *injera* quality were studied using 12 Ethiopian sorghum cultivars of varying kernel characteristics. White tef with good *injera* making quality was included as a reference. *Injera* quality was evaluated using two techniques: descriptive sensory analysis of fresh *injera* and instrumental texture analysis of *injera* stored over a storage period of 48 hr using three point bending rig. Principal Component Analysis (PCA) of sensory data associated fresh *injera* from sorghum cultivars 3443-2-op, 76TI #23, and PGRC/E #69349 of varying endosperm texture, with positive *injera* texture attributes of softness, rollability and fluffiness. Across the two seasons, texture analysis showed *injera* prepared from AW and CR:35:5, both with soft endosperm, required the least force to bend after 48 hr of storage. Bending force was negatively correlated with softness and rollability ($r = -0.51, -0.52, p < 0.05$) and positively with grittiness ($r = 0.54, p < 0.01$) after 48 hr of storage. Sorghum cultivar has an influence on both *injera* making and keeping qualities.

3.2.1. Introduction

Injera is a fermented leavened, flat Ethiopian traditional bread made from cereals such as tef and sorghum (Gebrekidan and GebreHiwot 1982). Its surface has essentially evenly spaced gas holes, which make up a honeycomb-like structure formed due to the production and escape of gas during fermentation and baking respectively. The bottom surface of *injera* is smooth and shiny. A good *injera* is soft, fluffy and able to be rolled without cracking. It should retain these textural properties after 2 to 3 days of storage, which is traditionally done in a straw basket. A slight sourness is a characteristic taste of *injera.* Because *injera* is a leavened bread made from non-gluten containing flour, it has great potential for commercial production internationally.

Injera prepared from flour of tef [*Eragrostis tef* (Zucc.) Trotter], a tiny, millet like grain, is the most preferred. The annual production of tef in Ethiopia is about 1.32 million metric tons (Central Statistical Authority 1998). Of note is the fact that tef commands a higher market price than other cereals in Ethiopia (Seyfu 1993). Sorghum (*Sorghum bicolor* (L.) Moench) is the second most preferred cereal for *injera* preparation in Ethiopia (Gebrekidan and GebreHiwot 1982) with an annual grain production of about 1.82 million metric tons (FAO 2003). Preparing *injera* from sorghum has considerable economic benefits over tef, as sorghum commands a much lower price. However, the problem is that sorghum *injera* rapidly becomes firm and friable upon storage.

Gebrekidan and GebreHiwot (1982) reported that sorghum cultivar differences existed for *injera* making quality and staling property. Yetneberk and Adnew (1985) developed a standard procedure for sorghum *injera* preparation and used it to evaluate the *injera* making qualities of different sorghum cultivars obtained from the Ethiopian Sorghum Improvement Program (ESIP). They confirmed the existence of sorghum cultivar differences for *injera* making quality. It has also been found that the use of composite flour of sorghum and tef improved *injera* texture compared to 100% sorghum (Gebrekidan and GebreHiwot 1982, Yetneberk and Haile 1992). Zegeye (1997) conducted a consumer preference sensory test of *injera* from different cereals and reported that sorghum was accepted as a substitute for tef in *injera* preparation.

The above studies indicate that sorghum cultivar does have an influence on *injera* making and keeping qualities. Thus sorghum cultivars with improved *injera* making quality could probably be selected on the basis of positive *injera* quality attributes. Previous researchers (Gebrekidan and GebreHiwot 1982, Yetneberk and Haile 1992) used a trained panel as consumer panel to evaluate sorghum *injera* making qualities. However, the use of descriptive sensory analysis and instrumental textural analysis to quantitatively evaluate *injera* quality has not been reported. Descriptive sensory analysis detects, identifies, describes and quantifies attribute differences between products and gives information on how raw material and process variables affect sensory characteristics (Stone and Sidel 1985).

The objective of the present study was to determine the influence of sorghum cultivar on *injera* making and keeping quality using descriptive sensory analysis and texture analysis with a view to objectively evaluate sorghum cultivars for selection in sorghum breeding. A wide range of Ethiopian lowland sorghums was used and compared with a white tef cultivar of known good *injera* making quality.

3.2.2. Materials and methods

3.2.2.1. Materials

Twelve sorghum cultivars IS-777, Aligider Wodifereja (AW), PGRC/E #69441, Seredo, CR:35:5, 3443-2-op, SK-82-022, 76TI #23, Gambella 1107, PGRC/E #69349, [(SC-423xCS-3541)-2-1xRS/R-20-8614-2] (SC-423), [(SC-108-3xCS-3541)-19-1xRS/R-20-8614-2)] (SC-108) grown in both the 1999 and 2000 growing seasons, at the Melkassa Agricultural Research Center, Nazareth, Ethiopia were used.

These cultivars had different endosperm texture and pericarp color. Figure 3.2.1 shows the variability in color, size and shape of the 12 sorghum cultivars and a white tef. Seven were white tannin-free, one red tannin-free and four tannin types, as indicated by presence of pigmented testa in the latter (Table 3.2.2). The cultivars are adapted for cultivation in the lowland (high temperature, erratic rainfall) areas of Ethiopia. A white tef cultivar DZ-01-196 with excellent *injera* making quality, grown in 1999 and 2000 at

Figure 3.2.1. Variations in color, size and shape of the 12 sorghum cultivars and a white tef.

the Debre Zeit Research Center, Ethiopia, was included for comparison. All sorghum grains were decorticated to about 80% extraction rate, using a carborundum cone abrasive rice pearler (MIAG, Braunschweig, Germany) and milled to flour using Falling Number hammer mill 3100 (Huddinge, Sweden) fitted with a 500 μm opening screen. Tef was not decorticated prior to milling.

3.2.2.2. Kernel characterization

Sorghum grains were characterized visually for pericarp and endosperm color by comparing with color plates (Rooney and Miller 1982). Glume color was determined by examining the inside of the glume after removing the kernel as described by Rooney and Miller (1982). Pericarp thickness was subjectively rated as thin, intermediate and thick, by scraping through the pericarp with a sharp razor blade. Endosperm texture, the relative proportion of vitreous to floury endosperm, was determined by cutting ten kernels, in halves, longitudinally, and evaluating using a rating scale of 1 (vitreous) to 5 (floury), as described by Rooney and Miller (1982). Grain hardness (extraction rate) was measured by using Tangential Abrasive Dehulling Device (TADD) according to Reichert et al (1982), with extraction rate calculated as percent weight recovered (high recovery indicates harder grain) after abrasion of 20 g of grain for 2 min using sand paper of 60 grit

(Norton type R284 metalite) (Norton Abrasives, Worcester, USA). The presence of a pigmented testa was determined using the Chlorox Bleach Test method described by Waniska et al (1992).

3.2.2.3. Injera making procedure

A flow diagram of the standardized *injera* making procedure is presented in Fig 3.2.2. The procedure involved milling decorticated sorghum or whole tef grain into a flour, preparation of a dough and fermentation of the dough after adding starter culture, a batter from a previous batch (back slopping) and fermenting at room temperature for about 48 hr. The organisms involved in tef dough fermentation are reported to be Gram negative rods, lactic acid bacteria and yeasts growing in succession (Gashe et al 1982). After fermentation, about 25% of the fermented dough was thinned with 30 mL water and cooked in 200 mL boiling water for 1 min. The objective of gelatinization (cooking) was primarily to bring about cohesiveness of the dough and secondly to provide easily fermentable carbohydrate to leaven the *injera*. 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. Additional water (20 mL) was added to fermented tef dough to bring to batter consistency. Adding back the warm gelatinized starch into the fermented dough promotes the growth of mesophilic microorganisms by raising the fermentation temperature to about 30 °C. About 500 g of the fermented batter was poured in a circular manner, on a 50 cm diameter hot clay griddle (*mitad*), covered and baked for about 2 min.

3.2.2.4. Descriptive sensory analysis

A panel was trained based on the method described by Einstein (1991). The selected panelists were tested for their ability to detect sweet, sour, bitter and salty tastes (Jellinek 1985). The selected panel consisted of 10 people, as recommended by Stone and Sidel (1985). They were females and males, aged between 20 and 35 years who work at Melkassa Agricultural Research Center.

Nineteen *injera* quality descriptors: Whiteness of top surface, whiteness of bottom surface, redness of top surface, redness of bottom surface, shininess of top surface, eye size, eye evenness and distribution, *injera* softness, stickiness, fluffiness, rollability, grittiness in the mouth, sourness, sweetness, bitterness, sour aftertaste, sweet aftertaste and bitter aftertaste were generated and selected by the trained panel. A score sheet was prepared using the selected descriptors. Each attribute was evaluated using a 10 point numerical scale (0-9) anchored on both sides with verbal descriptions such as 0 = not white, 9 = very white, to allow the panel to score the intensity on a framed common scale. Definitions of the 19 descriptors used for scoring *injera* are given in Table 3.2.1.

The actual product evaluations were performed following good sensory practices according to Lawless and Heymann (1999). Rolled pieces of *injera* (3 cm wide) were presented to the panelists on a tray at ambient temperature (about 25 °C) within 2 hr after baking. A glass of drinking water was provided for rinsing between samples. A maximum of five *injera* samples were served at each session

3.2.2.5. Texture analysis

Texture analysis of *injera* made from tef and cultivars of sorghum grown for two seasons was performed using a TA-XT2 Texture Analyser (Stable Micro Systems, Godalming, UK). After baking, *injera* samples were allowed to cool for about 30 min at room temperature (about 25 °C). Each *injera* was cut into three equal sized pieces. Each piece was placed in a separate polythene bag of storage and the open end of each bag was folded. The *injera* were stored at room temperature in the dark for 1, 24 and 48 hr. For texture analysis, *injera* samples were cut into strips of 9 cm x 4 cm. Five strips per treatment were measured for maximum bending force using a three point bending rig attachment at a cross-head speed of 0.4 mm/sec for a distance of 10 mm.

Decorticated, sorghum flour or whole grain tef flour

↓

Mix flour with water (200 g flour + 180 mL water) and knead for about 5 minutes

↓

Add starter culture (5% flour weight basis) on top of the dough →

Ferment for 24-48 hr, at room temperature (25 °C) depending on the level of sourness required

↓

Mix part of the dough (80 g) with 30 mL of water, and cook in 200 mL boiling water (for tef use 2/3 of these proportions) for 1 min, cool to 45 °C and add back to the fermenting dough and mix well

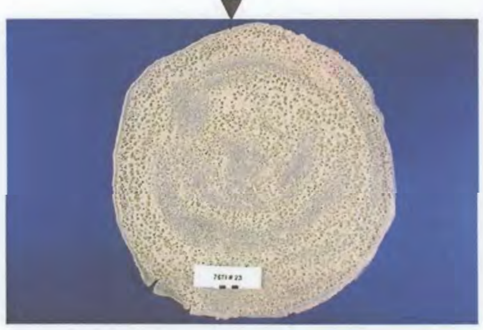
↓

Add 100 mL of water and ferment the batter for 2-3 hr, at room temperature (25 °C) until foam and bubbles are formed

↓

Pour about 500 mL of the batter in a circular manner; on a 50 cm diameter hot clay griddle *mitad* and bake covered for about 2 min. Remove the *injera* by lifting it off the hot griddle and sliding over a straw mat

↓



Sorghum *injera*

Figure 3.2.2. Flow diagram of standardized *injera* making procedure.

Table 3.2.1. Definitions of the 19 descriptors used by the trained sensory panel for scoring sorghum and tef *injera*

Descriptors	**Definitions**
Appearance	
Whiteness of top surface	Intensity of white color of the top surface of the *injera* (0 = low and 9 = high)
Whiteness of bottom surface	Intensity of white color of the bottom surface of the *injera* (0 = low and 9 = high)
Redness of top surface	Intensity of red color of the top surface of the *injera* (0 = low and 9 = high)
Redness of bottom surface	Intensity of red color of the bottom surface of the *injera* (0 = low and 9 = high)
Shininess of top surface	Intensity of shininess of the surface of *injera* (0 = low and 9 = high)
Eye size	Size of the "eyes" (gas holes) on the surface of *injera* (0 = low and 9 = high)
Eye evenness	Intensity of uniformity of the size of the "eyes" (0 = low and 9 = high)
Eye distribution	Evenness of distribution of the "eye" on the surface of *injera* (0 = low and 9 = high)
Texture	
Softness	Intensity of softness of *injera* when lightly pressed between the thumb and forefingers (0 = low and 9 = high)
Stickiness	Intensity of the stickiness of the *injera* when pressed between thumb and forefingers (0 = low and 9 = high)
Fluffiness	Intensity of fluffiness of the *injera* when flapped on the fingers (0 = low and 9 = high)
Rollability	Intensity of rollability by rolling the *injera* strips by hand, samples that are rollable remain rolled (0 = low and 9 = high)
Grittiness in the mouth	Extent of grittiness perceived in the mouth during mastication (0 = low and 9 = high)
Flavor	
Sourness	Intensity of sourness of the *injera* as perceived in the mouth during mastication (0 = low and 9 = high)
Sweetness	Intensity of sweetness of the *injera* as perceived in the mouth during mastication (0 = low and 9 = high)
Bitterness	Intensity of bitterness of the *injera* taste as perceived in the mouth during mastication (0 = low and 9 = high)
Aftertaste sourness	Intensity of residual sourness after swallowing the *njera* (0 = low and 9 = high)
Aftertaste sweetness	Intensity of residual sweetness after swallowing the *injera* (0 = low and 9 = high)
Aftertaste bitterness	Intensity of residual bitterness after swallowing the *injera* (0 = low and 9 = high)

3.2.2.6. Data analysis

The instrumental texture data were analyzed using multifactor analysis of variance and multiple range analysis. Principal Component Analysis (PCA) of the sensory attributes was conducted using a covariance matrix with cultivar means in rows and attributes in columns.

3.2.3. Results and discussion

3.2.3.1 Kernel characterization

Pericarp colors of the sorghum cultivars ranged from white to red (Table 3.2.2) and were similar for both growing seasons. Pericarp color is genetically controlled (Rooney and Miller 1982). Tef is also known to vary in pericarp color from white to red (National Research Council 1996). White tef is, however, the most preferred grain for *injera* production. The glume color of the sorghum cultivars varied from tan to purple. Glume colors have the tendency to stain the sorghum kernel due to leaching of polyphenolic pigments into the pericarp (Rooney and Miller 1982), which might in turn affect the color of the food product. The pericarp thickness of the sorghum cultivars ranged from thin to thick, while tef pericarp, as observed by Parker et al (1989), was thin and membranous. In the eastern part of Ethiopia, sorghum consumers traditionally use a wooden mortar and pestle to remove the pericarp by hand pounding. An inverse relationship between pericarp thickness and the time required for hand pounding decortication was reported by Scheuring et al (1983). Since sorghum pericarp thickness affects milling performance (Rooney and Miller 1982), cultivars with thicker pericarp are preferred for traditional hand pounding decortication. Endosperm color of all the sorghum cultivars was white.

Four sorghum cultivars, IS-777, PGRC/E #69441, Seredo and CR:35:5 had pigmented testa (Table 3.2.2). The tef cultivar did not have a pigmented testa. The pigments responsible for testa color are polymeric polyphenols known as tannins (Butler 1990). Tannins are known to cause dark color and astringent taste in foods prepared from whole sorghum (Earp et al 1983). As described in Chapter 3.1 *injera* prepared from whole sorghum with pigmented testa had a brown color, "bitter" taste and poor eye quality, which made it unacceptable to consumers. However, decorticating the sorghum grain with a TADD or compositing the flour with tef at a ratio of 1:1 improved the *injera* quality.

Endosperm texture of two sorghum cultivars, PGRC/E #69349 and SC-108, was relatively vitreous, whereas AW, CR:35:5 and Seredo were essentially floury. The floury endosperm area has loosely packed endosperm cells (Rooney and Miller 1982). For the 1999 growing season grain hardness expressed as % extraction rate varied from 56.5 % (AW) to 84.5% (SC-108). For the 2000 growing season, grain hardness increased and varied from 67.1% (Seredo) to 89.7% (SC-108). It appears that cultivars with a high proportion of floury endosperm generally had lower extraction rate compared to the cultivars with more vitreous endosperm. Lawton and Faubion (1989) also reported that sorghums with softer endosperm had higher rates of loss than did harder sorghums. Sorghum grain hardness is related to the distribution density of protein bodies and matrix in the endosperm (Shull et al 1990). Hard grains had higher milling yields after abrasive dehulling (Mwasaru et al 1988). For sorghum, decortication removes the pericarp and improves the color and quality of *injera* (Yetneberk and Haile 1992). SC-108, a more vitreous sorghum cultivar, had a high extraction rate (89.7%) after abrasive decortication. This suggests that vitreous sorghum cultivars are suitable for mechanical decortication. Because of its small size, tef grain does not lend itself to mechanical decortication and is not decorticated to make *injera.* Since tef *injera* is preferred, the bran of tef does not obviously cause acceptability problems.

Sensory textural attributes of *injera* from sorghum cultivars and tef are shown in Table 3.2.3. Mean softness score of sorghum *injera* ranged from 6.4 (PGRC/E #69441) to 7.7 (AW). Tef *injera* had a higher score of 8.2 for softness. The mean score for stickiness ranged from 1.4 (PGRC/E #69349) to 3.5 (IS-777). Tef *injera* had mean stickiness score of 2.4. The score of sorghum *injera* for fluffiness ranged from 6.5 (SC-108) to 7.5 (AW). Tef *injera* had a higher score of fluffiness 8.1. Sorghum *injera* rollability scores ranged from 6.9 (SC-108) to 7.7 (CR:35:5 and 76TI #23). Tef *injera* had a higher mean score of rollability 8.3. The mean scores for sorghum *injera* grittiness ranged from 1.9 (CR:35:5) to 3.1 (3443-2-op). Tef *injera* had a lower score of 0.8 of grittiness.

Table 3.2.2. Pericarp and glume color, pericarp thickness, endosperm color, pigmented testa, endosperm texture and hardness of sorghums and a tef cultivar from the 1999 and 2000 growing seasons

Growing season	Physical variables	Sorghum cultivar												Tef
		IS-777	AW	PGRC/E #69441	Seredo	CR:35:5	3443-2-op	SK-82-022	76TI #23	Gambella 1107	PGRC/E #69349	SC-423	SC-108	DZ-01-196
Across seasons	Pricarp color	Red	Red	Red	Light Red	White	White	White	White	White	White	White	White	White
	Glume color	Purple	Purple	Purple	Purple	Tan	Tan	Purple	Tan	Tan	Tan	Tan	Tan	Tan
	Pericarp thickness	Thick	Thick	Thick	Thick	Thick	Inter-mediate	Thick	Inter-mediate	Thick	Inter-mediate	Thin	Thin	V. thin
	Endosperm color	White	White	White	White	White	White	White	White	White	White	White	White	ND[d]
	Pigmented testa[a]	Yes	No	Yes	Yes	Yes	No	No	No	No	No	No	No	No
1999	Endosperm texture[b]	3	5	3	4	4	3	3	3	3	2	4	2	ND
	Hardness (%)	71.2cd[c] ±2.9[e]	56.5a ±1.0	76.8def ±2.8	66bc ±4.9	62.2ab ±4.4	71.7cd ±7.0	80.3fg ±2.4	73.3de ±3.5	73.5de ±0.9	78.8efg ±3.1	63.8b ±5.0	84.5g ±1.8	ND
2000	Endosperm texture[b]	4	4	3	4	4	3	3	3	2	2	3	2	ND
	Hardness (%)	73.6bc ±3.0	76.2bcd ±5.1	83.0gh ±4.8	67.1a ±2.0	72.0ab ±2.2	78.2efg ±3.6	80.0fg ±4.5	73.3bcd ±3.8	87.2hi ±2.3	86.3hi ±1.0	83.3gh ±1.6	89.7i ±0.6	ND

[a]Yes = pigmented testa present, No = pigmented testa absent.
[b]Subjectively rated on a 1 to 5 scale, where 1 = vitreous and 5 = floury.
[c]Values followed by the same letter in the same row are not significantly different ($p > 0.05$).
[d]ND = not determined.
[e]Standard deviation of three replicates.

Table 3.2.3. Sensory textural attributes of *injera* from the 12 sorghum cultivars and tef from the 1999 and 2000 growing seasons

		Sorghum cultivar												Tef
Parameter	**Season**	**IS-777**	**AW**	**PGRC/E #69441**	**Seredo**	**CR:35:5**	**3443-2-op**	**SK-82-022**	**76TI #23**	**Gambella 1107**	**PGRC/E #69349**	**SC-423**	**SC-108**	**DZ-01-196**
Softness	1999	7.2bc[a]	7.8e	7.4cd	7.6de	7.6de	7.4cd	7.0ab	7.1bc	7.7de	6.7a	7.1bc	6.9ab	8.2f
	2000	7.2cde	7.6de	5.5a	7.6de	7.7de	7.0cd	7.4cde	7.3cde	5.9ab	6.8bcd	6.8bcd	6.5abc	8.2e
	Mean[b]	7.2abc	7.7bc	6.4a	7.6abc	7.6bc	7.2abc	7.2abc	7.2abc	6.8ab	6.8ab	7.0ab	6.7ab	8.2c
Stickiness	1999	2.2de	1.8c	1.3b	1.9cd	1.8c	1.0a	2.0cd	1.5b	1.0a	0.8a	1.0a	0.8a	2.4e
	2000	4.9e	3.4bc	1.9a	4.0cd	2.5a	2.3a	2.7ab	4.8de	2.5a	2.1a	2.5a	2.7ab	2.5a
	Mean	3.5cd	2.6bc	1.6a	3.0c	2.2bc	1.6a	2.3bc	3.1c	1.7ab	1.4a	1.8ab	1.7ab	2.4bc
	1999	7.1abc	7.7bcd	7.5abcd	7.0ab	7.3abc	7.6abcd	6.9a	7.2abc	7.8cd	7.0a	7.3abc	7.0ab	8.0d
Fluffiness	2000	6.9cd	7.3d	5.8a	6.6bc	7.3d	7.0cd	7.0cd	7.1d	6.2ab	6.8cd	7.0cd	5.9a	8.2e
	Mean	7.0ab	7.5ab	6.6a	6.8a	7.3ab	7.3ab	7.0ab	7.1ab	7.0ab	6.9a	7.1ab	6.5a	8.1b
	1999	7.5a	7.8ab	8.0bc	7.9abc	7.7ab	7.8ab	7.6ab	7.7ab	7.8abc	7.7ab	7.7ab	7.5a	8.3c
Rollability	2000	7.6cd	7.2abc	6.1a	7.8cd	7.8cd	7.0abc	7.3bcd	7.6cd	6.8abc	7.3bcd	6.9abc	6.3ab	8.3d
	Mean	7.6ab	7.5ab	7.1a	5.3ab	7.7ab	7.4ab	7.4ab	7.7ab	7.3ab	7.5ab	7.3ab	6.9a	8.3b
	1999	2.6f	1.5b	2.3de	2.0c	2.5ef	3.1g	2.7f	2.6ef	2.1cd	2.7f	2.6ef	2.4ef	0.7a
Grittiness	2000	3.2cd	2.7bcd	3.3d	3.0cd	1.3a	3.2cd	2.3bc	1.8ab	3.5d	2.8bcd	2.5bcd	2.8bcd	0.8a
	Mean	2.9bc	2.1bc	2.8bc	2.5bc	1.9ab	3.1c	2.5bc	2.2bc	2.8bc	2.8bc	2.5bc	2.6bc	0.8a

[a]Values followed by the same letter in the same row are not significantly different ($p > 0.05$).
[b]Mean values are mean of the two seasons.

3.2.3.2. PCA of sensory attributes

The product of a PCA is a data map illustrating the various relationships among multiple dependent variables and samples (Lawless and Heymann 1999). Principal components (PCs) are orthogonal directions of maximum variance in the original data. The first two principal components described 70% of the total variance in sensory attributes of *injera* made from sorghum and tef from the 1999 growing season (Fig 3.2.3). The abscissa, which corresponds to the first principal component (Destefanis et al 2000), explained 44% of the total variance. Cultivars that were clustered together on the left were the white cultivars, PGRC/E #69349, 3443-2-op, SC-423, Gambella 1107, SC-108 and 76TI #23 (Fig 3.2.3A). The attributes that described *injera* from these white pericarp sorghum cultivars were grittiness, even eye size and distribution, white top and bottom surfaces, sweet and sweet aftertaste (Fig 3.2.3B). On the right plane of the first principal component were the tannin-containing sorghum cultivars (IS-777, PGRC/E #69441, CR:35:5 and Seredo), which were generally characterized as having bitter taste and aftertaste, red top and bottom surfaces, sour taste and aftertaste and stickiness. SK-82-022, a white sorghum cultivar with purple glume color, gave a faint red colored *injera*, possibly imparted by leaching of the glume color through the pericarp into the peripheral endosperm.

The ordinate of the PCA corresponds to the second principal component (Destefanis et al 2000). The second principal component of the 1999 season explained an additional 26% of the total variance (Fig 3.2.3). PC 2 separated cultivars mainly on the grounds of *injera* texture characteristics and appearance of eyes. Cultivars in the upper part of the plot were associated with *injera* of more gritty texture but evenly distributed larger eyes compared to the lower part of the plot (Fig 3.2.3A). Concerning the bottom part of the plot, AW, a red pericarp sorghum cultivar with floury endosperm was associated with soft, and rollable *injera*, while *injera* from tef was characterized by a fluffy texture with a more shiny top surface.

For the 2000 growing season, the first two principal components described less of the total variance (59%) (Fig 3.2.4), compared to the 1999 growing season (70%) (Fig 3.2.3). The third principal component accounted for an additional 15% (Fig 3.2.5), so that 75%

of the total variance in the 2000 data could be explained (Figs 3.2.4 and 3.2.5). The first principal component which described 40% of the variance of the 2000 season, showed a similar trend to the 1999 data. *Injera* from the white pericarp sorghums and tef were characterized by being sweeter and whiter, while *injeras* from the tannin sorghums were characterized by more bitter taste with red top and bottom surfaces (Fig 3.2.4A). *Injera* from the red tannin free sorghum (AW) produced red *injera* and the white sorghum cultivar with purple glume color SK-82-022 produced a faint red colored *injera*, as noted for the previous season.

In the upper plot of the second principal component of the 2000 season, a white pericarp-containing sorghum cultivar, SC-108 was associated with *injera* of a more sour aftertaste compared to other sorghum cultivars. This may have been due to the lactic acid fermentation of this cultivar being rapid. In the lower part of the plot, tef was grouped among the white sorghum cultivars (76TI #23, 3443-2-op and PGRC/E #69349). The *injera* attributes associated with these cultivars were sweet taste, positive textural attributes (fluffy, rollable and soft), and shiny surface with more evenly distributed eyes. The endosperm texture of these cultivars varied from intermediate to relatively vitreous.

The third principal component of the 2000 season further explained differences in the texture (softness, rollability, fluffiness and grittiness), eye appearance and sweetness of the *injera* (Fig 3.2.5). White pericarp-containing sorghum cultivars (PGRC/E #69349, 3443-op, Gambella 1107, SC-423 and 76TI #23) were associated with evenly distributed eyes, sweet taste and white top and bottom surfaces. Tef and a white sorghum cultivar with relatively vitreous endosperm (SC-108) produced soft, rollable and fluffy *injera*. Although seasonal variation in cultivar association was observed, both seasons showed similar trends in terms of grouping cultivars with similar *injera* attributes as perceived by the trained sensory panel.

According to Destefanis et al (2000), variables close together in the loading plot are positively correlated while variables lying opposite to each other are negatively correlated. As expected, whiteness and redness of top and bottom surfaces of the *injera* were negatively correlated (Figs 3.2.3B, 3.2.4B and 3.2.5B). *Injera* softness was very

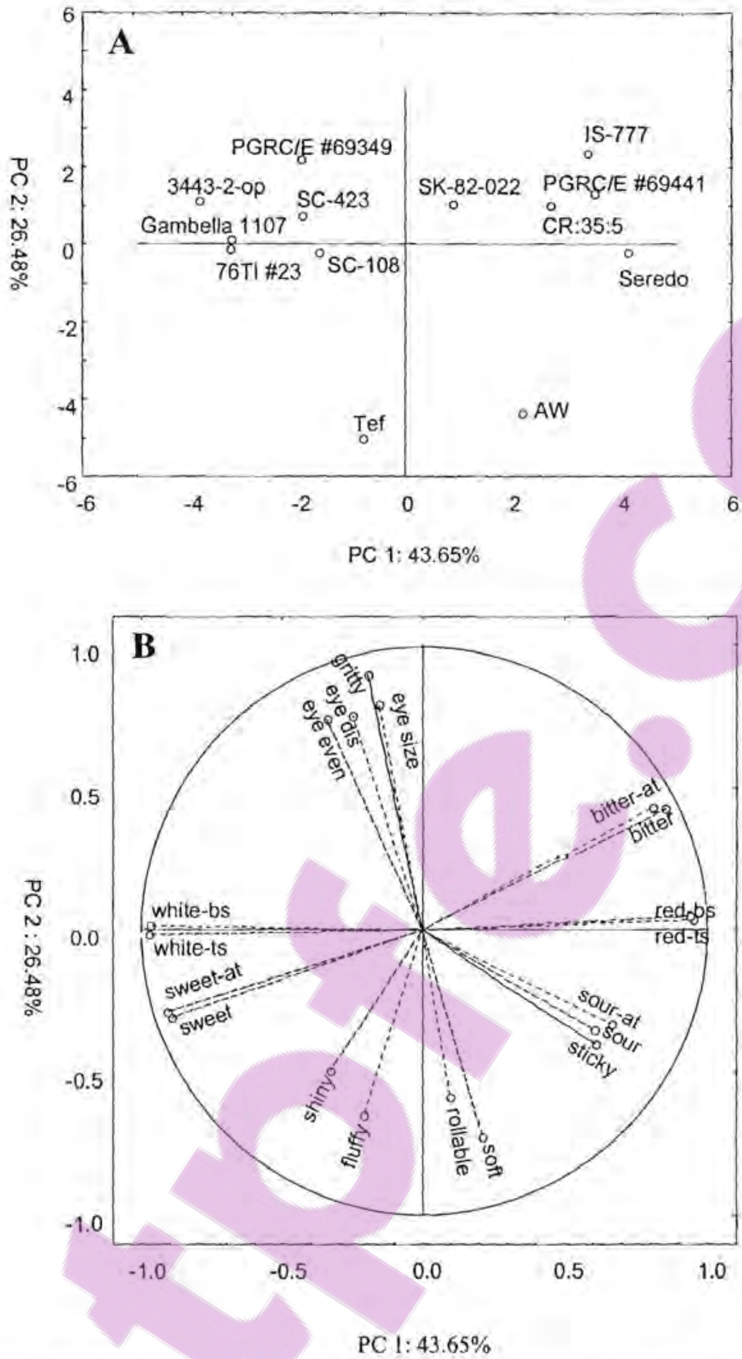


Figure. 3.2.3. Principal component analysis of *injera* from 12 sorghums and a tef cultivar grown in 1999. Plot of the first two principal component scores of the cultivars **A**. Plot of the first two principal component loading vectors of sensory attributes **B**. White-ts = whiteness of top surface; white-bs = whiteness of bottom surface; red-ts = redness of top surface; red-bs = redness of bottom surface; eye dis = eye distribution; eye even = eye evenness; sour-at = sour aftertaste; sweet-at = sweet aftertaste; bitter-at = bitter aftertaste.

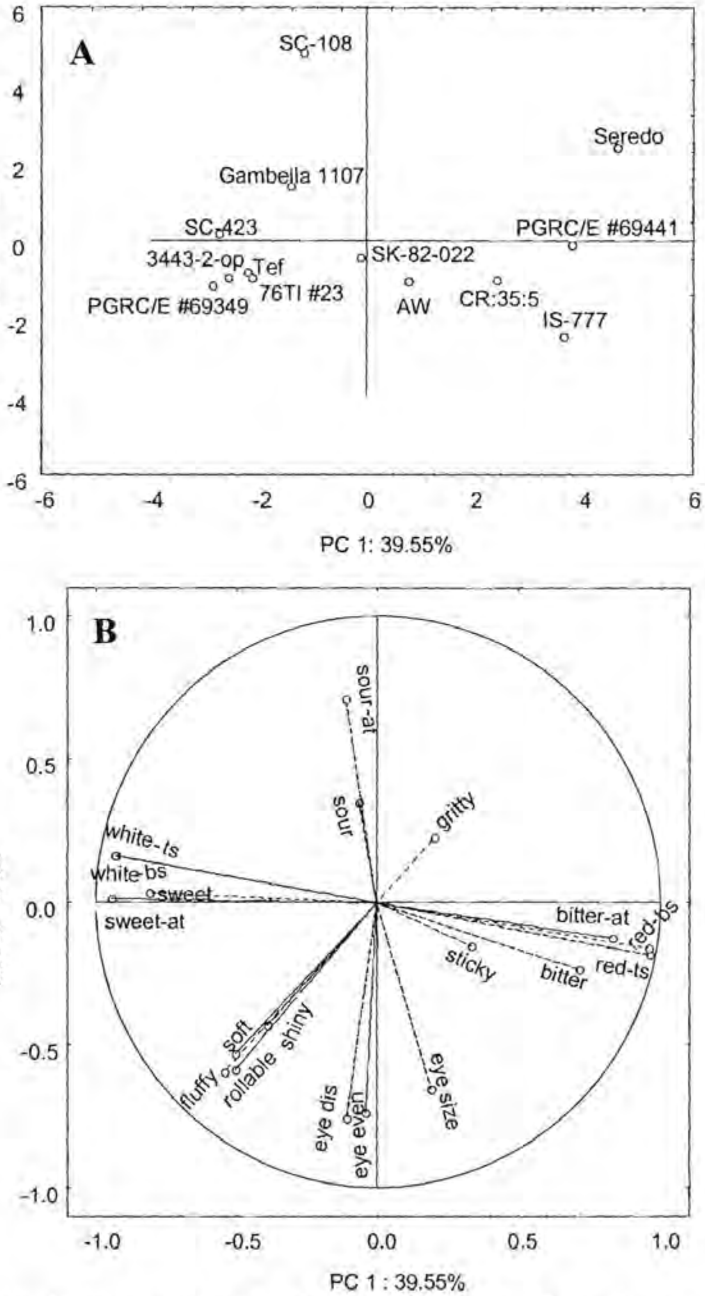


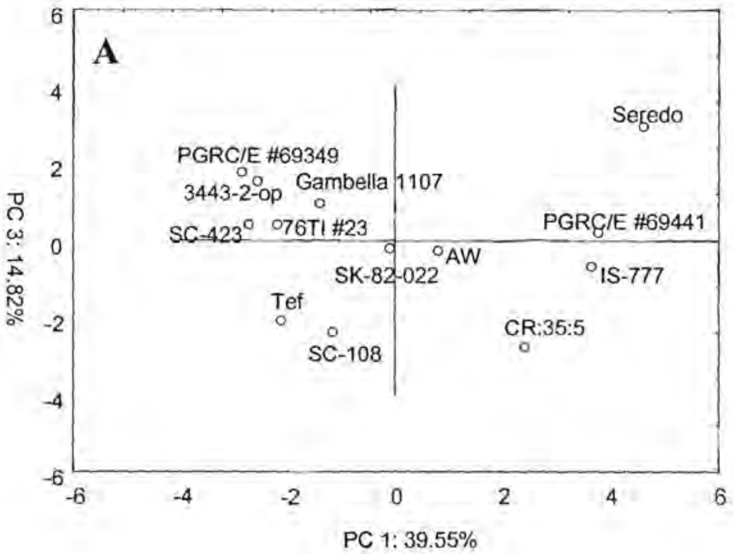
Figure 3.2.4. Principal component analysis of *injera* from 12 sorghums and a tef cultivar grown in 2000. Plot of the first two principal component scores of the cultivars **A**. Plot of the first two principal component loading vectors of sensory attributes **B**. White-ts = whiteness of top surface; white-bs = whiteness of bottom surface; red-ts = redness of top surface; red-bs = redness of bottom surface; eye dis = eye distribution; eye even = eye evenness; sour-at = sour aftertaste; sweet-at = sweet aftertaste; bitter-at = bitter aftertaste.

closely associated with rollability (Figs 3.2.3B, 3.2.4B and 3.2.5B). This agrees with the observed tendency of soft *injera* to roll easily. Both characteristics are considered important eating quality attributes of *injera*. Good *injera* is soft and rollable in order to wrap and hold the sauce (*wot*) during consumption (Gebrekidan and GebreHiwot 1982). *Injera* bitterness and bitter aftertaste were negatively correlated with sweetness and sweet aftertaste (Figs 3.2.3B, 3.2.4B and 3.2.5B). The consumption of tannin-rich foods and beverages is associated with astringency or dryness and roughness felt in the mouth (Bacon and Rhodes 2000). It appears as if this sensation was perceived by the panel as bitter.

3.2.3.3. Instrumental texture measurement

The maximum force required to bend fresh *injera* and *injera* stored for 24 and 48 hr are presented in Table 3.2.4. *Injera* from tef required the least force in all cases, while *injera* from the sorghum cultivars increased in the force required to bend over the 48 hr storage, indicating that firming (staling) of sorghum *injera* is time dependent. The example of PGRC/E #69349 (a high staler) is shown in Figure 3.2.6. The force required to bend sorghum *injera* varied between cultivars for both fresh and stored *injera* and across seasons. For the 1999 growing season, fresh *injera* from cultivars PGRC/E #69441, SK-82-02 and CR:35:5 required the least force and were similar to *injera* from tef, which had the most bendable *injera*. Fresh *injera* from cultivars SC-423, Seredo, 76TI #23 and 3443-2-op required the highest force to bend. After a storage period of 48 hr, *injera* from sorghum cultivars AW and SK-82-022 required the least force, whereas 76TI #23 and 3443-2-op required the most. This is illustrated in Figure 3.2.7. The low stalers were both tannin-free but varied in pericarp color and endosperm texture. AW had red pericarp color and floury endosperm, while SK-82-022 had white pericarp color and an intermediate endosperm texture. The high stalers were both white, tannin-free cultivars with intermediate endosperm texture.

For the 2000 growing season, fresh *injera* from sorghum cultivars (76TI #23, SK-82-02, CR:35:5, AW and PGRC/E #69441) required the least force to bend, while SC-423 and PGRC/E #69349 required the most (Table 3.2.4). After two days of storage, CR:35:5 and



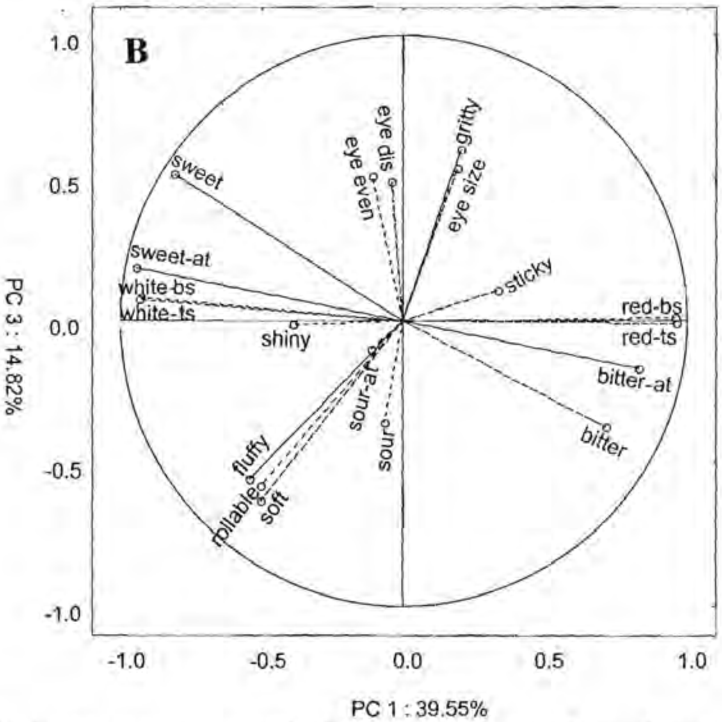


Figure 3.2.5. Principal component analysis of *injera* from 12 sorghums and a tef cultivar grown in 2000. Plot of the first and third principal component scores of the cultivars **A**. Plot of the first and third principal component loading vectors of sensory attributes **B**. White-ts = whiteness of top surface; white-bs = whiteness of bottom surface; red-ts = redness of top surface; red-bs = redness of bottom surface; eye dis = eye distribution; eye even = eye evenness; sour-at = sour aftertaste; sweet-at = sweet aftertaste; bitter-at = bitter aftertaste.

Table 3.2.4. Maximum force (N) required to bend *injera* stored at 25 °C over a period of two days from sorghums and a tef cultivar grown for two seasons

Season	Storage time (hr)	Sorghum cultivar: IS-777	AW	PGRC/E #69441	Seredo	CR:35:5	3443-2-op	SK-82-022	76TI #23	Gambella 1107	PGRC/E #69349	SC-423	SC-108	Tef: DZ-01-196
1999	1	0.18bcd[a] ± 0.03[b]	0.19bcd ± 0.06	0.14ab ± 0.03	0.26gh ± 0.05	0.17abcd ± 0.06	0.24efgh ± 0.05	0.16abc ± 0.15	0.24fgh ± 0.08	0.21def ± 0.05	0.19cde ± 0.08	0.27h ± 0.08	0.21defg ± 0.08	0.12a ± 0.01
	24	0.25def ± 0.05	0.18bc ± 0.03	0.23cde ± 0.06	0.21bcd ± 0.06	0.27ef ± 0.03	0.29f ± 0.05	0.15ab ± 0.02	0.36g ± 0.17	0.27ef ± 0.06	0.25def ± 0.04	0.29f ± 0.05	0.20bcd ± 0.03	0.11a ± 0.02
	48	0.26bcd ± 0.01	0.19ab ± 0.06	0.26cd ± 0.07	0.33d ± 0.1	0.33d ± 0.06	0.47e ± 0.19	0.22abc ± 0.07	0.42e ± 0.09	0.27cd ± 0.07	0.32d ± 0.09	0.32d ± 0.03	0.27cd ± 0.01	0.15a ± 0.06
2000	1	0.21bc ± 0.03	0.19b ± 0.04	0.20b ± 0.06	0.24cd ± 0.03	0.19b ± 0.05	0.28df ± 0.06	0.19b ± 0.03	0.18ab ± 0.03	0.29f ± 0.04	0.37g ± 0.05	0.43h ± 0.09	0.26de ± 0.05	0.14a ± 0.05
	24	0.31de ± 0.06	0.23bc ± 0.04	0.37f ± 0.06	0.26cd ± 0.04	0.19b ± 0.06	0.47g ± 0.11	0.26cd ± 0.03	0.36ef ± 0.09	0.32ef ± 0.08	0.54h ± 0.02	0.70i ± 0.03	0.33ef ± 0.05	0.13a ± 0.05
	48	0.42ef ± 0.05	0.28c ± 0.04	0.52g ± 0.09	0.33cd ± 0.07	0.22b ± 0.03	0.58h ± 0.11	0.33cd ± 0.05	0.45f ± 0.08	0.47fg ± 0.06	0.62hi ± 0.07	0.66i ± 0.07	0.37de ± 0.04	0.15a ± 0.03

[a]Values followed by the same letter in the same row are not significantly different ($p > 0.05$).
[b]Standard deviation of two *injera* baked on separate days (5 determinations per *injera*).

AW required the least force, whereas SC-423 and PGRC/E #69349 required the most. CR:35:5 was a tannin-containing sorghum with floury endosperm. Both the high stalers had white pericarp color with intermediate endosperm texture and were tannin-free. When sorghum endosperm texture data expressed as corneousness (vitreousness) (Murty et al 1982) was related to the shelf life of *injera* made from these cultivars reported by Gebrekidan and GebreHiwot (1982), there was no consistent trend between endosperm texture and staling property. This agrees with the present finding.

When the means of *injera* sensory textural scores and instrumental texture measurements across seasons for *injera* stored for 48 hr were correlated, bending force was found to be negatively correlated with softness and rollability ($r = -0.51, -0.52, p < 0.05$) and positively with grittiness ($r = 0.54, p < 0.05$). This relationship indicates that as would be expected soft *injera* requires less force to bend. This was clearly demonstrated by the fact that tef *injera*, which is known to be soft, had the lowest bending force throughout the 48 hr of storage. Conversely, *injera* perceived as being gritty (a negative attribute) by the panel required the most force to bend. These relationships show that bending force could be used as an indication of the quality of fresh and stored *injera*.

Across seasons, cultivars AW and CR:35:5 staled least, while cultivars PGRC/E #69349, SC-423 and 3443-2-op staled most. The low stalers had floury endosperm. The high stalers were white with intermediate endosperm and were tannin-free sorghums. *Injera* from AW, one of the low stalers across seasons, was also noted by the sensory panel as being soft and rollable (positive attributes) for the 1999 growing season (Fig 3.2.3). Conversely, for the same season, *injera* from PGRC/E #69349, one of the high stalers across seasons, was perceived as gritty by the sensory panel (Fig 3.2.3).

In the course of the storage trial, it was noted that for both seasons after a storage period of only one day, *injera* from PGRC/E #69349, SC-423, 76TI #23, Gambella 1107, and 3443-2-op, all cultivars giving *injera* with relatively high staling, had a moist bottom surface. Water was probably released (syneresis) out of the *injera* matrix due to

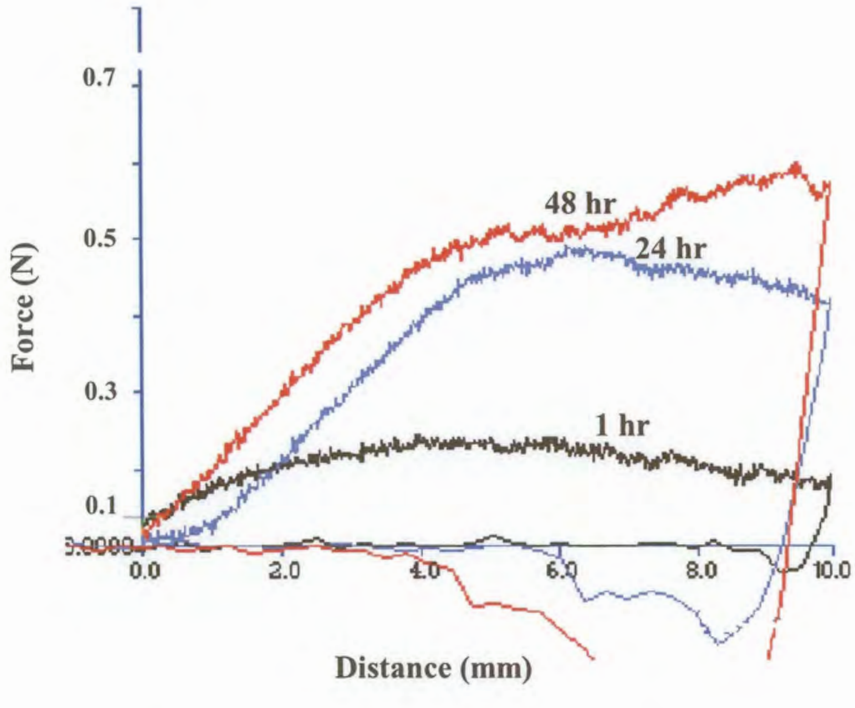


Figure 3.2.6. Effect of storage time (1, 24, 48 hr) on maximum force required to bend sorghum *injera* from PGRC/E #69349 (high staler) from the 1999 growing season.

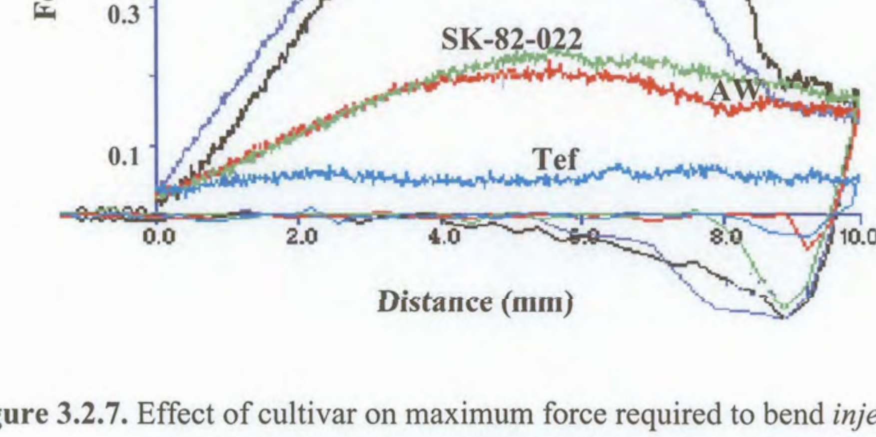


Figure 3.2.7. Effect of cultivar on maximum force required to bend *injera* stored for 48 hr from the 1999 growing season.

re-association (retrogradation) of starch components, causing increased firmness, as reported by Lineback and Rasper (1988) with regards to rigidity of wheat bread crumb. Staling is due, at least in part, to the gradual transition of amorphous starch to a partially crystalline, retrograded state (Whistler and BeMiller 1999). Martin and Hoseney (1991) suggested wheat bread firming as also being a result of cross-links between starch granule remnants and protein fibrils. During the baking of *injera*, starch granules completely gelatinize and fuse into a continuous amorphous matrix (Parker et al 1989). This amorphous matrix probably transforms to a retrograded state upon storage.

3.2.4. Conclusions

Sorghum cultivar affects *injera* making quality. AW (floury endosperm), 3443-2-op and 76TI #23 (intermediate) and PGRC/E #69349 (with more vitreous endosperm) were generally associated with soft, rollable and fluffy *injera*, which were positive attributes as perceived by the sensory panel. *Injera* from AW and CR:35:5 (both floury endosperm) required least force to bend after 48 hr of storage. More detailed work on the physico-chemical properties of flours of the 12 sorghum cultivars should be conducted and correlated with *injera* quality. This should lead to identification of specific flour quality parameter(s) that are related to good sorghum *injera* quality. The range in quality of fresh and stored sorghum *injera* seems quite substantial, and indicates that sorghum can be bred for better *injera* making quality.

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3.3. Grain and flour quality of Ethiopian sorghums in respect of their *injera* making potential

Abstract

Injera is an Ethiopian fermented leavened flat bread made from cereals, with tef preferred for the best quality *injera*. Grain and flour of 12 Ethiopian sorghums and a white tef cultivar grown for two seasons were evaluated in terms of their physico-chemical properties. These were related to the sensory attributes of *injera*. Variability in physico-chemical characteristics among sorghum cultivars and between sorghum and tef were evident. Linear regression correlation analysis between the physico-chemical parameters and sensory attributes of *injera* showed that grain hardness, measured by the Tangential Abrasive Dehulling Device was significantly negatively correlated with the positive *injera* textural attributes of softness and rollability ($r = -0.70$, $r = -0.66$, $p < 0.001$). Endosperm vitreousness, measured by image analysis, was negatively correlated with *injera* softness ($r = -0.59$, $p < 0.01$). Endosperm texture, visually evaluated, was positively correlated with *injera* softness ($r = 0.59$, $p < 0.01$). Water solubility index (WSI) of the flour was positively correlated with *injera* fluffiness ($r = 0.48$, $p < 0.05$), probably due to its influence on the dough rheology. Generally, sorghum cultivars with soft endosperm and higher WSI appeared to produce soft and rollable *injera*. The above grain and flour parameters have potential to be used as indirect indices in predicting the quality of sorghum *injera* in the Ethiopian Sorghum Improvement Program. However, additional research is needed to test larger number of genotypes from multi-location trials to further evaluate their effects on *injera* quality attributes.

3.3.1. Introduction

Injera is an Ethiopian fermented, leavened flat bread made from cereals, with tef preferred for the best quality *injera* (Gebrekidan and GebreHiwot 1982). Because the major component of *injera* is the flour, the various chemical and other functional components of the flour are potentially important with regard to determining the *injera* making potential of sorghum cultivars. Starch, protein and lipids are the three major components in cereal based food products and the interactions among them in a food system are of importance to functionality and quality (Zhang and Hamaker 2003). During the baking of *injera*, starch is completely gelatinized to form a steam-leavened, spongy matrix, in which fragments of bran, embryo, microorganisms and organelles are embedded (Parker et al 1989). Subramanian and Jambunathan (1990) related panelist responses of sorghum *injera* with grain properties and reported a positive correlation between *injera* texture and starch total setback ($r = 0.62$) and a negative correlation ($r = -0.63$) between "eye quality" (honeycomb structure of the *injera* surface) and protein content.

However, our understanding of the effects of sorghum grain characteristics and flour components to *injera* making quality is very limited. Sorghum genotypes have mainly been evaluated on the basis of the sensory attributes of *injera* without relating it to the grain characteristics and flour components (Gebrekidan and GebreHiwot 1982, Yetneberk and Haile 1992). This approach lacks a deep scientific basis for selecting good *injera* making cultivars and is unable to complement the breeding effort in the Ethiopian Sorghum Improvement Program (ESIP). The influence of cultivars on *injera* making quality has been reported (Gebrekidan and GebreHiwot 1982, Subramanian and Jambunathan 1990), and has been confirmed (Chapter 3.2).

The objectives of this investigation were to determine the physico-chemical properties of sorghums with varying endosperm texture and relate them to the sensory attributes of *injera* set out in Chapter 3.2, in order to identify the specific grain or flour quality parameter(s) to be used as indirect indices in predicting the quality of sorghum *injera* in the ESIP.

3.3.2. Materials and methods

3.3.2.1. Materials

Twelve sorghum cultivars grown in the 1999 and 2000 seasons at the Melkassa Agricultural Research Center, Ethiopia were used. They were of different endosperm textures and grain colors. A white tef cultivar was included for comparison (see Chapter 3.2).

3.3.2.2. Kernel characterization

Characterization of kernel and endosperm color, endosperm texture (vitreous or floury endosperm), grain hardness and presence of a pigmented testa were determined by using methods described in chapter 3.2.

Vitreousness of the kernel endosperm was measured by image analysis. Kernels were adjusted to 12 % moisture and allowed to equilibrate for 24 hr, then halved longitudinally using a sharp razor blade. One half of each kernel was fitted on an aluminium stub with the aid of double-sided adhesive tape. Each half was viewed using a stereomicroscope Nikon, Tokyo, Japan). Images were captured with a digital camera attached to the stereomicroscope. Images were enhanced for contrast using an Adobe Photo Shop 5.5 Program (Adobe Systems, San Jose, USA). The total endosperm and floury endosperm areas were measured using the UTHSCSA, Image Tool Software, version 2.0 (University of Texas Health Science Center, San Antonio, USA). Six half grains were viewed for each cultivar. The results were computed and expressed as percent vitreousness.

Thousand kernel weight (TKW) was determined by weighing 1000 randomly selected unbroken kernels. Test weight was determined as hectoliter weight. Grain and whole grain flour colors were measured in L, a b units using a Hunter Color Quest 45/0 (Hunter Associates, Reston, USA). Water Absorption Index (WAI) and Water Solubility Index (WSI) were determined according to Anderson et al (1969).

3.3.2.3. Chemical characterization

Moisture, ash and fat contents of whole grain flours were determined according to AACC approved methods (American Association of Cereal Chemists 2000), methods 44-15A, 08-17 and 30-25, respectively. Protein (N x 6.25) was determined by the Dumas combustion method. Lysine was determined by reversed phase high performance liquid chromatography using the PICO.TAG method, according to the procedure of Bidlingmeyer et al (1984). Total starch was determined by the Megazyme Total Starch Assay Procdure (Amyloglucosidase/α-amylase method), (Megazyme International, Bray, Ireland). Cultivars with a pigmented testa were treated with very dilute (0.04%) formaldehyde solution (Daiber and Taylor 1982) to react with the tannins, to prevent their subsequent inactivation with the enzymes involved in the total starch assay. Apparent starch amylose content of whole ground grain was determined colorimetrically (Faulks and Bailey 1990) based on preferential binding of iodine by amylose.

3.3.2.4. Pasting properties and gel firmness

Whole meal flour pasting properties were determined using a Rapid Visco Analyser (RVA) Model 3D (Newport Scientific, Warriewood, Australia) as described in Chapter 3.1. From the RVA pasting curves, peak viscosity (PV), hot paste viscosity (HPV), breakdown viscosity (BV) (PV-HPV), cold paste viscosity (CPV), setback viscosity (SBV) (CPV-HPV), pasting temperature (PT) and peak time duration (PTD) were computed.

Gel firmness of wholemeal flour (6 g, 14% moisture basis suspended in 25 ml distilled water) was determined by pasting the suspension in the RVA. The hot paste was immediately placed into plastic dishes (40 mm diam x 10 mm depth); the depth of each dish had been increased by approximately 5 mm by taping clear adhesive tape around its rim. The dishes were covered and rested for 24 hr at ambient temperature (approx. 25 ^{o}C) for gelation to take place. After the tape was removed, the surface gel was scraped off with a sharp knife to level to the container's rim (Takashi and Sieb 1988). The texture of the freshly cut gel surface was analyzed using a TA-XT2 Texture Analyser (Stable Micro Systems, Godalming, UK). A standard single-cycle program was used to compress the gel for a distance of 5 mm at a cross speed of 0.5 mm/s using a 20 mm cylindrical perspex probe with a flat end. Gel firmness (maximum force required for deformation) was computed from the force-time curve. To compare the elasticity of gels from flours of sorghum cultivar 76TI #23 and the tef cultivar, the gels were stored at 4 °C for 24 hr and removed from the dishes for texture analysis. A standard double-cycle program was used to compress the gels for a rupture distance of 50% of the gel height at a crosshead speed of 1 mm/s using 50 mm cylindrical aluminium probe with a flat end.

3.3.2.5. Statistical analysis

The various physical and chemical characteristics, pasting properties, gel texture and microstructure measurements were analysed by one-way analysis of variance (ANOVA) and tested for level of significance by Duncan's multiple range test. Means were compared for relationships by Pearson Product-Moment correlation using Statistica for Windows (Statsoft, 1995).

3.3.3. Results and discussion

3.3.3.1. Kernel characterization

Variation in kernel color has been noted in sorghums, ranging from white to red (Table 3.3.1) and is genetically controlled (Rooney and Miller 1982). Tef varies in kernel color (National Research Council 1996). However, white grain tef was selected for comparison because people prefer *injera* from white tef. Pericarp thickness of sorghums varied from thin to thick, while tef pericarp was thin and membranous (Parker et al 1989). Figure 3.3.1 shows micrographs of the 12 sorghum cultivars with varying pericarp thickness. A thin pericarp is manifested by the presence of a single dominant Z allele, whereas the thick pericarp is determined by two recessive alleles, zz (Rooney and Miller 1982, Scheuring et al 1983). In case of sorghum, decortication removes the pericarp and improves the color and quality of *injera* (Gebrekidan and GebreHiwot 1982, Subramanian and Jambunathan 1990, Yetneberk and Haile 1992) (Chapter 3.1).

Table 3.3.1. Pericarp color and thickness, pigmented testa and endosperm texture of sorghums and tef from the 1999 and 2000 growing seasons (from Chapter 3.2)

		Sorghum cultivar												Tef
Parameter	**Season**	**IS-777**	**AW**	**PGRC/E #69441**	**Seredo**	**CR:35:5**	**3443-2-op**	**SK-82-022**	**76TI #23**	**Gambella 1107**	**PGRC/E #69349**	**SC-423**	**SC-108**	**DZ-01-196**
Pericarp color	Both seasons	Red	Red	Red	Light red	White	White	White	White	White	White	White	White	White
Pericarp thickness	Both seasons	Thick	Thick	Thick	Thick	Thick	Inter mediate	Thick	Inter mediate	Thick	Inter mediate	Thin	Thin	Very thin
Pigmented testa[a]	Both seasons	Yes	No	Yes	Yes	Yes	No	No	No	No	No	No	No	No
Endosperm texture[b] (visual)	1999	3	5	3	4	4	3	3	3	3	2	4	2	ND[c]
	2000	4	4	3	4	4	3	3	3	2	2	3	2	ND

[a]Yes = pigmented testa present, No = pigmented testa absent.
[b]Subjectively rated on a 1 to 5 scale, where 1 = vitreous and 5 = floury.
[c]ND = not determined.

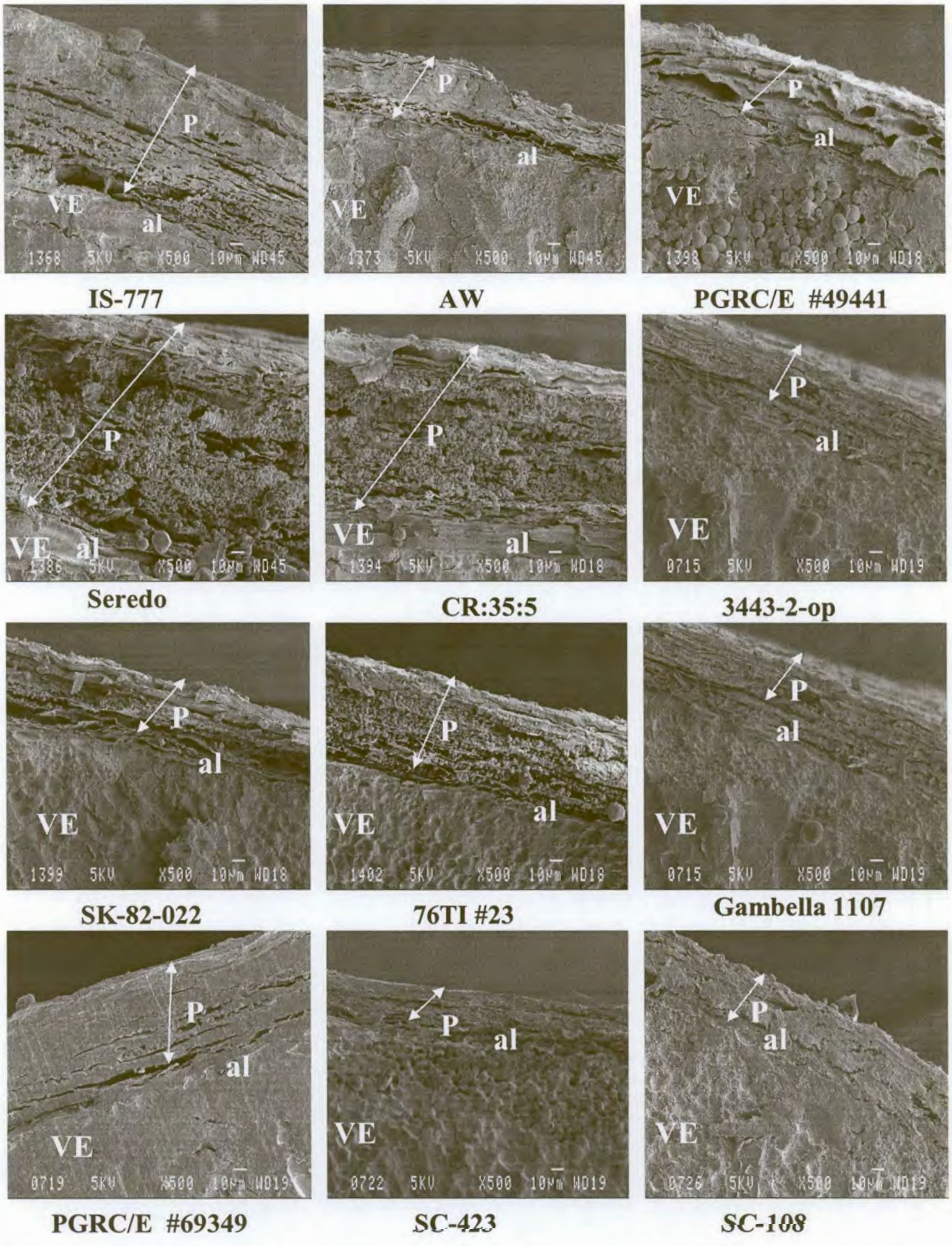

Figure 3.3.1. Micrographs of the 12 sorghum cultivars varying in pericarp thickness from the 1999 growing season. P = pericarp; VE = vitreous endosperm; al = aleurone layer.

Visual rating of endosperm texture indicated that three sorghum cultivars PGRC/E #693496, SC-423 and SC-108 possessed essentially vitreous endosperm. Two cultivars, AW and CR:35:5, were essentially floury, indicating the existence of cultivar differences for endosperm texture. Endosperm texture (visual) expectedly highly negatively correlated with test weight, vitreousness (image) and hardness (TADD) ($r = -0.68$, $r = -0.77$, $r = -0.83$, $p < 0.001$), respectively (Table 3.3.2). The inverse relationships indicate that the softer the kernel, the less vitreous and less hard it was. Endosperm texture positively correlated with *injera* softness, a positive textural attribute of *injera* ($r = 0.59$, $p < 0.01$) (Table 3.3.3) indicating that cultivars with soft endosperm tend to make *injera* with soft texture. This agrees with the observation by Rooney et al (1986) that sorghum cultivars with softer endosperm texture produce *injera* with the most desirable texture and keeping quality.

Four sorghum cultivars (IS-777, PGRC/E #69441, Seredo and CR:35:5) had a pigmented testa as revealed by the Chlorox Bleach Test. Tef grain used in this study did not have a pigmented testa. In sorghum the presence or absence of testa 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). The pigments responsible for this color are polymeric polyphenols known as tannins (Butler 1990), which cause dark color and astringency in food prepared from whole sorghum with pigmented testa (Bacon and Rhodes 2000). Thus, it is essential to decorticate tannin-containing sorghums to remove the tannin layer or composite with tannin-free tef to act as tannin diluent and improve the *injera* quality (Chapter 3.1).

The L-values (lightness) of the sorghum kernels across seasons ranged from 27.3 (IS-777) to 53.5 (CR:35:5) (Table 3.3.4). Tef had L-value of 53.4. The L-values of sorghum flours ranged from 59.61 (IS-777) to 75.6 (PGRC/E #69349). Tef flour had a mean L-value of 73.7 less light than some of the white sorghum flours. Among the sorghum cultivars, significant differences between cultivars were apparent for grain and flour lightness, redness and yellowness. In sorghum, pericarp color is genetically controlled and can be red, lemon yellow or white (Rooney and Miller 1982). Color is one of the most important considerations in assessment of flour quality in *injera* preparation. Consumers prefer

Table 3.3.2. Significant correlations among physico-chemical parameters of the 12 sorghum cultivars across the 1999 and 2000 growing seasons

Parameter	TW	TKW	Protein	Ash	Fat	Starch	Amylose	Vitreous-ness (image)	Extraction rate (TADD)	WSI	Peak viscosity	Hot paste viscosity	Breakdown viscosity	Final viscosity	Setback viscosity
TW															
TKW	0.42*														
Protein															
Ash	-0.71***														
Fat															
Starch		0.44*													
Amylose		-0.48*													
Vitreousness (image)	0.66***			-0.62**	0.51*		-0.45*								
Extraction rate (TADD)	0.78***			-0.60**				0.65***							
Endosperm texture (visual)	-0.68***			0.62**				-0.77***	-0.83***						
WSI															
WAI		-0.44*						-0.44*		-0.52*					
Peak viscosity					-0.43*	0.51*									
Hot paste viscosity						0.55**		-0.54**			0.86***				
Breakdown viscosity			-0.49*												
Final viscosity		0.57**				0.61**					0.79***	0.84***			
Setback viscosity	0.50*	0.60**				0.54**					0.61**	0.59**		0.93***	
Pasting temperature												0.43*	-0.42*	0.43*	
PTD			-0.69***										0.69***		0.56**
Gel firmness	0.44*		-0.55**	-0.56**									0.57**		0.43*

Level of statistical significance at p <0.05 (*), p <0.01 (**), p <0.001 (***).
TW = Test weight, TKW = Thousand kernel weight, WSI = Water solubility index, WAI = Water absorption index, PTD = Peak time duration.

Table 3.3.3. Significant correlations between physico-chemical parameters of the 12 sorghum cultivars and sensory and instrumental textural attributes of *injera* across the 1999 and 2000 growing seasons

	Parameter											
***Injera* attribute**	**Test weight**	**Ash**	**Starch**	**Vitreousness (image)**	**Extraction rate (TADD)**	**Endosperm texture (visual)**	**Water solubility index**	**Water absorption index**	**Peak viscosity**	**Hot paste viscosity**	**Cold paste viscosity**	**Setback viscosity**
Shininess	-	-	-	-	-	-	-	-	-	-	0.46*	0.50*
Eye evenness	-	-	0.52*	-	-	-	-	-	-	-	-	-
Eye distribution	-	-	0.55**	-	-	-	-	-	-	-	-	-
Softness	-0.61**	0.50*	-	-0.59**	-0.70***	0.59**	-	-	-	-	-	-
Stickiness	-	-	-	-	-	-	-	0.45*	0.46*	0.50*	-	-
Fluffiness	-	-	-	-	-	-	0.48*	-0.71***	-	-	-	-
Rollability	-0.54**	0.50*	-	-	-0.66**	-	-	-	-	-	-	-
Grittiness	-	-	-	-	0.42*	-	-	-	-	-	-	-
Bending force (after 1 hr)	-	-	-	-	-	-	-	-	-	-	-	0.43*
Bending force (after 24 hr)	-	-	-	-	-	-	-	-	-	-	-	0.62**
Bending force (after 48 hr)	-	-	-	-	-	-	-	-	-	-	-	0.61**

Level of statistical significance at p <0.05 (*), p <0.01 (**), p <0.001 (***).
- = not significant.

injera prepared from white tef or white sorghum cultivars (Gebrekidan and GebreHiwot 1982). Decortication of sorghum increases lightness of the flour possibly through the removal of pigments associated with the bran.

Table 3.3.5 shows TKW, test weight, endosperm texture and hardness (extraction rate) of sorghum and tef. TKW across seasons ranged from 19.8 g for IS-777 to 32.6 g for PGRC/E #69349, indicating cultivar differences for TKW. Grain tef had extremely low TKW (0.33 g) compared to sorghums due to its small size, less than 1.5 mm in length (Parker et al 1989). In general, sorghum cultivars with larger kernel size also had higher kernel weight. TKW positively correlated with test weight ($r = 0.42$, $p < 0.05$) (Table 3.3.2). It seemed that the heavier the kernel the denser it was. However, further verification is needed with respect to this statement due to relatively low r-value.

Test weight for sorghums across seasons ranged from 70.1 (CR:35:5) to 78.5 kg/hl (PGRC/E #69441). Tef had a higher test weight (86.2 kg/hl) than the sorghum cultivars. This is due to tiny size of tef grain, which compacted in the hectoliter cup with minimum void space between the grains. Among the sorghum cultivars, test weight was highly positively correlated with vitreousness (image analysis) ($r = 0.66$, $p < 0.001$) (Table 3.3.2). This can be ascribed to the tightly packed cells and cellular components of the vitreous region of the endosperm (Shull et al 1990), which probably makes the kernel denser, hence higher test weight. Test weight was highly negatively correlated with ash content ($r = -0.71$, $p < 0.001$). It appears that dense kernels possess lower proportion of bran (rich in minerals) component resulting to lower ash content. Test weight was also negatively correlated with the positive *injera* textural attributes of softness and rollability ($r = -0.61$. $r = -0.54$; $p < 0.01$) (Table 3.3.3). This could relate to the amount and type of protein present in denser kernels to produce *injera* with firmer texture.

Vitreousness (image analysis) of sorghum cultivars ranged from 30.3% for the relatively floury cultivar IS-777, to 55.2% for the most vitreous cultivar SC-108 across the two seasons (Table 3.3.5). Figure 3.3.2 shows section through the 12 sorghum cultivars from the 1999 growing season, illustrating the varying proportions of vitreousness. The endosperm consists of an outer translucent vitreous area and an inner opaque floury area.

The proportions of the two vary from cultivar to cultivar. Such variation within the same season indicates the existence of genetic diversity for endosperm texture. 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 the genotypes differing in vitreousness. Vitreousness was highly positively correlated with test weight ($r = 0.66$, $p < 0.001$) and negatively with ash ($r = -0.62$, $p < 0.01$) (Table 3.3.2). It appears that vitreous grains have high test weight due to a higher proportion of the dense continuous starch-protein matrix. Low ash content can be attributed to low proportions of bran fraction rich in minerals. Vitreousness was also negatively correlated with *injera* softness ($r = -0.59$, $p < 0.01$) (Table 3.3.3). With few exceptions, cultivars with vitreous endosperm tend to produce firm *injera*. This could be due to less amylose leaching as starch granules are packed into dense protein matrices in the flour particles.

The difference in vitreousness was also reflected in a wide range of hardness (expressed as extraction rate) from 87.1% (SC-108), to 62.3% (AW). This is because the efficiency of removal of the bran depends on hardness, size and shape of the grain (Scheuring et al 1983). Within the sorghum cultivars, hardness was highly positively correlated with test weight and vitreousness ($r = 0.78$, $r = 0.65$, $p < 0.001$) (Table 3.3.2). These positive correlations can be explained by the sorghum grain hardness being related to the distribution density of protein bodies and matrix in the endosperm (Shull et al 1990). Sorghum grain hardness negatively correlated with the positive *injera* textural attributes of softness and rollability ($r = -0.70$, $r = -0.66$; $p < 0.001$) and positively correlated with grittiness, a negative textural attribute of *injera* ($r = 0.42$, $p < 0.05$) (Table 3.3.3). Rooney and Murty (1982) reported that sorghum cultivars with hard, corneous (vitreous) endosperms are undesirable for *kisra* (similar flat bread from Sudan). Grittiness of *injera* can be attributed to the particle size of the flour produced by milling. In maize, hard grain yields larger particle size flour than do softer grains (Pomeranz et al 1986), which may also apply to sorghum.

Table 3.3.4. Kernel and flour colors (Lab values) of the 12 sorghum cultivars and tef from the 1999 and 2000 growing seasons

			Sorghum cultivar												Tef
Parameter	**Season**	**Color L a b**	**IS-777**	**AW**	**PGRC/E #69441**	**Seredo**	**CR:35:5**	**3443-2-op**	**SK-82-022**	**76TI#23**	**Gambella 1107**	**PGRC/E #69349**	**SC-423**	**SC-108**	**DZ-01-196**
Kernel color	1999	L	27.3a[a]±0.2[b]	35.8c±0.4	32.3b±0.1	37.1d±0.2	52.9h±0.2	49.5f±0.1	45.0e±0.4	53.0h±0.4	54.5j±0.1	53.5i±0.3	54.3j±0.1	52.0g±0.1	53.4g±0.0
	2000		27.4a±0.1	35.4c±0.3	33.6b±0.1	39.9d±0.1	54.1j±0.3	54.0j±0.1	52.5i±0.1	47.8f±0.1	49.3g±0.2	50.6h±0.1	45.4e±0.1	47.9f±1.1	53.4i±0.0
	Mean[c]		27.3a±0.2	35.7b±0.4	32.9b±0.7	38.5c±1.6	53.5g±0.7	51.8ef±2.5	48.7d±4.1	50.4de±2.8	51.8ef±2.8	52.0ef±1.6	49.8de±4.9	50.0de±2.4	53.4ef±0.0
	1999	a	9.4k±0.0	8.2i±0.1	7.7h±0.1	8.7j±0.0	2.3a±0.1	3.5d±0.0	5.7g±0.1	4.1f±0.1	3.3c±0.1	3.4cd±01	3.6e±0.1	4.2f±0.1	2.9b±0.0
	2000		9.6g±0.2	9.7g±0.0	8.3f±0.1	8.6f±0.2	2.7a±0.2	2.8a±0.0	3.7bc±0.0	4.7e±0.0	3.4b±0.0	3.7c±0.0	4.8e±0.0	4.3d±0.0	2.9a±0.0
	Mean		9.5 g±0.2	8.9f±0.8	8.0e±0.4	8.6f±0.1	2.5a±0.2	3.1bc±0.4	4.7d±1.1	4.4d±0.3	3.3bc±0.1	3.5c±0.2	4.2d±0.6	4.2d±0.0	2.9ab±0.0
	1999	b	8.2b±0.1	11.8c±0.1	7.8a±0.1	13.5d±0.0	14.3f±0.0	15.1i±0.0	13.9e±0.1	14.7h±0.1	15.8j±0.0	16.6l±0.1	17.1m±0.0	15.9k±0.0	14.6g±0.0
	2000		8.1a±0.1	13.6d±0.0	9.3b±0.1	14.6e±0.1	13.7d±0.1	15.1g±0.0	14.9f±0.1	13.5c±0.1	15.1g±0.0	15.0g±0.0	15.8i±0.0	15.2h±0.1	14.6e±0.0
	Mean		8.1a±0.1	12.7b±1.0	8.5a±0.8	14.0c±0.6	14.0c±0.3	15.1de±0.0	14.4c±0.5	14.1c±0.7	15.5ef±0.4	15.8fg±0.9	16.4g±0.7	15.6ef±0.4	14.6cd±0.0
Flour color	1999	L	58.4b±0.1	62.4d±0.0	57.8a±0.1	61.0c±0.0	68.5e±0.0	74.0i±0.0	68.8f±0.1	76.0l±0.0	73.9i±0.0	74.8j±0.0	73.5g±0.1	74.9k±0.0	73.8h±0.0
	2000		60.7a±0.0	67.9d±0.1	63.0b±0.1	64.8c±0.1	70.7e±0.0	76.6l±0.1	73.7h±0.0	73.3f±0.1	74.9i±0.0	76.4k±0.0	74.8i±0.0	74.9j±0.0	73.7g±0.0
	Mean		59.6a±1.2	65.7c±2.4	60.4a±2.9	62.9b±2.1	69.6d±1.2	75.3ef±1.4	71.2d±2.7	74.6ef±1.5	74.4ef±0.5	75.6g±0.9	74.2ef±0.7	74.9ef±0.0	73.7e±0.1
	1999	a	5.8h±0.0	3.5f±0.0	6.6i±0.0	3.8g±0.3	1.3d±0.0	0.1a±0.0	2.3e±0.0	0.5c±0.0	0.1a±0.0	-0.03a±0.0	0.4b±0.0	0.6c±0.0	0.1a±0.0
	2000		5.3j±0.0	2.5g±0.0	5.2i±0.0	3.6h±0.0	1.8f±0.0	0.2b±0.0	1.2d±0.0	1.6e±0.0	-0.2b±0.0	0.4c±0.0	0.1a±0.01	0.4c±0.0	0.1a±0.0
	Mean		5.5f±0.3	3.0d±0.6	5.9f±0.8	3.7e±0.2	1.6c±0.2	0.1a±0.0	1.8c±0.6	1.1b±0.6	-0.1a±0.0	0.2a±0.2	0.5a±0.1	0.1a±0.0	0.0a±0.0
	1999	b	8.9c±0.0	9.4d±0.1	8.5 a±0.0	8.5a±0.0	8.6b±0.0	13.0k±0.0	10.7e±0.0	10.8f±0.0	12.4h±0.0	13.0j±0.0	13.6l±0.0	12.7i ±0.0	12.0g±0.0
	2000		8.8b±0.0	10.2e±0.0	8.6a±0.0	9.2d±0.0	9.2c±0.0	12.6m±0.0	11.0g±0.0	0.8f±0.0	12.3l±0.0	11.4h±0.0	11.8i±0.0	12.2k± 0.0	12.0j± 0.0
	Mean		8.8a±0.1	9.8b±0.5	8.6a±0.1	8.9a±0.4	8.9a±0.3	12.8g±0.2	10.8c±0.1	10.8c±0.0	12.4def±0.1	12.2de±0.9	12.7ef±1.0	12.5def±0.3	12.0d±0.0

[a]Values followed by the same letter in the same row are not significantly different (p ›0.05). [b]Values are standard deviations of three replicates.
[c]Values are the means of the two seasons. L = lightness, a (+) = redness, b (+) = yellowness.

Table 3.3.5. Thousand kernel weight, test weight, extraction rate and endosperm texture of sorghum cultivars and tef from 1999 and 2000 growing seasons

Parameter	Season	Sorghum cultivar												Tef
		IS-777	AW	PGRC/E #69441	Seredo	CR:35:5	3443-2-op	SK-82-022	76TI #23	Gambella 1107	PGRC/E #69349	SC-423	SC-108	DZ-01-196
Thousand kernel weight	1999	20.1b[a]±0.1[b]	29.3k±0.1	24.0f±0.3	21.6d±0.0	22.9e±0.1	25.2g±0.0	23.6f±0.3	25.8i±0.4	27.9j±0.4	25.6gh±0.2	20.9c±0.0	21.9d±0.2	0.32a±0.0
	2000	19.5b±0.3	35.3k±0.5	23.8ef±0.6	23.8f±0.0	23.3e±0.2	22.4d±0.1	24.5g±0.1	30.3i±0.1	31.4j±0.1	39.7l±0.4	25.9h±0.1	20.3c±0.0	0.34a±0.0
	Mean[c]	19.8b±0.4	32.3f±3.3	23.9bc±0.5	22.7bc±1.2	23.1bc±0.3	23.8bc±1.6	24.1cd±0.5	28.0de±2.5	29.7ef±1.9	32.6f±7.7	23.4bc±2.8	21.1bc±0.9	0.33a±0.0
Test weight (kg/hl)	1999	72.0c±0.2	71.0b±0.3	78.5h±0.2	69.7a±0.3	69.6a±0.1	74.3e±0.1	73.6d±0.1	77.4g±0.1	70.7b±0.2	74.2e±0.4	69.8a±0.2	75.1f±0.3	86.5i±0.2
	2000	71.9c±0.2	74.1d±0.1	78.5g±0.2	71.5b±0.2	70.6a±0.2	74.5e±0.2	74.1de±0.2	79.2h±0.3	78.0f±0.1	79.9i±0.3	78.7g±0.2	77.9f±0.3	86.0j±0.1
	Mean	71.9abc±0.2	72.6bcd±1.7	78.5f±0.2	70.6ab±1.0	70.1a±0.5	74.4de±0.2	73.9cd±0.3	78.3f±1.0	74.4cde±4	77.0f±3.1	74.3cde±5	76.5ef±1.5	86.2g±0.3
Vitreousness (%)[d]	1999	32.2a±4.2	34.1a±3.2	49.2de±2.7	38.2abc±3.7	33.0a±9.4	35.7ab±1.4	45.7cde±2.0	44.1bcd±1.3	41.5abcd±8.4	51.2ef±2.8	48.6de±5.2	59.2f±12.8	ND
	2000	28.4a±7.8	37.0bc±3.2	47.6de±4.4	30.9ab±4.6	30.8ab±6.9	39.5cd±6.3	37.2bc±6.9	50.1e±1.5	50.6e±1.8	48.4e±5.5	51.4e±3.6	51.1e±3.6	ND
	Mean	30.3a±5.9	35.5abc±3.2	48.4f±3.4	34.5ab±5.5	31.9ab±7.4	37.6bc±4.6	41.5cd±6.5	47.1df±3.5	46.1df±7.4	49.8fg±4.2	50.0fg±4.2	55.2g±9.5	ND
Hardness (%)[e]	1999	71.2cd±2.9	56.5a±1.0	76.8def±2.8	66bc±4.9	62.2ab±4.4	71.7cd±7.0	80.3fg±2.4	73.3de±3.5	73.5de±0.9	78.8cfg±3.0	63.8b±5.0	84.5g±1.8	ND
	2000	73.6bc±3.0	76.2bcd±5.1	83.0gh±4.8	67.1a±2.0	72.0ab±2.2	78.2efg±3.6	80.0fg±4.5	73.3bcd±3.8	87.2hi±2.3	86.3hi±1.0	83.3gh±1.6	89.7i±0.6	ND
	Mean	72.4±1.2	66.4±13.9	79.9±4..4	66.6±0.8	67.1 ±6.9	75.0±4.6	80.2±0.2	73.3±0.0	80.4±9.7	82.6±5.3	73.6±13.8	87.1±3.7	ND

[a]Values followed by the same letter in the same row are not significantly different (p ›0.05).
[b]Values are standard deviation of three replicates.
[c]Mean values are mean of the two seasons.
[d]Endosperm texture expressed as percent vistreousness (image analysis).
[e]Extraction rate expressed as percent hardness.
ND = Not Determined.

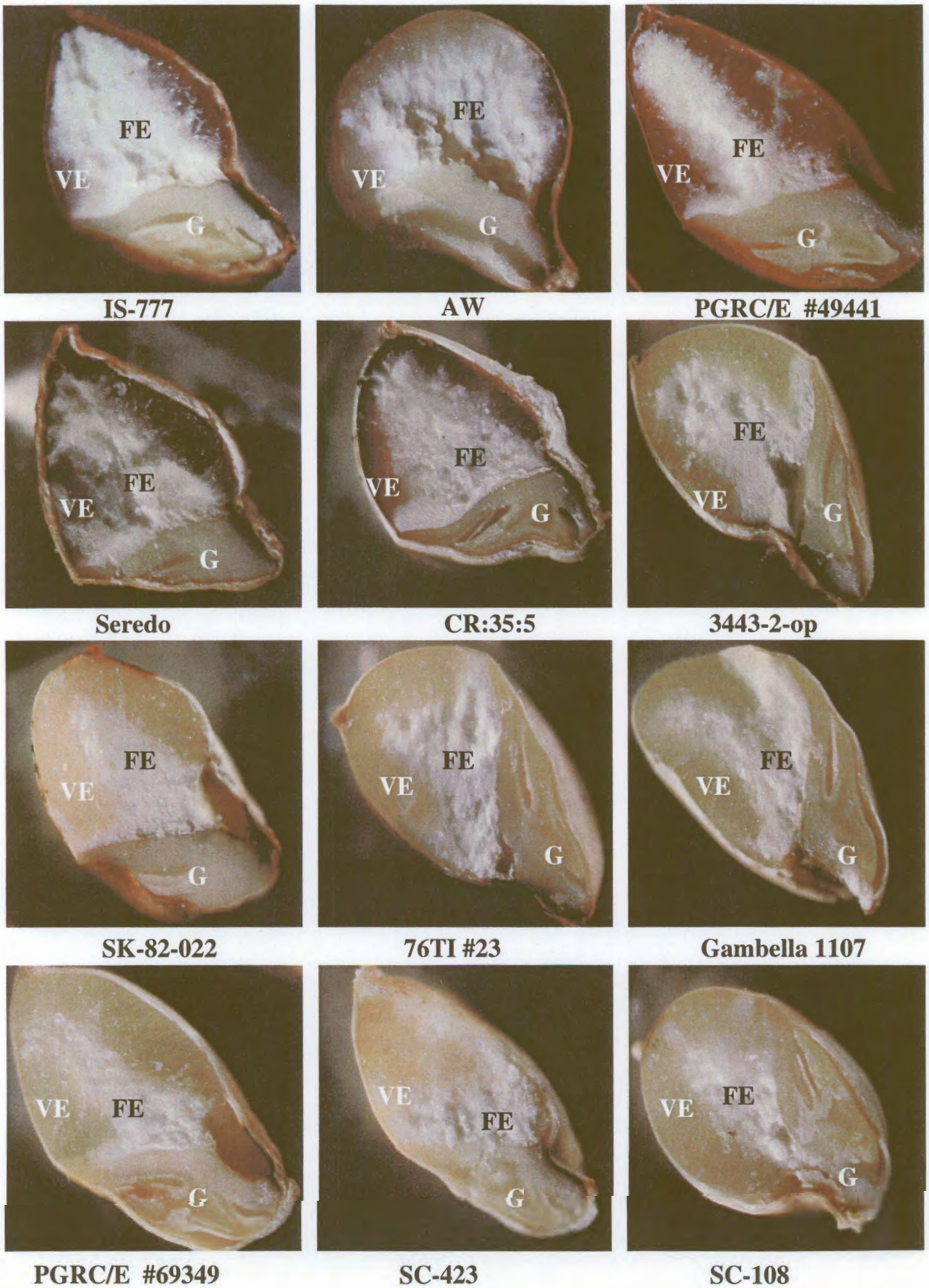

Figure 3.3.2. Micrographs of longitudinal sections of the 12 sorghum cultivars with varying endosperm texture from the 1999 growing season. FE = floury endosperm; VE = vitreous endosperm; G = germ.

3.3.3.2. Chemical characterization

Among the sorghum cultivars, protein content across seasons ranged from 10.5% for 76TI #23 to 15.2% for AW (Table 3.3.6). Protein content varied slightly between the seasons. In sorghum, protein content is influenced by cultivar and the environment, with considerable environmental variation (House et al 1995). The protein content of tef was lower (9.7%). These values lie within the range of reported values 7.3%-15.6% for sorghum (Serna-Saldivar and Rooney 1995) and 6.5%-9.3% for tef (Lester and Bekele 1981). Protein content negatively correlated with breakdown viscosity and peak time duration of the flour paste ($r = -0.49$, $r = -0.69$, $p < 0.05$, $p < 0.001$) respectively (Table 3.3.2). The negative relationship between protein and breakdown viscosity suggests that protein matrix inhibited the swelling of the starch granule and conferred added integrity/rigidity to the swollen granules, resulting in lower breakdown viscosity.

The lysine content of sorghums across the two seasons ranged from 1.7 g/100 g protein for 76TI #23 to 2.2 g/100 g protein for SK-82-022. Tef protein contained higher lysine (3.2 g/100 g protein). This value lies within the range of lysine content of tef (2.9-3.9 g/100g protein) as reported by Lester and Bekele (1981). In sorghum most of the endosperm protein is kafirin (prolamin), which is virtually lacking in the essential amino acid lysine (Taylor and Schüssler 1986). Umeta and Parker (1996) reported that the germ of tef grain is large in proportion to the rest of the kernel. The higher lysine content of tef is probably due to more albumins and globulins in the germ, which are relatively rich in lysine as reported for sorghum (Taylor and Schüssler 1986, Serna-Saldivar et al 1994). Tef is not decorticated prior to milling to flour; consequently, *injera* from tef is of better nutritional value compared to *injera* from decorticated sorghum.

The fat content of sorghum cultivars across seasons ranged from 2.8% (IS-777) to 3.8% (PGRC/E 69441), while the fat content of tef was in the lower range (2.8%). Differences in fat content among the sorghum cultivars appear to be due to differences in germ size and amount of oil in the germ, as reported for maize (Hoseney 1994). High fat content in whole flour of sorghum may result to rancidity problem upon storage due to oxidation of unsaturated fatty acids. Fatty acids of sorghum grain lipids are reported to be highly unsaturated (Maestri et al 1996).

Among the sorghum cultivars, ash content ranged narrowly from 1.6% to 1.9%, while tef had relatively higher 2.3% ash content. This could be attributed to the small grain size of tef resulting in a greater proportion of pericarp and aleurone layers that are rich sources of minerals (Serna-Saldivar and Rooney 1995). Among the sorghum cultivars, ash content highly negatively correlated with test weight ($r = -0.71$, $p < 0.001$) (Table 3.3.2). The negative relationship between ash and test weight suggests that cultivars with high test weight have lower proportion of bran resulting to low ash content.

The starch content of the sorghum cultivars across seasons ranged from 70.4% (SC-108) to 76.7% (PGRC/E #69349). Tef had relatively higher starch content (79.5%) and lower protein content. Starch plays a major role in the formation of the continuous matrix of *injera* during baking (Parker et al 1989). The continuous matrix formed due to complete gelatinization of starch during baking results to the structural integrity and texture of the *injera*. Starch content positively correlated with TKW ($r = 0.44$, $p < 0.05$) (Table 3.3.2). It seemed that higher kernel weight would mean more starch is present in the endosperm. Starch content also positively correlated with *injera* eye evenness and distribution ($r = 0.55$, $r = 0.52$, $p < 0.01$, $p < 0.05$), respectively (Table 3.3.3). Although these relationships were not easily explainable, this finding agrees with Subramanian and Jambunathan (1990) who reported a significant positive correlation between starch content and eye quality of *injera*.

The amylose content (amylose as percent of starch in the endosperm) across seasons for the sorghum cultivars ranged from 16.2% for (SC-108) to 25.8% for (CR:35:5). Amylose content of tef was in the lower range (18.8%) compared to sorghum cultivars. Differences in amylose content between seasons were observed for most of the sorghum cultivars. Ring et al (1989) also reported significant differences in amylose content for sorghums grown at different locations or at different seasons in the same locations. Amylose content was negatively correlated with TKW ($r = -0.48$, $p < 0.05$) (Table 3.3.2).

Table 3.3.7 shows that among the sorghum cultivars, WAI across seasons ranged from 1.2 g/g (AW) to 2.1 g/g (Seredo). Tef had lower WAI (1.1 g/g) and as mentioned contained higher starch (79.5%). High starch content may slow water absorption as water

Table 3.3.6. Chemical composition (dry weight basis) of whole grain sorghum and tef flours from the 1999 and 2000 growing seasons

Parameter	Season	Sorghum cultivar												Tef
		IS-777	**AW**	**PGRC/E #69441**	**Seredo**	**CR:35:5**	**3443-2-op**	**SK-82-022**	**76TI#23**	**Gambella 1107**	**PGRC/E #69349**	**SC-423**	**SC-108**	**DZ-01-196**
Protein (%)	1999	13.9i[a]±0.1[b]	16.0k±0.1	12.2e±0.1	14.4j±0.1	11.9c±0.0	12.2d±0.0	13.6h±0.1	9.3a±0.1	12.5f±0.0	12.6f±0.0	11.8c±0.1	13.1g±0.1	9.4b±0.1
	2000	14.0gh±0.1	14.4h±0.1	12.8d±1.3	10.1a±0.0	11.8c±0.0	12.7d±0.0	13.3ef±0.1	11.8c±0.0	13.2ef±0.1	10.8b±0.1	9.5a±0.1	13.7fg±0.0	10.1a±0.0
	Mean[c]	13.9f±0.1	15.2g±0.7	12.5cde±0.9	12.2cd±2.4	11.9cd±0.1	12.3cde±0.3	13.4ef±0.2	10.5a±1.4	12.9def±0.4	11.7bc±1.0	10.6ab±1.3	13.4ef±0.32	9.7a±0.4
Lysine (g/100 g protein)[d]	1999	1.6	1.7	1.9	1.8	1.9	1.7	1.6	2.1	1.8	1.8	2.1	1.9	2.5
	2000	2.2	2.9	3.0	2.9	2.2	2.8	2.8	2.6	2.2	2.7	2.8	2.4	3.8
	Mean	1.9	2.3	2.5	2.4	2.1	2.3	2.2	2.4	2.0	2.3	2.5	2.2	3.2
Fat (%)	1999	3.0a±0.0	3.2b±0.1	3.7de±0.0	3.0a±0.1	2.9a±0.0	3.6d±0.4	3.0a±0.1	3.4c±0.4	3.8e±0.1	3.9e±0.0	4.3f±0.0	3.6d±0.0	2.9a±0.0
	2000	2.7a±0.0	3.4ef±0.1	3.9i±0.0	3.2c±0.0	3.5fg±0.1	4.0j±0.1	3.3de±0.1	3.6h±0.3	3.3cd±0.1	3.3cd±0.0	3.4de±0.1	3.6gh±0.1	2.8b±0.0
	Mean	2.8a±0.1	3.3bc±0.1	3.8e±0.1	3.1ab±0.1	3.2b±0.3	3.7de±0.3	3.2b±0.2	3.5c±0.1	3.5cd±0.3	3.6cde±0.3	3.8e±0.1	3.6cde±0.0	2.8a±0.1
Ash (%)	1999	1.9cd±0.2	1.9cd±0.2	1.6ab±0.0	1.8abcd±0.2	1.7abc±0.0	1.8abcd±0.0	1.9d±0.0	1.7abcd±0.1	1.7abcd±0.0	1.8abcd±0.0	1.8bcd±0.0	1.6a±0.3	2.3e±0.0
	2000	1.9e±0.0	1.8c±0.0	1.6a±0.0	1.8c±0.0	1.7b±0.0	1.8c±0.0	1.7b±0.0	1.6a±0.0	1.6a±0.0	1.6a±0.0	1.6a±0.1	1.6a±0.1	2.4f±0.0
	Mean	1.9d±0.1	1.8cd±0.1	1.6a±0.0	1.8bcd±0.1	1.7abc±0.0	1.8bcd±0.0	1.8bcd± 0.1	1.6a±0.1	1.6a±0.1	1.7ab±0.1	1.7abc±0.1	1.6a±0.2	2.3e±0.3
Starch (%)	1999	71.0ab±0.4	73.7cd±3.5	74.8cdef±0.2	74.5cde±0.3	76.6efg±1.6	79.8hi±2.1	74.6cdef±0.1	77.6gh±2.6	77.0fg±0.7	75.6defg±0.6	72.7bc±0.9	69.2a±0.8	80.4i±0.9
	2000	71.5a±0.9	73.7abcd±2.2	75bcde±0.5	76.7def±0.8	73.3abc±1.0	74.8bcd±0.7	75.0bcde±0.5	76.1cdef±2.9	74.5abcd±1.8	77.9ef±1.6	72.4ab±4.7	71.5a±0.3	78.6f±0.2
	Mean	71.3a±0.7	73.7bc±2.6	74.9cd±0.4	75.6cde±1.3	74.9cd±2.2	77.3e±3.1	74.8cd±0.4	76.8de±2.6	75.8cde±1.9	76.7de±1.7	72.6ab±3.0	70.4a±1.4	79.5f±1.1
Amylose (% of starch)	1999	24.2gh±1.5	15.5a±0.5	22.6ef±1.0	20.3d±0.4	25.3i±1.5	23.9fg±0.7	24.3gh±0.0	20.6d±0.1	18.0c±0.5	16.3ab±0.4	21.4de±0.3	17.5bc±0.3	18.6c±1.2
	2000	26.3g±2.0	17.5bc±0.1	27.4g±2.4	19.9def±0.2	26.3g±1.6	20.9ef±0.2	21.3f±0.2	19.6de±0.2	16.7b±0.5	17.1b±0.2	19.9def±0.1	15.0a±0.1	19.1cd±0.2
	Mean	25.2g±1.9	16.5a±1.3	25.0g±3.1	20.1cd±0.3	25.8g±1.5	22.4f±1.7	22.8f±1.7	20.1cd±0.5	17.3ab±0.8	16.7a±0.6	20.6d±0.8	16.2a±1.4	18.8bc±0.8

[a]Values followed by the same letter in the same row are not significantly different ($p > 0.05$).
[b]Values are standard deviations of three replicates.
[c]Values are means of the two seasons.
[d]Single determinations.

may be differentially absorbed by the various components within the flour. Differences in WAI also appear to be due to differences in damaged starch during mechanical milling. Damaged starch absorbs more water as opposed to intact starch granules (Whistler and BeMiller 1999). Among the sorghum cultivars WAI was negatively correlated with TKW, vitreousness and WSI ($r = -0\ 44$, $r = -0\ 44$ $r = -0\ 52$, $p < 0.05$), respectively (Table 3.3.2).

WSI of sorghum flours across seasons ranged from 1.4 g/100 g (Seredo) to 2.8 g/100 g (AW). Tef flour had a higher WSI (3 g/100 g). Water-soluble pentosans and other low molecular weight components in tef flour might have contributed to its higher WSI. Whole sorghum flours were reported to contain high level of water insoluble cell wall material (5.3%) (Verbruggen et al 1993) that might have contributed to low WSI.

3.3.3.3. Pasting properties and gel firmness

Concerning pasting properties (Table 3.3.8), among the sorghum cultivars, peak viscosity (PV) across the two seasons ranged from 155 (SC-108) to 253 RVU (SK-82-022). The PV of tef was significantly higher (255 RVU). PV indicates the highest apparent viscosity obtained during pasting (Abd Karim et al 2000) and water-binding capacity of starch (Newport Scientific 1995). It appears that tef flour starch had a greater water-binding capacity than sorghum flours upon heating. This is probably due to the smaller tef starch granule size with higher surface area for more water penetration as opposed to the relatively larger sorghum starch granules. Among the sorghum cultivars, peak viscosity negatively correlated with fat content ($r = -0.43$, $p < 0.05$) and positively with starch content ($r = 0.52$, $p < 0.05$) (Table 3.3.2). Lipids in the flour tend to coat the surface of starch granule and act as physical barrier to starch swelling (Whistler and BeMiller 1999). Flours containing higher amount of starch have been associated with generally higher viscosities (Whistler and BeMiller 1999).

It has also been reported that the PV of sorghum starches is affected by growing environment (Beta and Corke 2001).

Table 3.3.7. Water absorption and water solubility indices of whole sorghum and tef fours from the 1999 and 2000 growing seasons

		Sorghum cultivar												Tef
Parameter	**Season**	**IS-777**	**AW**	**PGRC/E #69441**	**Seredo**	**CR:35:5**	**3443-2-op**	**SK-82-022**	**76TI #23**	**Gambella 1107**	**PGRC/E #69349**	**SC-423**	**SC-108**	**DZ-01-196**
Water absorption index (g/g)	1999	1.6fg[a]±0.2[b]	1.2a±0.0	1.5cd±0.0	1.8g±0.2	1.4bcd±0.1	1.4bcd±0.1	1.3abc±0.0	1.3ab±0.1	1.4bcd±0.0	1.4abc±0.01	1.6ef±0.1	1.5bcd±0.0	1.3ab±0.1
	2000	1.8g±0.1	1.2b±0.1	1.7efg±0.1	2.4h±0.2	1.8fg±0.2	1.5cde±0.1	1.6def±0.1	1.5cde±0.0	1.4bc±0.0	1.3b±0.1	1.3b±0.1	1.4bcd±0.1	1.1a±0.0
	Mean[c]	1.7e±0.2	1.2ab±0.0	1.6de±0.2	2.1f±0.4	1.6de±0.2	1.5cd±0.1	1.4cd±0.2	1.4bcd±0.1	1.4bcd±0.0	1.3abc±0.1	1.5cd±0.2	1.4bcd±0.1	1.1a±0.1
Water solubility index (g/100 g)	1999	2.3b±0.0	2.5b±0.6	2.4b±0.2	1.4a±0.3	2.3b±0.2	2.4b±0.4	2.8bc±0.2	2.5b±0.2	2.3b±0.4	2.5b±0.2	2.9bc±0.5	2.5b±0.5	3.2c±0.7
	2000	3.3g±0.5	3.1fg±0.3	2.0b±0.6	1.4a±0.2	1.9ab±0.1	2.7cde±0.0	2.9def±0.5	2.6cde±0.1	2.2bc±0.1	2.8de±0.4	2.2bc±0.1	2.4bcd±0.1	2.9def±0.3
	Mean	2.8de±0.7	2.8de±0.5	2.2bc±0.4	1.4a±0.2	2.1b±0.3	2.5bcd±0.3	2.8de±0.3	2.5bcd±0.2	2.2bc±0.3	2.7cde±0.3	2.6bcd±0.5	2.4bcd±0.3	3.0f±0.5

[a]Values followed by the same letter in the same row are not significantly different ($p > 0.05$).

[b]Values are standard deviations of three replicates.

[c]Values are means of the two seasons.

Hot paste viscosity (HPV) positively correlated with starch content and peak viscosity (r = 0.55, r = 0.86; p <0.01, p <0.001) and negatively with vitreousness (r = 0.86, p <0.001) (Table 3.3.2).

Breakdown viscosity (BV) of tef flour paste (135 RVU) across seasons was three times that of SK-82-022 sorghum, a cultivar with the lowest BV (37 RVU). Han and Hamaker (2001) reported that differences in breakdown value were due to differences in rigidity/fragility of the swollen granules. Highly swollen starch granules are fragile and easily broken by stirring, which leads to a decrease in viscosity (Whistler and BeMiller 1999). This agrees with the finding reported in Chapter 3.1. Zobel (1984) also reported that starches with greater shear thinning are more soluble. Among the sorghum cultivars breakdown viscosity negatively correlated (r = –0.49, p <0.05) with protein content (Table 3.3.2). This negative relationship suggests the involvement of protein in limiting shear thinning in the sorghum flour pastes.

Cold paste viscosity (CPV) of sorghum cultivars across the two seasons varied. The highest CPV was recorded for the cultivar 76TI #23 (457 RVU) and the lowest for SC-108 (235 RVU). Tef had a CPV of 270 RVU. CPV is related to the ability of starch to gel after cooling (Whistler and BeMiller 1999). It can vary with botanical source of the starches, amylose content and formation of amylose-lipid complex (Whistler and BeMiller 1999). CPV was positively correlated with TKW, starch content, PV and HPV (r = 0.57, r = 0.61, p <0.01; r = 0.79, r = 0.84, p <0.001) (Table 3.3.2).

Setback viscosity (SBV) across the two seasons for sorghum flour pastes ranged from 144 RVU (SC-108) to 278 RVU (76TI # 23). Tef flour paste showed lower setback viscosity (150 RVU). This agrees with the finding of Bultosa et al (2002) that tef starch had low setback viscosity compared to maize starch. As stated by Abd Karim et al (2000), setback is likely related to the retrogradation tendency of amylose. SBV was highly positively correlated (r = 0.93, p <0.001) with CPV (Table 3.3.2). This strong relationship explains the obvious fact that pastes with high setback giving rise to high cold paste viscosity. Setback viscosity also highly positively correlated with bending force of *injera* stored for 24 hr (r = 0.62 p <0.01) and 48 hr (r = 0.61 p <0.01) (Table 3.3.3). This long term retrogradation tendency is probably related to amylopectin molecules with a higher proportion of long chains.

Pasting temperature (PT) across seasons for sorghum flours ranged from 77°C (Seredo) to 85°C (3443-2-op). Tef flour showed substantially lower pasting temperature (71°C). This could probably be due to the higher amylopectin content of tef starch compared to sorghum (Table 3.3.6), as high amylose content is believed to actively inhibit swelling in normal cereal starches (Tester and Morrison 1990). As reported by Parker et al (1989), during the baking of *injera,* starch granules completely gelatinize and fuse into a continuous amorphous matrix in which gas bubbles are trapped. The lower pasting temperature of tef starch might allow faster matrix formation. This seems to favor trapping of numerous gas bubbles in the continuous amorphous matrix, which appears to give the desired textural properties (softness, fluffiness and rollability) of tef *injera*. In sorghum its higher pasting temperature might lead to more gas escape before the formation of the continuous matrix.

Peak time duration (PTD) across the two seasons for sorghum cultivars ranged from 1.7 min (SC-423) to 2.9 min (AW). Tef had a longer PTD (3.5 min), which probably resulted to low HPV (Table 3.3.8) due to shear force rupture and fragmentation of starch granules. Among the sorghum cultivars, PTD was positively correlated with breakdown viscosity and setback viscosity ($r = 0.69$, $r = 0.56$; $p < 0.001$, $p < 0.01$) and negatively with protein content ($r = -0.69$, $p < 0.001$) (Table 3.3.2).

Gel firmness (maximum force required for deformation) of the sorghum cultivars varied from 1.6 N (Gambella 1107) to 3.3 N (76TI #23) (Table 3.3.8). The gel firmness of tef flour was significantly higher (8.4 N). The low gel firmness of sorghum flours compared to tef flour appears to be due to differences in chemical composition. Hoseney (1994) reported that gel firmness is an important determinant of food quality as it influences textural properties. The higher tef gel firmness might be related to its soft *injera* texture. Among the sorghum cultivars seasonal and cultivar differences in gel firmness were also observed. This agrees with Murty et al (1982a) who reported significant cultivar differences for gel consistency of cooled thin porridges from sorghum. Gel firmness

Table 3.3.8. Pasting properties and gel firmness of whole sorghum and tef flours from the 1999 and 2000 growing seasons

		Sorghum cultivar												Tef
Parameter	**Season**	**IS-777**	**AW**	**PGRC/E #69441**	**Seredo**	**CR:35:5**	**3443-2-op**	**SK-82-022**	**76TI #23**	**Gambella 1107**	**PGRC/E #69349**	**SC-423**	**SC-108**	**DZ-01-196**
Peak viscosity (RVU)	1999	210f[a]±2[b]	187d±1	155c±3	202e±1	221i±1	217h±0	274k±2	253j±3	214g±1	219hi±0	136b±1.0	125a±1.5	251j±2
	2000	225d±2	234ef±1	196b±0	263h±1	237f±2	227d±1	231e±2	234ef±1	217c±2	255g±5	234f±5	186a±2	260h±1
	Mean[c]	217def±8	210cde±33	176ab±23	233efg±33	229defg±9	222def±5	253g±31	243fg±11	215def±2	237efg±20	185bc±54	155a±33	255g±5
Hot paste viscosity (RVU)	1999	159f±1	142d±1	112c±4	152e±1	164g±5	177h±2	138d±0	179h±8	165g±4	162fg±1	72b±2	61a±1	116c±3
	2000	166c±3	181fg±1	137b±4	213i±1	184g±2	174e±3	192h±0	180f±2	180f±0	179f±4	170d±0	122a±3	124a±4
	Mean	162c±5	162c±21	124b±17	182c±33	174c±12	176c±3	165c±30	179c±5	172c±9	170c±9	121b±54	91a±33	120b±5
Breakdown viscosity (RVU)	1999	52de±2	45bc±2	44b±1	50cd±1	57e±5	40ab±1	36a±2	74g±10	50cd±5	57e±2	65f±1	63f±1	136h±1
	2000	59cde±4	53bc±1	60def±4	51b±2	52b±1	53b±3	39a±3	54bcd±2	36a±2	77g±8	65f±4	64ef±1	135h±4
	Mean	55d±5	49bcd±5	52cd±9	51bcd±2	54d±4	46bc±7	37a±3	64e±13	43ab±8	67e±12	65e±3	63e±1	135f±3
Cold paste viscosity (RVU)	1999	332g±4	360h±1	273d±5	318f±1	362h±1	417j±1	308c±5	456k±2	321f±1	385i±3	181b±2	152a±3	260c±2
	2000	347d±2	394f±5	312b±1	403g±0	358e±2	399fg±2	355e±4	458i±2	358e±4	512j±9	435h±6	319c±1	281a±2
	Mean	340cde±9	377ef±19	292abc±21	361def±47	360def±3	408fg±10	331bcde±26	457g±2	340cde±20	449g±70	308bcd±139	235a±91	270ab±12
Setback viscosity (RVU)	1999	174g±4	218i±1	162de±2	167ef±1	199h±4	239j±1	170fg±5	278k±10	158d±5	223i±3	110b±1	91a±2	144c±1
	2000	182b±5	214d±5	176b±4	191c±1	174b±0	225e±1	163a±4	279g±1	178b±4	334h±13	265f±6	198c±1	157a±3
	Mean	178abc±6	216ed±4	169ab±8	179abc±13	186bc±14	232d±8	167ab±6	278c±6	168ab±12	278e±61	187bc±86	144a±59	150ab±7

Table 3.3.8 (continued).

Pasting temperature (°C)	1999	85gh±0	82de±1	83ef±1	79c±4	84fgh±0	86i±1	85gh±0	80cd±0	73b±0	84fg±1	74b±1	74b±2	71a±1
	2000	85ef±1	85ef±0	82d±1	76b±1	81cd±2	85ef±0	85ef±0	84e±2	86f±1	81cd±0	80c±1	80c±1	72a±1
	Mean	85def±0	83def±2	82cde±1	77b±3	83def±2	85f±1	85ef±0	82cd±2	79bc±7	82cdef±2	77b±3	77b±3	71a±1
Peak time duration (min)	1999	1.7a±0	1.8a±0	1.9b±0	2.1d±0	2.1d±0	2.0c±0	2.1d±0	2.4f±0	1.9bc±0	2.1d±0	2.3e±0	2.1d±0	3.5g±0
	2000	1.9b±0	1.6a±0	2.0bc±0	2.1c±0	1.9b±0	1.9b±0	1.9b±0	2.1c±0	1.7a±0	2.4d±0	2.3d±0	2.1c±0	3.5e±0
	Mean	1.8ab±0	1.7a±0	1.9bc±0	2.1d±0	2.0cd±0	1.9bc±0	2.0cd±0	2.2e±0	1.8a±0	2.2e±0	2.3e±0	2.1d±0	3.5f±0
Gel firmness[d] (N)	1999	2.0abc±0.5	2.1abc±0.2	2.6cd±0.1	2.8d±0.4	2.8d±0.3	2.3bcd±0.5	1.8ab±0.5	3.6e±0.2	1.5a±0.2	1.5a±0.3	2.2bc±0.3	2.1bc±0.2	9.1f±0.4
	2000	2.0ab±0.5	1.7a±0.2	3.9e±0.3	2.6bc±0.5	3.1cd±0.3	2.1ab±0.4	1.9a±0.4	3.1cd±0.4	1.6a±0.2	3.2d±0.1	3.6de±0.2	3.1cd±0.2	7.8f±0.5
	Mean	2.0abc±0.4	1.9ab±0.3	3.2fg±0.7	2.7defg±0.4	3.0efg±0.3	2.2abcd±0.4	1.8ab±0.4	3.3g±0.4	1.6a±0.2	2.4bcde±0.9	2.9efg±0.8	2.6cde±0.6	8.4h±0.8

[a]Values followed by the same letter in the same row are not significantly different (p ›0.05).
[b]Values are standard deviations of two replicates.
[c]Values are the means of two seasons.
[d]Values are mean of four replication.
RVU = Rapid Visco Analyser Units.

positively correlated with test weight, SBV and BV ($r = 0.44$, $r = 0.43$ $p < 0.05$; $r = 0.57$, $p < 0.01$) and negatively correlated with protein content and ash content ($r = -0.55$, $r = -0.56$, $p < 0.01$) (Table 3.3.2).

Figure 3.3.3 illustrates the properties of double compressed sorghum, and tef flour gels. In the first compression cycle, the breaking point of sorghum flour gel was much lower compared to tef flour gel. Tef flour gel was firmer and required higher compression force to deform as shown by its higher peak. After the deforming force of the first compression cycle was removed and the second compression force was applied, tef flour gel almost returned back to its undeformed condition. It appears that tef flour gel is relatively elastic compared to sorghum flour gel. This can be attributed to higher levels of water soluble component in tef flour and lower setback viscosity of its flour paste that might have increased the soluble phase of the gel and promoted the formation of a stronger network structure. Because rigidity is as a result of starch granule swelling, the binding of solubilized molecules and the formation of physical cross-links resulting from molecular reassociation (Zobel 1984). In terms of physical measurement, rigidity results from the applied stress being stored in the paste rather than being dissipated, such a paste is said to be visco-elastic (Zobel 1984). Tef (DZ-01-196) flour starch had a similar low amylose content as sorghum (76TI #23). The difference in gel texture points to structural differences in the amylopectin component of the starch. During the cold storage of the gels, syneresis was observed for the sorghum gels. This agrees with Wu and Corke (1999) who associated softness of gel with release of water (starch syneresis) during storage.

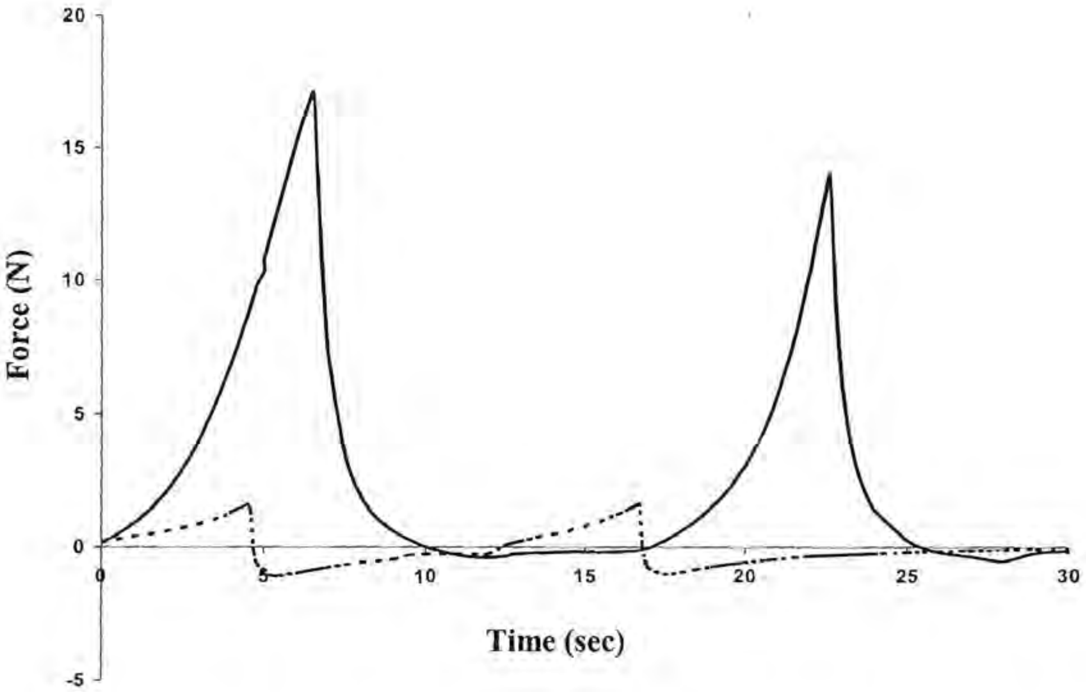

Figure 3.3.3. Double compression of sorghum and tef flour gels aged for 24 hr at 4 °C. Sorghum (76TI #23) .... and tef (DZ-01-196) ———

3.3.4. Conclusions

In terms of chemical composition, compared to tef flour, higher protein, lower protein lysine content, higher fat, and lower starch contents characterize sorghum flours. Sorghum flours showed higher pasting temperature, higher trough (holding strength), lower breakdown (shear thinning), higher final viscosity, and higher setback as compared to tef flour. Sorghum flours formed softer and less elastic gels. Based on linear regression correlation analysis across seasons, physical properties of the grain had a considerable effect on the sensory textural attributes of sorghum *injera*. Cultivars with floury endosperm, relatively lower test weight with low extraction rate were positively correlated with soft and rollable sorghum *injera* texture. Water solubility index of the flour was positively correlated with fluffiness of *injera*. These parameters have potential to be used as indirect indices in predicting the quality of sorghum *injera* in ESIP. However, further research is needed to test large numbers of genotypes from multi-location trials to further evaluate the effects on *injera* quality attributes.

3.3.5. References

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4. GENERAL DISCUSSION

The discussion will firstly examine the strengths and weaknesses of the more important methodologies used in this study and will then discuss in detail the sorghum physico-chemical parameters which correlated with *injera* sensory attributes, in order to identify appropriate parameter(s) and method(s) to be used as selection criteria in the Ethiopian Sorghum Improvement Program (ESIP).

4.1. Methodologies: A critical review

With regard to the selection of sorghum cultivars for this research, the number of cultivars used was too few to represent the broad genetic base of Ethiopian lowland sorghums. Initially we were limited by the available stock (16 cultivars) from the ESIP at Melkassa held for the purpose of seed increase at the time of request. Then four samples got lost in the course of postal parcel delivery from Ethiopia to South Africa. We were left with 12 sorghum cultivars grown for two seasons at the same location. Thus the data generated may not be sufficient enough to draw clear relationships between the measured parameters and come up with concrete selection criteria. A larger number of cultivars grown at a minimum of three different locations would have given a better database. However, in view of the above-mentioned problems and the fact that this study was time-bound it was not possible to deal with such a large number of samples. Nevertheless, the present study did establish evaluation methods, relate measured parameters and established some relationships for future fine-tuning. Therefore, similar work should continue with sorghum cultivars from one of the varietal development stages of the ESIP. The Pre-National Variety Trial handles 15-20 cultivars grown at 2-3 locations for up to two years (personal communication with Ato Geremew Gebeyhu, sorghum breeder, Ethiopian Agricultural Research Organization).

Concerning the method of *injera* preparation, the procedure involved milling decorticated sorghum or whole tef grain into a flour, preparation of a dough and fermentation of the dough after adding a starter culture (a batter from a previous batch, i.e. back slopping) and fermenting at room temperature for about 48 hr. A second stage fermentation was initiated after cooking (gelatinizing) a portion of the fermented dough. After adding back the gelatinized starch to the fermenting dough, the mix was brought to a batter consistency by adding more water. The microorganisms involved in natural fermentation of tef dough are reported to be gram-negative rods, lactic acid bacteria and yeasts, growing in succession (Gashe et al 1982). The end product of a mixed culture spontaneous fermentation is bound to vary, depending on the number and type of microorganisms present in the air and the raw materials, namely the flour and the water. A partial solution to this problem would have been to use a well-identified starter culture. However, as different microorganisms are involved in the fermentation and microorganisms are contributed by the environment, it probably would have made no difference. Fermentation temperature was also dependent on the prevailing ambient temperature. Variation in the ambient temperature affects microbial growth, fermentation rate, rate and amount of lactic acid and carbon dioxide gas production, and the viscosity of the batter. These variations inevitably lead to some inconsistency in *injera* quality between replicates. A water bath incubator at 25 °C was used for the starter culture and dough incubation for experiments conducted in winter. This assisted to some extent in achieving consistency between fermentations.

During baking, the batter was manually poured and spread on the hot clay griddle (*mitad*). Thus, the thickness of the *injera* depended on the consistency of the operator. The electrically heated *mitad* used for baking was not thermostatically controlled. Hence, the time which elapsed between applications of batter on the hot clay griddle needed to be kept as constant as possible to limit variations in batter cooking temperature.

Thus, all the above factors contributed to some variation in *injera* quality not attributable to sorghum cultivar or growing season.

With respect to the evaluation of *injera* quality from different sorghum cultivars, two methods were employed, sensory analysis and instrumental texture analysis. As described in chapter 3.1, a small semi-trained panel (6 people) was used to make subjective judgments about the quality of *injera*, e.g. an overall rating of "poor" or "excellent. In retrospect, this was probably an error, since trained panelists, even if they are consumers of a product, should only rate characteristics objectively. Similar weaknesses in *injera* sensory evaluation are apparent in other studies. Gebrekidan and GebreHiwot used a rating scale of "good" and "poor" with a trained panel. This approach involves emotional judgments. Additionally, what might be "good" for one person might be only "fair" for another (Jellinek 1985). Such a scoring test reflects a mixture of quality rating and hedonic evaluation (Jellinek 1985). Yetneberk and Haile (1992) also used similar rating scale with a semi-trained panel. Jellinek (1985) suggested that the scores have to be anchored and defined, to obtain a true quality rating. In chapter 3.2 descriptive sensory analysis was performed to obtain comprehensive objective measurements of the characteristics of *injera* from the different sorghum cultivars.

Descriptive sensory analysis detects, identifies, describes and quantifies attribute differences between products and gives information on how raw material and process variables affect sensory characteristics (Stone and Sidel 1985). It has been described as the most comprehensive, flexible and useful sensory method, providing detailed information on all sensory properties of a product (Murray et al 2001). The procedure used involved panel selection and training, generation of terms, preparation of score sheet and a series of product evaluation sessions. The trained panel generated 19 *injera* quality descriptors. In accordance with Murray et al (2001), the trained panelists, through the training process, acquired a common qualitative and quantitative frame of reference for use of a standard language and a common scale. However, a few of the panel members could not accurately communicate their perceptions. Further, two panelists were not capable of producing reliable and consistent judgments. It seemed that they interpreted the scales incorrectly. Their responses were eliminated from the data evaluations. The number of terms generated (19) was rather many but enabled the product to be well described. This helped in documenting virtually all possible *injera* sensory characteristics. It has been reported that descriptive sensory analysis is flexible and can include all parameters of the product or it can be limited to certain aspects (Keane 1992). Therefore, in future for the purpose of routine cultivar evaluation, restricting to the most important *injera* quality attributes will be worthwhile. The attributes: white color, soft, rollable, fluffy with even eye size and distribution, in decreasing order of importance are proposed.

Some drawbacks were encountered with descriptive sensory analysis. Panel selection and training was time consuming. The method could only handle a limited number of samples, a maximum of five per session. The success of the method was dependant on the interest, time devotion and motivation of the panel to perform the task. It also involved a very large amount of data capturing from the score sheets. Regarding the outputs obtained, the statistical method, principal component analysis (PCA) used for computing the present data was a powerful tool, which enabled the generation of a clear data map illustrating the various relationships among multiple dependent variables and samples. This would not have been possible with non-visual statistical methods.

Instrumental texture measurement was performed using a TA-XT2 Texture Analyser (Stable Micro Systems, Godalming, UK) with a three-point bending rig attachment. The rig is built on the heavy-duty platform and principally measures the fracture characteristics or brittleness of a product. The *injera* samples were cut into strips of 9 cm x 4 cm. The parameter measured was maximum force required to bend fresh and stored *injera* to measure cultivar differences and to measure the rate of *injera* staling. A problem was that the instrument was sensitive to the thickness of the *injera*. Variation in *injera* thickness from the same sample led to considerable variation between replicates. Hence, a larger number of replicated samples of uniform dimensions were required to obtain acceptable data. Notwithstanding this, the texture analysis method was highly sensitive, simple to operate, required small sample size and the data captured was graphically displayed. Because of these user-friendly inbuilt properties, it lent itself to handling large numbers of samples. A problem, especially for the desired applications, is that a texture analyzer is very expensive to purchase. For practical purposes, a subjective rollability test for measuring changes in staling of *injera* can be employed.

However the major problem was that human sensory perception, which is highly complex, had to be correlated with the instrumental texture data, which are due to the nature of the equipment limited (Szczesniak 2000), in this case only a single physical parameter. Nevertheless there were some valuable significant correlations between the instrumental and the sensory data. Over the two seasons, bending force of sorghum *injera* stored for 48 hr was negatively correlated with fresh *injera* softness and rollability ($r = -0.51$, $r = -0.52$, $p < 0.05$) and positively with grittiness ($r = 0.54$, $p < 0.01$).

Concerning measurement of flour pasting properties, the changes in viscosity during programmed heating and cooling were measured using the Rapid Visco Analyser (RVA)

(Newport Scientific, Warriewood, Australia). The RVA differs from the traditional Brabender Viscoamylograph in two important features: a more rapid rate of heating and a stronger mixing action (Abd Karim et al 2000). Other advantages include small sample size and ability to set a temperature profile. A drawback of all such instruments for the intended application is their high purchase price.

Pasting properties of the flours were probably affected by the bran and germ, and endosperm protein and cell wall components in the whole flour (Chapters 3.1 and 3.3). Working with isolated starch would have eliminated all these effects. However, extracting starch from many samples would have been very time demanding. Additionally, working with flour was appropriate, since *injera* is made from flour and not starch. It may have been better to have used decorticated flour for the pasting work, as decorticated flour was used to make the *injera*. However, the objective was to look at potential methods that could be used to evaluate cultivars. Decortication would add another time-consuming step.

With regard to measurement of endosperm texture, three methods were used: visual assessment, image analysis and measurement of extraction rate using a Tangential Abrasive Dehulling Device (TADD). Visual assessment of endosperm texture was determined by cutting ten sorghum kernels in half longitudinally, and evaluating the proportion of vitreous and floury endosperm using a rating scale of 1 (vitreous) to 5 (floury), as described by Rooney and Miller (1982). These ratings are determined by comparing the sections with photographs of sections with ratings. This method is cheap, simple and applicable to field conditions, but sample size representing a population is very small indeed and judgments are subjective.

With image analysis, the longitudinal section of the grain was viewed using a stereomicroscope and images were captured with a camera. Total vitreous and floury endosperm areas of captured images were measured using image analysis software. This process involved manual tracing of the area with the aid of inbuilt command. A major problem with this is that the accuracy of the traced area is operator-dependent. Image analysis also deals with very small sample to represent a population. Some other problems associated with this method were uniformity of the longitudinal sections, the levelness of section mounting and angle of viewing, all of which can vary due to size and shape differences between samples. This variability might affect the resolution of the images captured and in turn the measurements. Other drawbacks are that the image analysis hardware and software are expensive for the intended use and its use is limited to laboratory conditions.

Grain hardness, expressed as percentage extraction rate, was measured using the TADD, essentially as described by Reichert et al (1982) but the TADD was fitted with abrasive paper of 60 grit (Norton type R284 metalite), (Norton Abrasives, Worcester, USA) instead of a carborundum disk. The abrasive paper wears out frequently and a standard check sample needs to be included in each run to monitor wear. A drawback associated with the method is that it requires larger sample size, which might be a limitation for the intended use of breeder samples. The large sample size is, however, advantageous, as the results are more representative of the whole batch. An inherent problem with the TADD and similar milling tests is that they are only an indirect method of measuring endosperm texture. Rather they measure the hardness (strength) of the grain to abrasive action (Chandrashekar and Mazhar 1999). Other factors influencing the accuracy of the TADD include uniformity of size and sphericity of the grains. Notwithstanding the relative advantages and disadvantages of each of the three methods, as shown in Chapter 3.3, they were all highly significantly correlated with each other for the sorghum samples across the two growing seasons.

4.2. Relating physico-chemical parameters to *injera* sensory textural attributes

An aim of this study was to identify the most appropriate physico-chemical parameters that relate to *injera* sensory attributes, which could thus be used for screening in the Ethiopian Sorghum Improvement Program. Based on the correlations obtained between the sorghum grain physico-chemical parameters and sorghum *injera* sensory textural attributes (Chapter 3.3), the following parameters gave significant correlations and have potential as screening parameters.

As stated, the maximum force required to bend *injera* as measured using a TA-XT2 Texture Analyser negatively correlated with the positive quality attribute of rollability (r

= –47, p <0.05), after storing *injera* for 24 hr (Table 4.1). As the storage period extended to 48 hr, bending force negatively correlated with the positive quality attribute of softness, as well as rollability (r = –0.51, r = –0.52, p <0.05), and positively with the negative quality attribute of grittiness (r = 0.54, p <0.01). These relationships suggest that *injera* bending force is an appropriate criterion to determine the inherent sorghum cultivar related property of sorghum *injera* staling upon storage. It is significant that bending force revealed the existence of sorghum cultivar differences for fresh and stored *injera* (Chapter 3.2). As stated staling is the major problem associated with the use of sorghum for *injera* making (Gebrekidan and GebreHiwot 1982). In the Ethiopian Sorghum Improvement Program it is therefore important to identify and research into sorghum cultivars which give *injera* with low staling properties. The texture analyzer *injera* bending force method is sensitive and simple to perform. However, as stated, purchase of the equipment is expensive and making the *injera* requires a large amount of flour.

Grain hardness (extraction rate), as measured using the TADD, was significantly negatively correlated with the positive *injera* textural attributes of softness and rollability (r = –0.70, –0.66, p <0.001). A drawback of these correlations is that they suggest that the lower the grain extraction rate, the better the *injera*. Obviously, low flour yield is very uneconomic for millers. Thus in a specification for TADD extraction rate for sorghum cultivars of good *injera* making quality, the minimum as well as maximum extraction rate will have to be specified. The TADD method is simple, rapid and easy to perform but requires a large amount of grain and obviously after milling the grain is rendered non-viable for planting. Decortication improves the color and quality of *injera*. Therefore, a relatively low cost barley pearler could be utilized for both decortication and hardness trials.

Endosperm texture visual rating was positively correlated with the positive textural attribute of *injera* softness (r = 0.59, p <0.01). Higher visual ratings correspond to higher proportions of floury endosperm area. The visual endosperm texture rating method is cheap, simple and rapid and destroys only a small amount of grain. However, it is operator dependent and the small sample size may result in unrepresentative results.

Vitreousness (image analysis) was negatively correlated with the positive *injera* quality textural attribute of softness ($r = -0.59$, $p < 0.01$). This indicates that sorghum cultivars with vitreous endosperm give firm *injera*, as was also indicated by the visual endosperm texture rating and TADD results. Due to the very small sample size used in the image analysis method, coupled with the high cost of image analysis equipment, the method will not be proposed as a method for selecting sorghum cultivars of *injera* making quality.

Test weight (hectoliter weight) is a measure of grain bulk density. It is important in marketing as generally, higher premiums are paid for grains with higher test weight. Sorghum grain test weight was negatively correlated with the positive *injera* textural attributes of softness and rollability ($r = -0.61$, $r = -0.54$, $p < 0.01$). However, a problem with grain of very low test weight is that it often shriveled, with a very low amount of endosperm (Shipman and Eustrom, 1995). Therefore, in order to use test weight as a screening method for sorghum cultivars of good *injera* making quality, it will be necessary to specify a minimum as well as a maximum test weight to avoid its negative implications. The test weight method is non-destructive, rapid, cheap and easy to perform. However, it requires a large amount of grain. The test weight test can be modified for reduced sample size by using a smaller volume vessel. Hence, it can be used for selection at early generation of sorghum breeding.

Concerning the pasting properties of sorghum flours, some RVA parameters positively correlated with sensory textural attributes of *injera*. Peak viscosity correlated with the negative attribute of stickiness ($r = 0.46$, $p < 0.05$). Final viscosity correlated with the positive attribute of shininess ($r = 0.48$, $p < 0.05$). Setback viscosity correlated with the positive attribute of shininess ($r = 0.50$, $p < 0.05$). Hot-paste viscosity correlated with the negative attribute of stickiness ($r = 0.50$, $p < 0.05$). These numerous relationships indicate that RVA could be applicable as one of the screening methods. The RVA pasting test is a rapid test, involving a simple procedure with a relatively small sample size and has easy data management (Almeida-Dominguez et al 1997). However, as can be seen the correlations with *injera* sensory textural attributes are weak. Thus, the RVA will not be considered as a screening test for sorghum cultivars of good *injera* making quality.

Water solubility index (WSI), a measure of the amount of soluble components in the flour, was positively correlated with fluffiness, a positive attribute of *injera* texture ($r = 0.48$, $p < 0.05$). Measurement of WSI is simple, and, although destructive, requires a small amount of flour. Additionally, and very importantly, the residue from the WSI determination can also be used to measure the water absorption index (WAI) of the same sample. WAI positively correlated with the negative *injera* quality attribute of stickiness ($r = 0.45$, $p < 0.05$) and strongly negatively with the positive attribute of fluffiness ($r = -0.70$, $p < 0.001$).

Table 4.1. Correlations between sorghum grain and sorghum physico-chemical parameters and sensory textural attributes of sorghum *injera* across the 1999 and 2000 growing seasons

Parameter		Sensory textural attributes and correlation coefficients
Maximum force required to bend *injera* (texture analysis)		
(after 24 hr of storage)	vs	Rollability –0.47*
(after 48 hr of storage)	vs	Softness –0.51*, rollability –0.52*, grittiness 0.54**
Hardness (TADD)	vs	Softness –0.70***, rollability –0.66***
Endosperm texture (visual rating)	vs	Softness 0.59**
Vitreousness (image analysis)	vs	Softness –0.59**
Test weight (hectoliter weight)	vs	Softness –0.61**, rollability –0.54**
RVA parameters		
Peak viscosity (flour)	vs	Stickiness 0.46*
Final viscosity (flour)	vs	Shininess 0.48*
Setback viscosity (flour)	vs	Shininess 0.50*
Hot-paste viscosity (flour)	vs	Stickiness 0.50*
Water solubility index (flour)	vs	Fluffiness 0.48*
Water absorption index (flour)	vs	Stickiness 0.45*, fluffiness –0.70***

Level of statistical significance at $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

4.3. Proposed selection criteria

Due to the limited grain sample size and differences in the number of breeder material samples handled at the different stages of the cultivar development, it is proposed that the process for selecting sorghum cultivars of good *injera* making quality be split into two stages. Relevant parameters requiring a small sample size and short time to determine are proposed for consideration at the early generation stage. This is the Nursery stage with 80 to 100 lines grown at a single location. At this stage, the main objective of testing the lines would be to predict their *injera* making potential. As the lines are advanced to the stage of the Pre-National Variety Trial (advanced breeding stage), the grain sample size increases and the number of cultivars decreases; 15 to 20 cultivars grown at 2 to 3 locations. Tests requiring relatively larger sample size, longer time and involving preparing *injera* would be performed at the this stage.

The acceptable ranges of values for the proposed selection criteria (Tables 4.2 and 4.3) were arrived at by selecting values for each parameter that corresponded with those of the sorghum cultivars which made good fresh *injera*: AW, SK-82-022, 3443-2-op, 76TI #23 and PGRC/E #69439 or those that made *injera* that staled slowly: AW, CR:35:5 and SK-82-022 (Chapter 3.2). The details of the basis of selection of acceptable ranges (proposed standard) for each selected parameter are described below.

4.3.1. Early generation selection criteria (Table 4.2)

At the early generation stage, classification of sorghum lines in terms of whether they are tannin types and overall grain color is proposed, since both these factors have fundamental influence on *injera* quality (Chapter 3.1). The Chlorox Bleach Test method (Waniska et al 1992) is proposed for detecting sorghums with a pigmented testa (tannin-containing). Visual classification of grains as white, yellow, red and brown is proposed. For bird-prone areas, where white sorghums are not grown, compositing of tannin-containing sorghums with tef is recommended for *injera* production.

Regarding endosperm texture (visual rating), AW, which made a soft and rollable *injera* (Chapter 3.2), was rated 5 and 4 for the 1999 and 2000 seasons, respectively. SK-82-022, which made a soft *injera* had a rating of 3 for both growing seasons. Other cultivars associated with soft, fresh *injera* texture 3443-2-op, 76TI #23 and PGRC/E #69349 had visual ratings of 3 and 3, 3 and 3, and 2 and 2 respectively, for both seasons. Therefore an acceptable range for sorghum endosperm texture (visual rating) of 3-5 was chosen as the standard.

WSI for AW was 2.5 and 3.1 g/100 g for the 1999 and 2000 seasons, respectively (Chapter 3.3) and for SK-82-022 was 2.8 and 2.9 g/100 g. 3443-2-op, 76TI #23 and PGRC/E #69349 had WSIs of 2.4 and 2.7, 2.5 and 2.6, and 2.5 and 2.8 g/100 g respectively, for both seasons. Therefore an acceptable range for sorghum flour WSI of ≥2.5 g/100 g was chosen as the standard.

WAI for AW was 1.2 g/g for both seasons (Chapter 3.3) and for SK-82-022 was 1.3 and 1.6 g/g. 3443-2-op, 76TI #23 and PGRC/E #69349 had WAIs of 1.4 and 1.5, 1.3 and 1.5, and 1.4 and 1.3 g/g respectively, for both seasons. Therefore an acceptable range for sorghum flour WAI of ≤1.5 g/g was chosen as the standard.

Table 4.2. Proposed selection criteria at early generation for selection of sorghum cultivars of good *injera* making potential

Parameter/method	Acceptable range	Remarks
Pigmented testa (Chlorox Bleach Test)	Absent	These methods require
Pericarp color (visual rating)	White preferred	small sample size and
Endosperm texture (visual rating)	3-5	are predictive tests for
Water solubility index (whole flour)	≥2.5 g/100 g	*injera* making potential
Water absorption index (whole flour)	≤1.5 g/g	

4.3.2. Advanced breeding stage selection criteria (Table 4.3)

Regarding grain hardness (TADD), the % extraction rate of AW was 56.5 and 76.2% for the 1999 and 2000 seasons, respectively (Chapter 3.3) and for SK-82-022 80.3 and 80.0%. 3443-2-op, 76TI #23 and PGRC/E #69349 had % extraction rates of 71.7 and 78.2, 73.3 and 73.3, and 78.8 and 86.3% respectively, for both seasons. Therefore an acceptable range for sorghum grain extraction rate of 56-79% was chosen as the standard.

The test weight of AW was 71.0 and 74.1 kg/hl for the 1999 and 2000 seasons, respectively (Chapter 3.3) and for SK-82-022, 73.6 and 74.1 kg/hl. 3443-2-op, 76TI #23 and PGRC/E #69349 had test weights of 74.3 and 74.5, 77.4 and 79.2, and 74.2 and 79.9 kg/hl respectively, for both seasons. Therefore an acceptable range for sorghum grain test weight of 71.0-75.0 kg/hl was chosen as the standard.

Concerning the *injera* sensory textural attribute of softness, a positive attribute, AW gave a softness score of 7.8 and 7.6 for the 1999 and 2000 seasons, respectively (Chapter 3.2) and SK-82-022 gave 7.0 and 7.4. 3443-2-op, 76TI #23 and PGRC/E #69349 gave scores of 7.4 and 7.0, 7.1 and 6.8, and 6.7 and 6.8, respectively for the two seasons. These values are lower than the 8.2 and 8.2 for tef *injera* for the 1999 and 2000 seasons, respectively. Therefore an acceptable score for sorghum *injera* softness of ≥6.7 was chosen as the standard.

Stickiness is a negative attribute of *injera*. AW gave a stickiness score of 1.8 and 3.4 for the 1999 and 2000 seasons, respectively (Chapter 3.2) and SK-82-022 gave 2.0 and 2.7. 3443-2-op, 76TI #23 and PGRC/E #69349 gave scores of 1.0 and 2.3, 1.5 and 4.8, and 0.8 and 2.1, respectively for the two seasons. These values are generally similar to the 2.4 and 2.5 for tef *injera* for the 1999 and 2000 seasons, respectively. Therefore an acceptable score for sorghum *injera* stickiness of ≤2.0 N was chosen as the standard.

Fluffiness is a positive attribute of *injera*. AW gave a fluffiness score of 7.7 and 7.3 for the 1999 and 2000 seasons, respectively (Chapter 3.2) and SK-82-022 gave 6.9 and 7.0. 3443-2-op, 76TI #23 and PGRC/E #69349 gave scores of 7.6 and 7.0, 7.2 and 7.1, and 7.0 and 6.8, respectively for the two seasons. These values are slightly lower than the 8.0 and 8.2 for tef *injera* for the 1999 and 2000 seasons, respectively. Therefore an acceptable score for sorghum *injera* fluffiness of ≥6.8 was chosen as the standard.

Rollability is a positive attribute of *injera*. AW gave a rollability score of 7.8 and 7.2 for the 1999 and 2000 seasons, respectively (Chapter 3.2) and SK-82-022 gave 7.6 and 7.3. 3443-2-op, 76TI #23 and PGRC/E #69349 gave scores of 7.8 and 7.0, 7.7 and 7.6, and 7.7 and 7.3, respectively for the two seasons. These values are slightly lower than the 8.3 and

8.3 for tef *injera* for the 1999 and 2000 seasons, respectively. Therefore an acceptable score for sorghum *injera* rollability of ≥7.2 was chosen as the standard.

Grittiness is a negative attribute of *injera*. AW gave a grittiness score of 1.5 and 2.7 for the 1999 and 2000 seasons, respectively (Chapter 3.2) and SK-82-022 gave 2.7 and 2.3. 3443-2-op, 76TI #23 and PGRC/E #69349 gave scores of 3.1 and 3.2, 2.6 and 1.8, and 2.7 and 2.8, respectively for the two seasons. These values are somewhat higher than the 0.7 and 0.8 for tef *injera* for the 1999 and 2000 seasons, respectively. Therefore an acceptable score for sorghum *injera* grittiness of ≤2.7 was chosen as the standard.

High values for maximum force (texture analysis) to bend *injera* are related to its staling property after baking. After 24 hr storage, AW *injera* required a maximum bending force of 0.18 and 0.23 N for the 1999 and 2000 seasons, respectively (Chapter 3.2). CR:35:5 *injera* required a force of 0.27 and 0.19 N for the two seasons and SK-82-022 *injera* required a force of 0.15 and 0.26 N. These values are somewhat higher than the 0.11 and 0.13 N for tef *injera* for the 1999 and 2000 seasons, respectively. Therefore an acceptable score for sorghum *injera* maximum bending force at 24 hr of ≤0.27 N was chosen as the standard.

After 48 hr storage, AW *injera* required a maximum bending force of 0.19 and 0.28 N for the 1999 and 2000 seasons, respectively (Chapter 3.2). CR:35:5 *injera* required a force of 0.33 and 0.22 N for the two seasons and SK-82-022 *injera* required a force of 0.22 and 0.33 N. These values are somewhat higher than the 0.15 and 0.15 N for tef *injera* for the 1999 and 2000 seasons, respectively. Therefore an acceptable score for sorghum *injera* maximum bending force at 48 hr of ≤0.33 N was chosen as the standard.

Table 4.3. Proposed selection criteria at advanced breeding stage for selection of sorghum cultivars of good *injera* making quality

Parameter/method	Acceptable ranges	Remarks
Hardness (TADD) (extraction rate)	56.0-79.0%	
Test weight (hectoliter weight)	71.0-75.0 kg/hl	The sample size from advanced lines is large enough to test the actual product
Sensory textural attributes of fresh *injera*		
Softness	Score of ≥6.7	
Stickiness	Score of ≤2.0	
Fluffiness	Score of ≥6.8	
Rollability	Score of ≥7.2	
Grittiness	Score of ≤2.7	
Maximum force required to bend *injera* (texture analysis)		
(after 24 hr of storage)	≤0.27 N	
(after 48 hr of storage)	≤0.33 N	

4.4. Future research needs

In order of priority:

It is required to test a larger number of sorghum lines, about 15-20 cultivars across 2-3 locations, from multilocation trials such as the Pre-National Variety Trial of the ESIP to fine-tune the proposed selection criterion.

An experiment needs to be conducted with exclusively soft and hard endosperm sorghum cultivars to more clearly understand the effect of grain endosperm texture on sorghum *injera* textural attributes. Cultivars with vitreous endosperm producing soft *injera* will be studied further because of their desirable agronomic and milling properties.

Differences in *injera* staling properties were observed among the sorghum cultivars studied. There was no significant correlation between amylose content of the flour and staling of stored *injera*. The detailed structural properties of the amylose and amylopectin of the cultivars might have partly contributed to these differences. Thus, a study on the structural properties of starch components of the cultivars with high and low staling properties is required to understand more about the cause of differences in *injera* staling property upon storage.

Gel firmness and water solubility index of tef flour were much higher compared to sorghum flours. These flour functional properties probably contribute to soft *injera* from tef compared to sorghum. Further investigation on the protein and cell wall components of tef and sorghum is required to understand what is in tef but lacking in sorghum as related to the textural properties of *injera* from these two species of cereals.

Preliminary work conducted to study the effects of emulsifiers on sorghum *injera* quality revealed that glycerol monostearate (GMS) improved the eye quality (evenly distributed and smaller eye sizes) of *injera* (data not presented in the thesis). However, it did not improve the texture of the *injera.* Further work on the use of different types of emulsifiers, for example calcium stearoyl lactylate, sodium stearoyl lactylate and GMS at various levels of addition might give better understanding of the potential of emulsifiers to improve the textural quality and softness over storage of sorghum *injera.*

5. CONCLUSIONS AND RECOMMENDATIONS

By using the simple processing technologies of decortication of whole sorghum flour and composting whole sorghum flour with tef flour, *injera* quality from high-tannin and non-tannin red sorghums can be improved. With regard to decortication, mechanical Abrasive decortication is more effective than hand pounding because acceptable *injera* can be obtained with lower milling loss. However, the major problem with decortication is with soft endosperm sorghum cultivars there is low milling yield.

Without removing the tannin, a dilution effect can be achieved by compositing with tef flour. Tef probably acted mainly as tannin diluent, overcoming the inhibitory effects of tannins on fermenting microorganisms. Compositing progressively improves the quality of *injera* as the level of tef increases. It also modifies the pasting properties of composite flours by progressively reducing peak, hot paste and cold paste viscosities as level of tef increases. Thus, composting with tef seems to be a more useful method of improving sorghum *injera* quality than decortication as it modifies the intrinsic flour properties and avoids grain loss associated with decortication.

Principal component analysis of sensory data associated fresh *injera* from sorghum cultivars AW (red, floury endosperm), 3443-2-op (white, intermediate endosperm), 76TI #23 (white, intermediate endosperm), and PGRC/E #69349 (white, relatively vitreous endosperm) with the positive *injera* texture attributes of softness, rollability and fluffiness. Across the two seasons, texture analysis showed *injera* prepared from AW and CR:35:5 (both with floury endosperm) required the least force to bend after 48 hr of storage. Thus, from the standpoint of *injera* making quality it appears that floury to intermediate endosperm texture sorghums are most suitable.

Texture analysis shows cultivar differences for the force required to bend fresh and stored sorghum *injera*. An increase in bending force due to firming (staling) of *injera* over the storage period is evident. Thus, this method can be used to follow the staling process of *injera*.

Sorghum flour quality is distinctively different from that of tef flour. Lower water solubility index and higher water absorption index, higher hot paste, setback and cold paste viscosities with a soft gel texture are characteristics of sorghum flours. Tef flour gel is firmer and more elastic and requires higher compression force to deform. This can be attributed to the higher water solubility index of the flour and lower setback viscosity of tef flour paste. Softness of sorghum gel is associated with release of water (starch syneresis) during storage.

On the basis of linear regression correlations between physico-chemical properties and sensory data, it appears that the sorghum grain physical properties of endosperm texture, test weight, hardness (decortication extraction rate), water solubility and water absorption indices affect the sensory textural attributes of *injera*. These relationships enabled the development of indirect and direct selection criteria for use in the Ethiopian Sorghum Improvement Program (ESIP) for selection of sorghum cultivars of good *injera* making quality. Grain endosperm texture (visual rating) of 3-5 (intermediate to floury), flour water solubility index of ≥2.5 g/100 g and water absorption index of ≤1.5 g/g are proposed as selection criteria at the early generation, (nursery) breeding stage. Milling extraction rate (TADD) of 56.0-79.0%, a test weight of 71-77 kg/hl, *injera* softness score of ≥6.7, stickiness score of ≤2.0, fluffiness score of ≥6.8, rollability score of ≥7.2 and grittiness score of ≤2.7, maximum force required to bend *injera* after 24 hr of storage ≤0.27 N, and after 48 hr of storage ≤0.33 N are proposed as selection criteria for the advanced breeding stage. However, testing a larger number of sorghum lines, about 15-20 cultivars across 2-3 locations, from multilocation trials such as the Pre-National Variety Trial of the ESIP will be required to fine-tune these proposed selection criteria.

To further elucidate the effect of sorghum endosperm texture on *injera* textural attributes, research needs to be conducted with exclusively soft and hard endosperm sorghum cultivars. Additionally, more in-depth investigation of the amylose and amylopectin fine structure, protein and cell wall components of tef and sorghum is required to understand what is in tef but lacking in sorghum as related to the textural properties of *injera* from these two species of cereals.

6. REFERENCES

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Appendix I

Publications and presentations from this work

Scientific papers

Yetneberk, S., de Kock, H. L. Rooney, L. W. and Taylor, J. R. N. Effects of sorghum cultivar on *injera* quality, (In press: Cereal Chemistry, 2004).

Yetneberk, S., Rooney, L. W. and Taylor, J. R. N. Improving the quality of sorghum *injera* by decortication and compositing with tef, (submitted for publication to the Journal of the Science of Food and Agriculture, October, 2003).

Conference posters

Yetneberk, S., Rooney, L. W. and Taylor, J. R. N. Relating sensory and instrumental texture measurements of *injera* texture. Poster presented at the International Sorghum and Millet (INTSORMIL) Principal Investigators Conference, 18- 20 November 2002, Addis Ababa, Ethiopia.

Yetneberk, S., Rooney, L. W. and Taylor, J. R. N. Effects of sorghum cultivar on *injera* quality. Poster presented at the AFRIPRO International Workshop on Sorghum and Millets Proteins, 2-4 April 2003, Pretoria, South Africa.

Conference papers

Yetneberk, S., Hamaker, B. R., and Taylor, J. R. N. Value added products from sorghum: The prospect in Ethiopia. Paper presented at the First National Workshop on Sorghum and Millets Research, Extension and Production in Ethiopia. 12-14 November 2002, Melkassa, Ethiopia.

Yetneberk, S., de Kock, H. L. Rooney, L. W. and Taylor, J. R. N. Effects of sorghum cultivar on *injera* quality. Oral presentation at South African Association for Food Science and Technology (SAAFoST), September 2003, Pretoria, South Africa.

Taylor, J. R. N., Bultosa, G., and Yetneberk, S. Properties of tef starch and its role in *injera* quality. Annual Meeting of the American Association of Cereal Chemists, Portland, USA, September 2003.

Taylor, J. R. N., Hugo, L. F., and Yetneberk, S. Development in sorghum bread making. 12th International Cereal and Bread Congress, Harrogate, UK, May 2004.

Workshop presentation

Yetneberk, S. lectured and demonstrated sorghum *injera* preparation procedure at a one-day International Workshop on Tortillas, Flatbreads and Wraps, (ICC-SA), 25 March 2003, Pretoria, South Africa.