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 small sample size and are predictive tests for *injera* making potential
Pericarp color (visual rating)	White preferred	
Endosperm texture (visual rating)	3-5	
Water solubility index (whole flour)	≥2.5 g/100 g	
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.