# Genetic diversity of sorghum (*Sorghum bicolor* L. Moench) germplasm and hybrid potential under contrasting environments in Mozambique

By

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# Abstract

Sorghum is the second most important grain cereal after maize in most African countries, including Mozambique. However, despite the increase in production in Sub-Saharan region, productivity is still very low averaging 0.4 t.ha$^{-1}$ compared to a potential yield of 3.0 t.ha$^{-1}$. The use of improved cultivars such as hybrids selected by farmers could double current yields. The objectives of this study were to: i) assess farmers' preferences and needs in sorghum varieties through participatory rural appraisal and participatory variety selection, ii) determine diversity of the important morphological traits of Mozambican germplasm using multivariate analysis; iii) study the genotype by environment (G x E) interactions during development of improved varieties and iv) construct a selection index that can be used to select for multiple traits in hybrid development. The results of participatory rural appraisal showed that attributes preferred by farmers were high grain yield, good food quality and suitability of the harvested grain for various uses. Besides yield, farmers identified additional important traits such as earliness, grain size, and grain colour. Drought tolerance and head size were mentioned as key traits used to compare new varieties to the local varieties. Involving farmers in the evaluation of the hybrids and during selection revealed the importance of not focusing on yield only during the development of a new variety.

The available germplasm in Mozambique exhibited genetic diversity as they were grouped into four clusters. The Shannon Diversity index (H') distinguished days to 50% flowering, thousand seed weight, seed size, leaf colour, inflorescence compactness, head shape and presence of awns as the traits with high genetic diversity. It implies that these characters can be utilized in the breeding process in selecting parents for use in sorghum improvement. Moreover, results from genotype x environment showed a highly significant ($P<0.001$) hybrids main effects and hybrid x environment interactions for grain yield indicating differences between hybrids and variation of the environments. The genotype and genotype-environment interaction (GGE biplot) analyses identified genotypes with wide adaptation as well as genotypes with specific adaptation. Hybrids with wide adaptation and high yield were: GS11 (SPL 38A x SDS 6013R), GS18 (TX 628A x IS14257R) and GS36 (TX631A x MZ 37R) and, those with specific adaptation were GS 5 (8610A x MZ 2R), GS 25 (ICSA 12A x MZ 2R), GS 22 (ICSA 21A x MZ 2R), GS 1 (LARSVYT 46A x MZ 2R), GS 24 (ICSA 21A x MZ 37R), GS 30 (CK 60A x IS 14257R) and GS 2 (LARSVYT 46A x IS 14257R).

All testers had significant GCA effects on grain yield, days to 50% flowering and plant height. Testers IS 14257R and MZ 37R showed positive GCA values for grain yield while some hybrids and the two parents had positive SCA values. Lines LARSVYT 46A, SPL 38A and TX

631A also had positive GCA effects for grain yield. Highly significant negative GCA effects for days to 50% flowering were observed for lines 8601A, ICSA 12A, TX 631A and LARSVYT 46A. For plant height, line TX 631A, ICSA 12A, ICSA 21A and TX 628A were significant negative while panicle length showed positive significant GCA effect for the lines LARSVYT 46A, SPL 38A and TX 631A. Hybrids ICSA 12A x MZ 2R, ICSA 12A x SDS 6013R and TX 631A x SDS 6013R were resistant to rust, while moderate resistance was detected in LARSVYT 46A x IS 14257R, LARSVYT 46A x SDS 6013R and 8601A x MZ 37R. Overall, most of the hybrids were classified as resistant to moderately resistant to *Cercospora* spp*,* whereas all the hybrids were classified as resistant to anthracnose. The parents involved in the crosses could be used as sources of resistance in future studies. Among the lines, TX 631A, ICSA 12A and SPL 38A performed well for most of the characters compared to mid-parent heterosis.

Analysis of variance for on-farm trials identified hybrid TX 631A x MZ 37R as high yielding with short plants. The tallest plants on-station were detected for hybrid SPL 38A x SDS 6013R. In contrast, the local variety had the tallest plants in on-farm trials and was late in flowering. Hybrid SLP 38A x MZ 2R was also late in flowering. The mean grain yield for the local variety was 1.0 t.ha$^{-1}$ and the highest yielding hybrid had 3.0 t.ha$^{-1}$. These results showed the grain yield potential of the hybrids over the local variety, ranging from 150% to 200% above the local variety yield. In addition to yield, farmers identified additional important traits that included earliness, large grain size, and white grain colour. Drought tolerance and head size were used as benchmark traits for comparing new varieties to the local variety.

Results from selection indices showed that the highest grain yielding genotypes were not associated with high index scores. For Smith-Hazel selection index, the genotype CK 60A x MZ 37R had the highest score followed by TX 631A x MZ 37R, CK 60A x MZ 2R, SPL 38A x MZ 37R and TX 628A x MZ 37R. For the desired gain index, the top five genotypes were ICSA 19A x MZ 37R, 8601A x SDS 6013R, SPL 38A x SDS 6013R, CK 60A x MZ2R and TX 628A x IS 14257R. The only genotype that appeared in the top five scores using the two indices was CK 60A x MZ 2R. The selection index proposed by Smith-Hazel was the most efficient in simultaneously selecting hybrids for grain yield and other yield attributes. Overall, the results of this study revealed that involving farmers in the evaluation of hybrids and during selection is important as the farmers choose hybrids not only for yield. Having hybrids with farmers' preference can speed up the adoption of new varieties. Additionally, selection of multiple traits simultaneously using an index score results in a realistic response to selection for all the traits that are being combined. This can speed up breeding for the traits instead of focusing on one trait at a time.

# Declaration

I, Eduardo Pinto Mulima, declare that:

1. The research reported in this thesis, except where otherwise indicated, is my original research.
2. This thesis has not been submitted for any degree of examination at any other university.
3. This thesis does not contain other persons' data, pictures, graphs or other information unless specifically acknowledged as being sourced from persons.
4. This thesis does not contain other persons' writing unless specifically acknowledged as being sourced from other research. Where other written sources have been quoted, then:
    a. Their words have been re-written but the general information attributed to them has been referenced;
    b. Where their exact words have been used, then their writing has been placed in italics and inside quotation marks and referenced.
5. This thesis does not contain text, graphs or table copied and pasted from internet unless specifically acknowledged, and the source being detailed in the thesis and in the references section

Signed

Eduardo Pinto Mulima

As the candidate's supervisor, I agree to the submission of the thesis:

Sibiya

Dr Julia Sibiya (Supervisor)

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# Dedication

I dedicate this thesis first to God Almighty and to my beloved wife, Eugénia Raúl Zavala Mulima, my son, Ednésio Eduardo Mulima and my daughter Sara Suzana E. E. Mulima. My parents, brothers and sisters.

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# List of Acronyms

IIAM – Agricultural Research Institute of Mozambique

ICRISAT - International Crops Research Institute for the Semi-Arid Tropics

IBPGR - International Board for Plant Genetic Resource

PCA - Principal component analysis

UPGMA - Unweighted pair-group method with arithmetic average

CMS - Cytoplasmic Male Sterile

CMF – Cytoplasmic Male Fertile

m.a.s.l. – meter above sea level

GCA – General Combining Ability

SCA – Specific Combining Ability

GLS – Grey Leaf Spot

MOI – Grain Moisture Content

ANOVA – Analyses of Variance

MPH – Mid-parent heterosis

HBP – Heterosis of the best parent

GEI – Genotype by Environment Interaction

AMMI – Additive Main Effects and Multiplicative Interaction

GGE – Genotype and Genotype-Environment Interaction

PVS – Participatory Variety Selection

# CHAPTER I: INTRODUCTION

## 1.1. Background

Agriculture sector is one of the largest contributors to the economy and livelihoods of the majority of people in Africa. In Mozambique, agriculture plays a vital role in the development of the country and is one of the pillars for economic growth. According to USAID (2017), agriculture remains the backbone of Mozambique's economy, employing more than 80% of its labour force and contributing more than a quarter of its GDP. Nearly 90% of the domestic foods are produced by families or smallholder farmers. The existing vast potential for crop production makes the country suitable for farming and for improved agricultural productivity. Unfortunately, farmers are still using unimproved varieties that are low yielding and susceptible to adverse effects of climate changes. The farmers grow cassava and maize as the main crops while sorghum, millet, rice and beans are among the food security crops in the country. Among these crops, sorghum responds best to a wide range of environments (Machado and Paulsen, 2001).

Sorghum is a very important cereal in the semi-arid areas of the tropics and sub-tropics in sub-Saharan Africa. It is a main cereal grain in Mozambique after maize with a total area under cultivation of 2.9 million hectares (FAOSTATS, 2014). Moreover, the majority of agricultural production depends on rainfall thus is severely affected by weather variability. Although, sorghum production falls under different agro-ecological zones of the north and central regions where annual rainfall is between 500-700 mm, the crop still grows well in areas with good rainfall (Olembo *et al.*, 2010). This crop is adapted to widely differing climatic and soil conditions, it tolerates drought and high-temperature stress better than many crops, remaining inactive during dry periods (Gnansounou *et al.*, 2005; Olembo *et al.*, 2010). Although drought has been affecting crop production, sorghum performed better during such conditions, an indication of its ability to withstand drought in semi-arid regions of Africa (Machado and Paulsen, 2001), particularly central and north Mozambique.

It was reported that the use of low grain yielding varieties has not changed substantially over the past five years in Mozambique with the average yield ranging from 0.4 $t.ha^{-1}$ to 0.6 $t.ha^{-1}$ (Tsusaka *et al.*, 2015). This has been due to a number of factors including the fact that, agriculture in the sorghum producing areas, namely  the central regions of Nampula, Sofala and Manica, has remained basically under rain-fed and zero-input systems (WorldBank, 2004; Goodbody *et al.*, 2010). Low productivity in sorghum has also been linked to a lack of modern farming technologies, therefore, a combination of classic and modern plant breeding methods is desired to develop farmer-preferred cultivars with high grain yield potential relative to current commercial and local cultivars. The local cultivars are usually adapted to multiple biotic and abiotic constraints, but the grain yield is usually low and thus requires improvement. In view of the aforesaid, improved cultural practices such as crop rotation, timeous weeding, bird control and the inclusion of improved cultivars, especially the use of hybrids by the farmers, could double the current yields (WorldBank, 2004; FAO, 2013).

In many areas where sorghum is produced, farmers continue to use their local varieties with low yield potential (Tsusaka *et al.*, 2015). Therefore, there is a need to increase productivity of this crop through development of high yielding varieties with resistance to pests and diseases. The use of available local resources (germplasm and agronomic practices) to improve productivity based on management practices and development of new varieties requires knowledge of genetic variability. Knowledge of genetic variability within cultivars has a strong impact on plant breeding strategies and on genetic conservation (Simioniuc *et al.*, 2002). Conventionally, plant breeding and testing used to focus more on yield improvement, nutrition and disease resistance but less on plant adaptation to natural environmental constraints. The crop environment adaptation can be influenced by altitude, rainfall, temperature and growing period (Ayana and Bekele, 2000) as well as poor field management and use of non-improved seed. The variation in these factors affects sorghum agronomic characters. These characters include plant height, days to flowering, peduncle exsertion, panicle length and width, number and length of primary branches per panicle as well as thousand seed weight. Consequently, recommendation of varieties must be according to agro-ecological zones and farmers' preferences.

Farmers tend to rely on crops such as sorghum and pearl millet when faced with unfavorable climatic conditions (Tsusaka *et al.*, 2015). Nonetheless, there is still a remarkably low sorghum production as well as consumption among some Mozambican communities. In addition, sorghum productivity and market supply have declined in recent years due to unfavorable climatic conditions, low yields and damage by field pests (Benfica *et al.*, 2014). This suggests that households can be motivated by improving market access, offering high prices for the product, which can help the farmers to invest in improved agricultural technologies and put more effort in increasing agricultural productivity (Benfica *et al.*, 2014). In addition, increased productivity and processed sorghum products can create high amounts of marketable surplus, such that, with market access, this can result in increased market participation leading to potential improvements in overall household welfare.

Moreover, there is a need to determine the causes of low adoption and release of improved varieties in the country. This could be achieved through clearly identifying what farmers prefer in a cultivar through researcher-farmer interaction and collaboration (Witcombe *et al.*, 1996).

This method involves encouraging farmers to participate in experiments using their own fields where they can learn, adopt and spread new technologies to other farmers (Leeuwis, 2013). Participatory approaches should be adopted on selection criteria of traits that are important to the farmers so that they can easily accept and adopt the new cultivars. This depends on farmers' needs and it varies from location to location. Participatory plant breeding (PPB) is a breeding method that brings farmers and researchers together and enables them to select crop varieties suitable to their specific environmental conditions. The use of PPB approach could have various incentives, including understanding of farmers' criteria, improved biodiversity, empowering farmers, facilitating farmers learning, increasing productivity, and speeding the process to release and adoption of varieties (Sperling *et al.*, 2001). Involvement of farmers in breeding programmes increases efficiency because breeders are better able to orient their breeding strategies to the needs of farmers. This process moves from participatory plant breeding to participatory variety selection (PVS).

Many studies have outlined the advantages of participatory variety selection (PVS) on adoption of new varieties and increased productivity (Bänziger and Cooper, 2001; Witcombe *et al.*, 2005; Trouche *et al.*, 2012). Participatory breeding has been proposed as an active approach for developing varieties combining productivity gains, adaptability to a particular system and quality traits for subsistence agriculture in marginal environments (Trouche *et al.*, 2011). Consequently, farmers should identify environments to assess new germplasm and take into consideration the various quantitative and qualitative traits important to their own environment (Morris and Bellon, 2004; Trouche *et al.*, 2011). Trouche *et al.* (2012) concluded that on-farm selection has many limitations depending on seed generation evaluated but the trial produces more stable genotypes having a combination of earliness, plant height, grain size and yield closer to that expected by farmers. Understanding farmers' preferences and acceptability of a new variety are essential parameters for its adoption and use (Horn et al., 2015; Olubunmi, 2015). Therefore, for the plant breeder it is essential to study the genotype-environment interaction effects on grain yield during the development of the new improved varieties.

Mohammadi and Amri (2008) reported that the identification of superior genotypes is complicated by genotype x environment interaction. Several statistical methods facilitate the interpretation of the genotype x environment interactions and are used to explain adequately the genotype performance across environments. These procedures are based on analysis of variance, multivariate analysis, linear regression, non-linear analysis and biplot analysis. The commonly used approaches for analysis of genotype by environment interaction (GEI) are additive main effects and multiplicative interaction (AMMI) and genotype and genotype-environment interactions (GGE biplot) analysis (Duarte and Vencovsky, 1999; Yan *et al.*, 2000). The advantage of GGE biplot analysis over AMMI analysis lies in the fact that biplots explain an intermediate fraction of sum of squares of genotypes + genotypes by environments (G + GE), making the graphical illustration more accurate and more practical (Yan *et al.*, 2007). Sibiya (2009) compared the two methods and found AMMI and GGE biplot analysis to depict similar results for maize hybrid selection. On the other hand, Balestre *et al.* (2009) found GGE2 biplot better than AMMI1 and graphical accuracy was higher in representing the proportion of G + GE. In addition, Ma *et al.* (2004) suggested that GGE biplot stands for genotype main effects plus GEI and it was confirmed by Yan *et al.* (2007) that GGE biplot had many visual interpretations than AMMI, including the visualization of crossover GEI. Therefore, GGE biplot was used to analyze and interpret the genotype performance across several environments in Mozambique.

The choice of an appropriate selection method for plant breeding may favour identification of superior genotypes during the development of new cultivars and saves time and costs (Kurek *et al.*, 2001). Identification of superior genotypes requires selection methods that can exploit efficiently the available genetic material, maximizing the genetic gain in relation to the characteristics of interest (Vivas *et al.*, 2012). Therefore, a selection index that results from a combination of certain traits, which pursue simultaneous selection, allows identification of superior genotypes.

Selection of several traits at the same time is mostly facilitated by the establishment of a selection index that uses the optimal combination of multiple traits (Shook, 2006; Cruz, 2013). The use of the selection index allows identification of superior genotypes established by the optimal linear combination of various traits (Vittorazzi *et al.*, 2017). Selecting of traits simultaneously using an index provides useful information and realistic response to selection for all the traits that are being combined by giving a total genetic value to the individual line (Bänziger and Lafitte, 1997). Initially, Smith (1936) and Hazel (1943) reported the use of selection index in plants and animals, respectively, and then later other indices were proposed by Williams (1962), Pešek and Baker (1969) and Mulamba and Mock (1978).

The Smith-Hazel index has been shown to give maximum genetic advance (Strefeler and Wehner, 1986). However, the index is not as simple as other indices as it requires estimation of genetic variances and covariances and an assignment of economic weights for each trait (Strefeler and Wehner, 1986; Eshghi *et al.*, 2011). On the other hand, in the case of the desired gain proposed by Pesek and Baker (1969) they specify the desired gain value rather than economic weights. Hence, it maximizes the expected response in proportion to the gain specified by the breeder.

Moreover, the correlation between traits is also an alternative method for selection of genotypes. The weak correlation between traits of interests makes selection more complicated because sometimes it is difficult to associate the best genotypes for one trait with the best genotype for another trait. This was explained by Lande and Arnold (1983) who mentioned that selection of a specific trait produces not only direct effect of that trait but also include indirect effects on correlated traits or characters. Therefore, selection cannot be done for a single character without giving importance to another character that is correlated to it.

## 1.2. Problem statement and justification

The variation in temperatures in Mozambique in the last few years has affected maize production resulting in reduced yield, reduction in time to maturity and grain filling duration (Harrison *et al.*, 2011). This has opened a vista of opportunities for the production of neglected crops, such as sorghum, known as resilient crops that respond well to climate change conditions. Although sorghum is the second most important grain cereal after maize in most African countries, including Mozambique, its productivity has remained low averaging 0.4 $t.ha^{-1}$ compared to a potential yield of 3.0 to 6.0 $t.ha^{-1}$ (Kumar *et al.*, 2008).

Therefore, to increase grain yield in sorghum, it might be important to exploit the potential heterosis of the crop (Reddy *et al.*, 2012). According to Ashok Kumar *et al.* (2011), new sorghum hybrid varieties showed a 30-40% heterosis for grain yield compared to the best pure line varieties. Furthermore, Mahdy *et al.* (2011) recorded heterosis for sorghum grain yield over the best parent of between 9 to 97% while lower estimates were obtained in crosses with adapted parent lines. The potential hybrids are those with inherited traits such as grain yield, plant height, maturity, tillering and disease resistance. It is, therefore, essential for sorghum breeders to study the combining ability among parents for grain yield and secondary traits for improvement of grain yield potential which is one of the most important traits in sorghum breeding (Reddy *et al.*, 2012). According to Thomas *et al.* (2017), one of the strategies to increase the yield potential is manipulating heterosis. The use of improved cultivars such as hybrids selected by farmers could double current yields.

In order to improve adoption of improved cultivars, it is essential for the breeder to understand farmers' preferences and acceptability of a new variety (Horn et al., 2015; Olubunmi, 2015) and also study the combining ability and the genotype by environment interactions effects during the development of new improved varieties. Although studies have been done on GEI, combining ability and heterosis for sorghum grain yield, there is still limited information on combining ability in the sorghum germplasm available in Mozambique and the potential for exploitation of heterosis for hybrid development as well as their genotype-environment interactions effects.

Besides the exploration of heterosis and GEI, plant breeders have been facing challenges to select superior genotypes using one trait. The use of selection index allows the prediction of selection gains for the traits evaluated together and a more understanding and exploitation of superior genotypes. This suggests that sorghum breeders should consider the use of different selection strategies and indices to select superior genotypes for grain yield and other traits to improve the crop according to the trait of interest. Therefore, use of selection index will help on selection of superior genotypes in the present study and also facilitate selection of new superior genotypes in future work in the sorghum breeding programme in Mozambique.

## 1.3. Research objectives

The objectives of this study were to:

1. Assess farmers' preferences and needs in sorghum varieties through participatory rural appraisal and participatory variety selection,
2. Determine the morphological characteristics that distinguish desirable breeding materials to be exploited in hybrid development
3. Select adapted and superior genotypes and study their genotype by environment (G x E) interactions
4. Estimate combining ability of the genotypes and the heterosis of hybrids over the commercial cultivars for grain yield and
5. Construct a selection index that can be used to select superior genotypes.

## 1.4. Research hypotheses

The following hypotheses were tested:

1. Farmers have specific preferences for certain agronomic traits in sorghum and they are aware of the major production constraints in their areas, which should be considered in developing new varieties, especially the new sorghum hybrids.
2. There is a high genetic diversity for grain yield among the adapted national sorghum germplasm to distinguish desirable breeding material for hybrid exploitation.
3. Changes in environment affects the performance of the sorghum germplasm and that can be exploited to identify germplasm with wide or specific adaptation.

4. The selected sorghum germplasm have good combining ability for grain yield and yield components hence they can be exploited to make hybrids that are adapted to different agro-ecological regions in Mozambique.
5. High performance genotypes have high index in selection that can be used to identify superior genotypes.

## 1.5. Thesis structure

The above-mentioned objectives and hypotheses were tested and presented in different chapters, which constitute this thesis. The chapters are written as an independent manuscript for journal publication, therefore may contain some overlaps in information and references between the chapters. The structure of the thesis is presented as follows:

- Chapter 1: Thesis introduction
- Chapter 2: Literature review
- Chapter 3: An appraisal of sorghum farmers' trait preferences, production threats and opportunities for plant breeding in central region of Mozambique
- Chapter 4: Identification of important morphological traits in Mozambican sorghum germplasm using multivariate analysis
- Chapter 5: Combining ability and Heterosis for sorghum grain yield and secondary traits across lowlands and midlands Mozambique
- Chapter 6: Influence of genotype x environment interaction on grain yield performance of sorghum genotypes across lowlands and midlands of Mozambique
- Chapter 7: Participatory variety selection of sorghum hybrids using farmers' preferences and knowledge in central area of Mozambique
- Chapter 8: Identification of superior sorghum genotypes from farmers' preferences traits using selection indices
- Chapter 9: General Research Overview

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# 2. LITERATURE REVIEW

## 2.1. Introduction

This chapter reviewed the topics relevant to the research to provide the theoretical basis for the study. Therefore, it gives an understanding of sorghum production and their constraints at country and farmer level. Additional information on sorghum improvement and heterosis importance for hybrid development and yield increase is discussed. Moreover, it states combining ability effects and the methods used to estimate them and discusses the implications of genetic diversity, genotype by environment interaction and yield stability in breeding. The importance of involving farmers in breeding programmes is also highlighted.

## 2.2. Global sorghum production

In 2014, the world sorghum production was estimated at 59.3 million metric tonnes with the USA as the top producer with 8.8 million metric tonnes/annum (HarvestChoice, 2014). Currently, the production has been estimated with a decrease of 3.74 million tonnes around the world due to climate change effects (USDA, 2017). In the United States, 78% of the production is for grain, although some of the varieties are dual-purpose cultivars (grain and forage) mainly grown for feed (Vanderlip, 1998; Taylor, 2005; Acquaah, 2012). The second top producer is currently Nigeria with production of 6.6 million metric tonnes/annum and it is the largest producer in Africa (HarvestChoice, 2014; USDA, 2017). The other important producers in Africa are Burkina Faso, Cameroon, Chad, Mali and Rwanda (Acquaah, 2012).

The productivity of sorghum in various countries in sub Saharan Africa (SSA) has changed drastically over the years. In west and central Africa, grain yield has increased by 129% from the 1970s with actual production of 13 million metric tonnes (Reddy *et al.*, 2012; HarvestChoice, 2014; ICRISAT, 2017). Moreover, in 2008, Nigeria produced around 71% of the total regional sorghum (Gourichon, 2013). This increase was also experienced in eastern and southern Africa (ESA) during the same period, whereby an increase of 18% occurred, resulting in 8 million metric tonnes being realized. For southern Africa, South Africa is the major sorghum producer, producing between 100 000 to 180 000 tonnes annually (Plessis, 2008). Sorghum production has also been increasing in Mozambique since 2006, where the average production was estimated at 156 000 tonnes (Goodbody *et al.*, 2010) and rose to an average production of 260 000 tonnes in 2017 (FAO-GIEWS, 2017) (Table 2-1).

Table 2-1 Cereals production in Mozambique in the past 6 years

| Crop | 2012-2016 | 2016 | 2017 |
|---|---|---|---|
| | 000 tonnes | | |
| Maize | 1483 | 1794 | 2000 |
| Rice (paddy) | 352 | 333 | 360 |
| Sorghum | 212 | 240 | 260 |
| Others | 48 | 52 | 50 |
| Total | 2094 | 2419 | 2670 |

Source: FAO/GIEWS, 2017

## 2.3. Sorghum production in Mozambique

Although sorghum production in Mozambique has increased, the yield is still very low (0.4 t.ha$^{-1}$) compared to a potential yield in the world of 3.0 to 6.0 t.ha$^{-1}$ (Kumar *et al.*, 2008; Tsusaka *et al.*, 2015). In addition, the agricultural system is basically rain-fed and zero-input with the sorghum mainly produced in the central regions of Nampula, Sofala and Manica (WorldBank, 2004; Goodbody *et al.*, 2010). The use of cultural practices such as crop rotation, timeous weeding, bird control and improved cultivars especially the use of hybrids by the farmers could increase the current yields (Diao *et al.*, 2007). Thus, the rapid growth in economic and food security in Mozambique can be achieved through investment in research, with a focus on yield increases (WorldBank, 2004; FAO, 2013).

The use of sorghum hybrids has been reported to add value to a country’s production (Malali, 1980; Li and Li, 1998; Adugna and Tesso, 2008). For example, in Queensland, yield evaluation of different varieties was found to range from <1 t.ha$^{-1}$ to >3.5 t.ha$^{-1}$ (Chapman *et al.*, 2000). Furthermore, there is a need to increase grain yield by identifying adapted and stable hybrids that can be used in commercial production. This increase in yield can be achieved through the use of existing technologies (Sanchez *et al.*, 2007; Pronyk *et al.*, 2012) such as doubled haploids, molecular markers and participatory variety selection. China is a typical example of countries that have managed to achieve food security through increased use of hybrids and chemical fertilizer (Po-Chi *et al.*, 2008). Thus, in SSA including Mozambique, the use of modern crop varieties that effectively respond to most of the biotic and abiotic constraints could be the solution to food insecurity (Chen *et al.*, 2011). In general, crop breeding and genetic research can contribute more to the development of productive and efficient varieties to increase grain yield. In addition, this development must be accompanied by appropriate cropping systems to achieve both sustainable yield increase and a reduction in environmental degradation.

## 2.4. Sorghum production constraints

The yield gap between the potential grain yield and yield in farmers' fields in Mozambique still exists (Tsusaka *et al.*, 2015). This is mainly due to a number of factors that include limited inputs, biotic, abiotic, and socio-economic constraints (Waddington *et al.*, 2010). Among these, the biotic constraints in sorghum production play a major role in low productivity, especially in the field where plant diseases reduce grain and dry matter yield (de Milliano *et al.*, 1992).

### 2.4.1. Biotic constraints

The most important biotic constraints that affect grain yield in sorghum are diseases. Diseases that have been reported to contribute greatly to yield reduction include: ergot disease (*Claviceps africana*) (Pažoutová *et al.*, 2000; Dahlberg *et al.*, 2001; Bhanderi *et al.*, 2015), rusts (*Puccinia purpurea*) (Wang *et al.*, 2006; Silva *et al.*, 2015) and anthracnose (*Collectotrichum graminicola*).

The diseases which include grain mould and ergot reduce the economic value of the grain as they produce toxic chemicals which affect the grain quality. This is a major problem which occurs mainly in cool areas during the flowering stage of the plants (Little *et al.*, 2012). Biological and chemical control methods have been used, but these are not readily available or affordable to poor resourced farmers. In addition, ergot and some species of *Fusarium* have been managed through a reduction in the number of sclerotia per panicle as a result of chemical applications (Leslie, 2008). However, management of these diseases through genetic resistance is the most effective and economical control method as it is the most convenient to the small-scale farmer.

There are some encouraging reports on the control of these diseases, for example, Reed *et al.* (2002) reported ergot resistance in some varieties that was associated with rapid pollination characteristics. Other studies reported germplasm sources with physiological resistance to ergot in the A3 male sterile genetic background, based on a low-level infestation in male-sterile hybrids under field conditions (Dahlberg *et al.*, 2001; Reed *et al.*, 2002). Frederickson *et al.* (1991) reported that due to the increase in the use of male sterile lines in eastern and southern Africa in breeding high-yield varieties and hybrids, the disease has become more important.

Sorghum rust was found to have minimal effects on sorghum yield. However, it can expose plants to other major diseases such as stalk rots, charcoal rot and grain mould and contributes to lodging by reducing leaf area and increasing plant stress (White *et al.*, 2012). The disease can be managed through cultural practices such as planting date management and use of resistant plants (Pande *et al.*, 2003; McIntyre *et al.*, 2005).

Anthracnose, on the other hand, has been reported as one of the most common and destructive diseases affecting sorghum, particularly in hot and humid areas (White *et al.*, 2012). Use of susceptible cultivars can cause losses up to 50%. Symptoms are usually expressed from seedlings, leaves, stem, peduncles and the grain is also affected (Marley *et al.*, 2005; White *et al.*, 2012). Control of this disease is often difficult as it is less predictable year after year due to its dependence on the weather conditions. In seasons with high rainfall, the disease is prevalent and damaging. As a result, small-scale farmers are severely affected because they cannot afford to buy pesticides to control the disease. Disease control of anthracnose is through use of resistant germplasm and crop residue management by cleaning the fields after harvesting (Marley *et al.*, 2005). Therefore, identification and selection of genotypes with greater levels of disease resistance could be more sustainable and effective for grain yield increase in the smallholder farming sector.

Furthermore, downy mildew (*Peronosclerospora sorghi*) also results in yield losses in sorghum (Sharma *et al.*, 2012). Downy mildew is economically important as it causes death of plants or lack of panicle initiation (Jeger *et al.*, 1998). It causes substantial losses in grain yield in many parts of the semi-arid tropics where sorghum is the staple food. Downy mildew is mostly controlled by the use of treated seed with the systemic fungicide, metalaxyl (Leslie, 2008). Resistance has been identified and successful cultivars have been created (Bandyopadhyay and Frederiksen, 1999; Rosenow *et al.*, 2014). However, repeated cultivation of resistant cultivars has led to the emergence of new races of the pathogen that are virulent to the cultivar. This has, therefore, placed an emphasis on the need to utilize genes from diverse sources in order to create hybrids with durable resistance (Kamala *et al.*, 2002).

Other important biotic constraints are birds and Striga. Several studies revealed *Striga* (Mounde *et al.*, 2015; Dereje *et al.*, 2016; Ali and Mahdi, 2017) as an important sorghum pest. Ejeta (2007) reported that Striga can be controlled using resistant cultivars combined with field management. On other hand, reduction of Striga seed bank using organic matter and fertlizer to suppress soils (Ransom, 2000) is also recommended. For bird control, repellents are used combined with/or the use of bird-resistant cultivars (Crase and Dehaven, 1976; Kumar *et al.*, 2005). Therefore, sorghum breeders have a major task of developing cultivars adapted to farmers' conditions and resistant to the various biotic factors.

### 2.4.2. Abiotic constraints

Sorghum is widely adapted to varying climatic and soil conditions. It tolerates drought and high-temperature stress better than many crops, remaining inactive during dry periods (Gnansounou *et al.*, 2005; Olembo *et al.*, 2010). Although drought has been affecting crop production, sorghum performs better than other cereals under different environmental stresses, including drought stress an indication of its ability to withstand drought in semi-arid regions of Africa making it more economical to produce (Machado and Paulsen, 2001). However, Gill *et al.* (2001) reported that heat and drought are factors that significantly contribute to yield reduction and the water deficit affects plant growth, metabolism and productivity (Sharma *et al.*, 2004). Other abiotic constraints affecting sorghum plants are salinity, dehydration, cold weather, osmotic pressure (Gill *et al.*, 2003) and low soil fertility (Waddington *et al.*, 2010). There is, therefore, a need to breed sorghum cultivars that tolerate different abiotic factors.

### 2.4.3. Socio-economic constraints

Important socio-economic constraints in SSA that affect most crop production including sorghum are: inadequate fertilizer uses and management, use of unimproved or unsuitable varieties, planting time and density (Waddington *et al.*, 2010). Use of inorganic fertilizer in combination with other agronomic practices such as planting time and plant density can increase yields. For example in Nigeria, Amujoyegbe *et al.* (2007) reported that the use of inorganic fertilizer had a greater effect on grain yield and chlorophyll in sorghum than maize with a difference of 0.066 t.ha$^{-1}$.

The major sorghum socio-economic constraints in Mozambique are markets, high seed prices, limited access to markets for inputs, lack of extension services for sorghum, lack of preferred varieties and processing technologies (Nankani *et al.*, 2006; Asfaw *et al.*, 2010; Waddington *et al.*, 2010; Agumagu *et al.*, 2014). There is still lack of markets for farmers to sell their produce and unavailability of improved seed for farmers to purchase (Hamukwala *et al.*, 2010). The demand for sorghum products by the urban consumers as a result of migration of people from rural to urban areas and the increased awareness of the nutritional value of sorghum calls for sorghum commercialization rather than subsistence production (Macauley and Ramadjita, 2015). There is, therefore, a need to increased productivity to respond to the demand by use of improved varieties.

On the other hand, access to markets is also affected by poor road infrastructure between rural areas and the main urban markets. Consequently, in some rural areas the access to improved seed and new technologies is extremely limited. In these areas, the source of seed for farmers is mostly their own harvested seed, other farmers, from local grain markets and from the informal seed sector (Almekinders *et al.*, 1994). Most of the seed from these sources is usually adapted to farmers' agro-ecological and socio-economic conditions and the seed is often obtained without involvement of cash as it is used more for farmers subsistence (Almekinders *et al.*, 1994; Remington *et al.*, 2002). The transformation of subsistence agriculture to commercialized farming depends on the availability of improved seed and fertility inputs (Rohrbach and Kiala, 2000). Currently many farmers in Mozambique depend on subsistence agriculture with low productivity and low inputs. It is thus critical to enhance the productivity for those farmers who produce for the local markets.

Seed price and seed quality are also important factors for the market. Rohrbach and Kiala (2000) reported that the price of seed and grain on the local market was almost the same due to poor quality of seed on the market and limited markets for grain. It is, therefore, important that a trusting environment between farmers and companies who buy agricultural products be created, if strong markets are to be developed. Farmers need fair prices and companies need to feel confident to invest in farming (Nankani *et al.*, 2006). Zavale *et al.* (2005) observed in their study that education of farmers did not have a significant impact on the adoption decision. The reasons for the non-adoption of new technologies, for example, in eastern Africa, were a result of farmers not being aware of improved technologies, unavailability of improved technologies or unprofitable technologies (Doss, 2003).

Thus, the key for growth and increased productivity in agriculture involves the adoption and use of available new technologies, as well as access to markets. A combination of improved seed, fertilizer and irrigation are requirements for yield increase (Nankani *et al.*, 2006), but use of appropriate technologies to reach out farmers is important to ensure adoption of the technologies. However, increase in productivity due to innovative technologies cannot be achieved on its own, it has to be combined and complemented with improvements in Agricultural Institutions and human capital development (Zavale *et al.*, 2005).

## 2.5. Sorghum improvement

Sorghum is a self-pollinating diploid (2n=2x=20) species with a high photosynthetic efficiency. There are three important species of sorghum: *S. bicolor* (Linn.) Moench (2n=2x=20), *S. propinquun* (Kunth) Hitche (2n=2x=20) and *S. halepense* (Linn.) Pers.(2n=2x=40) (Acquaah, 2012). The most important species in crop production is *S. bicolor* and has been cultivated and inter-crossed with other sorghums to produce fertile hybrids. Initially, sorghum was typically tall, late to mature, easily lodged and very low yielding (Rooney, 2004). However, the interest to increase yield and improve other characteristics such as plant height, maturity, disease resistance, conceived the idea of hybrid development. Exploration of $F_1$ hybrids in sorghum started in the USA in the mid-1950s with the development of the cytoplasmic male sterility system (CMS) (Kramer, 1987; Menz *et al.*, 2004). The use of cytoplasmic male sterile system from the local material is a great step towards sorghum improvement in many countries.

The origin of the cytoplasmic male sterility is known to be geographically from America, India and Africa (Sane *et al.*, 1996). The CMS is broadly categorized into different groups that include $A_1$, $A_2$, $A_3$, $A_4$, etc. These groups depend on their maintainer and restorer crosses (Sane *et al.*, 1996; Schnable and Wise, 1998). The $A_1$ is mainly used for commercial hybrid production (Sane *et al.*, 1996), but it requires a very close management of the population during anthesis (Rooney, 2004). Therefore, the production of hybrids and improved varieties is the most significant successful breeding effort over the last few decades.

Understanding the selection method for population improvement of sorghum is another important step. Selection methods used to identify the most suitable parent genotypes with traits of interest range from mass selection to family-based selection methods (Rooney, 2004). The breeding efforts in sorghum are based on specific traits of interest and these traits vary from region to region where the majority of producers demand high yielding and stable hybrids. On the other hand, resistance/tolerance to a specific abiotic stress or biotic stress is also required. Additionally, consumers require a certain grain quality depending on the growing environment and grain use. Thus, defining the breeding priorities according to the producers and consumers preferences is an important initial step in the implementation of a breeding programme.

For instance, in the early 1980s, the Sorghum and Millet Improvement Programme (SMIP) managed by ICRISAT made significant efforts to bring improved varieties to different countries (Chisi, 2003; Olembo *et al.*, 2010). In addition, under this programme the variety Macia (open-pollinated variety-OPV) was released in Mozambique in 1996. This variety was widely accepted by farmers at the village level (Chisi, 2003). Nevertheless, yields and grain quality of these improved cultivars declined due to outcrossing with the non-adapted cultivars. As a result, in 2008 the Alliance for a Green Revolution in Africa (AGRA) funded the sorghum breeding programme in Mozambique to develop and promote the use of improved sorghum open pollinated variety (OPV) and hybrid varieties to increase grain yield, disease and pest resistance, and drought tolerance (AGRA, 2009). The goal for the sorghum programme is to accumulate favourable alleles for the traits of interest while maintaining as much genetic diversity as possible for further crosses.

## 2.6. Genetic diversity

Traditionally, sorghum farmers keep and cultivate diverse landraces that may have a lower risk of crop failure due to changes in climate, disease, pests, and soil limitations (Brush, 2000; Barnaud *et al.*, 2007). Therefore, knowledge of the local and improved cultivars and understanding their diversity is of interest in the breeding programme and has applications in the design of the breeding strategies.

### 2.6.1. Importance of genetic diversity in sorghum breeding

Information on the level of diversity in different germplasm is helpful for the identification of sources of improved breeding gene pools and the search for genes that have not been selected (Warburton *et al.*, 2008). The use of diverse landraces by farmers is to address complex problems in their farming systems that include various stresses such as diseases, pests as well as drought and low soil fertility. Farmers prefer varieties with good yield but also with potential market value and stable under these stresses (McGuire, 2000; Dossou-Aminon *et al.*, 2014). Therefore, availability of genetic diversity permits selection of germplasm that is stable and high yielding and with other traits preferred by farmers. This selection could be through heterotic groups or by use of molecular markers (Menz *et al.*, 2004). The identification of these groups and genetic distances may be based on several agronomic data and explored through multivariate analysis (Yeung and Ruzzo, 2001) and diversity index (Chikuta *et al.*, 2015). Use of these tools in characterizing diversity can give information regarding the germplasm that is important for yield improvement programmes. Therefore, it is important to characterize Mozambican germplasm since accessions in the collection have not been described.

### 2.6.2. Multivariate methods for genetic diversity analysis

An extensive variety of multivariate techniques is available for analysis of genetic diversity and the choice of the most suitable method depends on the type of data. Fundamentally, the analysis summarizes a large set of data by means of relatively few parameters (Chatfied and Collins, 1980). Three techniques are mostly used for multivariate analysis and these are principal component analysis (PCA), cluster analysis and discriminant analysis (Murtagh and Heck (2012). The first method focuses on inter-object correlations, reduction of their dimensionality and allows graphic presentation of the data, while the second is the application of automatic grouping procedures. The third method classifies items into pre-defined groups.

These methods have been applied in a number of studies. For example, principal component and cluster analysis were useful in characterizing sorghum germplasm based on morphological (Ngugi and Maswili, 2010; Seetharam and Ganesamurthy, 2013; Chikuta *et al.*, 2015) and molecular markers (Folkertsma *et al.*, 2005; Ali *et al.*, 2008; Upadhyaya *et al.*, 2012). Chikuta *et al.* (2015) found that using PCA and cluster analysis on phenotypic traits, genotypes were classified according to their genetic similarities or differences. Moreover, results from PCA can be helpful in parent selection, thus breeding improvement (Seetharam and Ganesamurthy, 2013). Furthermore, molecular markers have also been used to assess genetic diversity in sorghum. For example, Assar *et al.* (2005) used simple sequence repeats (SSRs) to assess genetic variability among sorghum germplasm from different origins and clustered them according to morphological and molecular markers. Therefore, use of different methods in assessing diversity is helpful in improving the breeder's parental selection and hybridization as high yielding parents with traits of interest can be targeted. On the other hand, diversity index is also commonly used to identify phenotypic diversity among diverse parents (Upadhyaya *et al.*, 2010).

## 2.7. Combining ability analysis

Hybrid development requires complementarity between parents. This complementarity in sorghum is achieved by the use of male sterility to facilitate crossing, resulting in identification heterosis for many traits such as yield (Reddy *et al.*, 2007). The information on combining ability of the parents is very important for a hybrid oriented breeding programme (Kenga *et al.*, 2004; Makanda *et al.*, 2010). Combining ability is defined as the capacity of a cultivar or individual parent to transmit superior performance or desired genes to its offspring (Fasahat *et al.*, 2016). There are two concepts of combining ability, general combining ability (GCA) and specific combining ability (SCA). Sprague and Tatum (1942) and Griffing (1956) defined general combining ability as the average performance of a parent in hybrid combination and specific combining ability as the performance of parent in a specific cross.

According to Goyal and Kumar (1991), the information on combining ability assists in identifying superior parents and hybrids and also to define the ideal gene action controlling the traits. The general combining ability (GCA) analysis is done in the process of developing superior genotypes while specific combining ability gives the performance of the hybrids (Cruz and Regazzi, 2004). Kenga *et al.* (2004) found that good general combiners do not always create superior hybrid combinations. This shows that there is a need of evaluating the $F_1$ hybrids first before such information is generated. For the hybrid combination, the importance of GCA essentially implies importance of additive gene action while the SCA shows the importance of non-additive gene effects and other interactions such as epistasis (Kenga *et al.*, 2004; Makanda *et al.*, 2010). Kenga *et al.* (2005) reported that the interaction between the GCA and SCA with environment indicates the response of different traits over environments.

Hussien (2015) identified sorghum hybrids and parents with good combining ability for grain yield and days to 50% flowering while Mohammed (2009) found good combining ability for forage yield and earliness in flowering. The hybrids developed also need to be evaluated in different environments to identify the best genotypes for specific or wide environment adaptation.

## 2.8. Genotype x environment interaction

Genotype by environment interaction is the differential response of two different genotypes to environmental variation (Yan *et al*., 2007). The genotype by environment interaction has implication on the genotype's adaption and evaluation, where unpredictable environments and/or reduction of genetic variance increases selection in one direction. The genotype-by-environment (GE) interaction is undesirable for breeders as it confounds genotype evaluation (Yan and Tinker, 2006). The crucial requirement for improvement of plant adaptation is the identification of the phenotypic stability and management of adapted genes (Farshadfar *et al.*, 2012). Phenotypic stability is often used to refer to variations in the phenotypic composition of the yield while the genotypic composition remains stable (Becker and Leon, 1988).

Several methods have been used to analyse multi-environment trial data and select superior genotypes for specific or wide adaptation. Methods such as additive main effects and multiplicative interaction (AMMI) (Gauch, 2006) and the genotype, genotype by environment (GGE) biplot method (Yan *et al*., 2007) have been suggested for exploring G x E in genotype evaluation. The AMMI model combines the analysis of variance and principal component analysis while GGE biplot is based on the principal component analysis (Gauch, 2006; Yan *et al.*, 2007). In the AMMI model, the main effects are retained as additive effects, while the GEI is treated as a multiplicative effect (Duarte and Vencovsky, 1999). Further, Yan *et al.* (2007) concluded that both GGE and AMMI analysis were able to separate genotype and genotype-by-environment in mega-environment but GGE biplot was more superior than AMMI1 graph in mega-environment analysis. The GGE biplot uses the principal component scores to plot the effective view of multi-environment trial by showing "which-won-where" (Yan *et al.*, 2007). It was reported in several studies that GGE biplot is an excellent method for visual data analysis (Yan and Tinker, 2006; Farshadfar *et al.*, 2012; Akter *et al.*, 2015). In the present study, GGE biplot analysis was used to identify the high yielding and stable genotypes.

The G x E interaction is important in determining the relationship of the traits such as linear and non-linear regression (Mungra *et al.*, 2011). This interaction is higher in semi-arid tropics due to the variability of abiotic and biotic factors (Alagarswamy *et al.*, 1996). However, the adaptability of the superior cultivars to certain environments is given by a cultivar superiority index (P*i*), where the lower value indicates general adaptation and higher value specific adaptation (Lin and Binns, 1988). This index can be used to measure performance and stability of a cultivar based on characteristics of the cultivar to allow better selections to be made. The achievement of the goals defined in the breeding programme depends on the method the breeder uses to identify and select the superior genotypes according to the traits of interest.

## 2.9. Heterosis in sorghum

### 2.9.1. Use of variability in sorghum

Genetic variability is essential to hybrid sorghum improvement. Variability determines genetic gain from selection and grouping of the cultivars into heterotic groups (Makanda *et al.*, 2009). In other words, the sorghum breeding programmes have been using A/B and R lines as the heterotic groups where the female lines A/B must be heterotic to the R line for a successful hybrid creation (Acquaah, 2012). However, in the development of a line, two groups are separated, whereby one is used as a tester for the other. Selection of an effective tester for evaluating the hybrid performance and heterosis of new inbred lines is crucial to ensure their accurate evaluation (Menz *et al.*, 2004; Packer and Rooney, 2011). The importance of heterosis in hybrid development is its contribution to increased yields. It is estimated that it increases yield by at least 15% (Lippman and Zamir, 2007). Kenga *et al.* (2004), reported that the use of sorghum hybrids in India achieved an 80% yield increase in production in the past 20 years with reduction of the area under the crop.

These results show that the yield increase needs to be improved through breeding for yield and other interest traits using hybrids. In sorghum hybrids, grain yields have been reported to vary from 1.6 $t.ha^{-1}$ to 6.4 $t.ha^{-1}$ depending on the complementarity of the lines (Patil, 2007). In addition, the crosses between male sterile and male-fertile from different heterotic groups, demonstrated to be productive in hybrid combinations (Li and Li, 1998; Kenga *et al.*, 2004) but it is crucial to determine the potential of the new hybrid cultivar by testing against the progenitors and successful varieties on the market. Makanda *et al.* (2010) reported in their study that the current varieties on the market are inferior in yield potential compared to hybrid cultivars in southern Africa. Therefore, the inclusion of local populations and exotic material in the crosses to produce stable hybrids with high heterosis from diverse genotypes is a good step in the hybrid production process (Hallauer *et al.*, 2010).

The Sorghum Breeding programme in Mozambique has been creating varieties and evaluating them under different environments for many years but it is still lacking information on the combining ability of the lines available for hybrid development. Although data have been collected from many trials, the information available is mainly limited to yield and the main genotype effect. Moreover, the information of interaction genotype by environment may be treated as noise or a confounding factor. A better understanding of the phenotypic effects is still required to relate genotypic to phenotypic variation during crop improvement.

### 2.9.2. Contribution of heterosis in sorghum

There are many morphological characteristics contributing to heterosis expression in sorghum. The effect of heterosis in the hybrid can be measured by the mid-parent values. Different studies reported hybrids that were early, taller and had higher grain yield than their better parents (Singhania, 1980; Premalatha *et al.*, 2006; Bagheri and Jelodar, 2010; Hussien, 2015). Haussmann *et al.* (2000) and Blum *et al.* (1990) reported mid-parent heterosis values of 13 and 88% and 24 to 40% respectively. This hybrid superiority was shown in grain yield. Hayes and Rooney (2014) reported grain yield heterosis of 172% over the line parents. Moreover, recent studies reported yield increases of up to 29% for lowland adapted hybrids and increased up to 52% for a highland adapted hybrid in Ethiopia (Mindaye *et al.*, 2016). Therefore, there is need to study different morphological traits to better understand the inheritance and selection or identification of superior genotypes.

## 2.10. Farmers' trait preferences for improved sorghum varieties

Adaptation of the variety in the local environment is a requirement for farmers when selecting a variety. Farmers in remote and variable environments prefer adaptable cultivars with stable yield and good for food security with yields which may be higher on average (Almekinders *et al.*, 2007). Thus, farmers prefer cultivars that have a substantial increase in yield under low-yielding conditions than those that give the same increase in yield under high yielding conditions (Tester and Langridge, 2010). However, it is important to consider other critical attributes considered by farmers such as food quality. Asrat *et al*., (2010) reported that the important attributes for farmers' variety selections are adaptability and stability. In addition, involving farmers in the breeding programme using participatory plant breeding (PPB) methods was reported by Manandhar *et al.* (2004) and Mekbib (2006). In these methods, several techniques can be used such as on-farm trials, questionnaires interviews, group discussions, matrix ranking and other methods according to the situation (Almekinders *et al.*, 2007; Nkongolo *et al.*, 2008).

An on-farm trial known as mother and baby trial has been used to assess technologies by farmers and has two main approaches (Snapp, 2002). Firstly, researchers conduct the trials at the research station with replications and secondly, they conduct a large number of on-farm trials across a spectrum of environments (Fielding and Riley, 1998). The second approach takes into consideration the variability of the environments characterizing farmers regions and each site performances, the reason to simultaneous replicate using the first approach (Fielding and Riley, 1997). University of Reading (1998), reported that for on-farm trials it is better to have more farmers with a single treatment, rather than fewer farms with many replications in each trial. The on-farm system has an advantage over conventional methods in selecting and spreading out varieties for the target environment with a specific constraint (Banziger and De Meyer, 2002). In general, mother and baby trials contribute rapidly to developing improved varieties and facilitate the exchange of information and experience among the partners. Gonsalves (2005) reported some of the advantages of using these approaches whereby: i) researcher-extension collects substantial amount of high quality data for both qualitative and quantitative traits; ii) easily observable and can be used to predict adoption of the potential technologies; iii) farmers rapidly gain experience and confidence in using technology in their fields and iv) it leads to joint research-extension learning, feedback, and changes in practices by both groups. This means that it helps to improve the efficiency of research and extension by making impact at farmers' level.

Many farmers in Africa, particularly in Mozambique choose to grow local varieties than new improved varieties due to the knowledge of the grain quality, adaptability and the performance under their local farming systems. Those attributes are supposed to be used to select a new cultivar and it can vary depending on location, gender and production costs (Vom Brocke *et al.*, 2003). Consequently, the production cost can be reduced with a gain in yield by use of an improved and high yielding variety (Deb *et al.*, 2005). In fact, selection of high yielding cultivars with farmers' preference traits is critical. Therefore, breeders need to involve farmers in assessments based on their preferences.

## 2.11. Selection Index

Selection of the characters based on the farmers' selection criteria is an important step for the adoption of a new cultivar. Selecting plants based on the economic values brings a value to the cultivar on the market. The economic value of a plant is mostly determined by several characters (Dabholkar, 1999). In sorghum, some of the preferred characters by farmers are grain yield, seed size, plant height, grain quality, and resistance to pests or diseases. For the breeder to achieve maximum improvement in the economic value of the cultivars it is important to have an efficient selection procedure which is determined by several characters (Dabholkar, 1999). The effects of selection on quantitative traits can indicate changes in the genetic properties of the population, such as means, variances and covariances. According to Singh *et al.* (2011), the main limitation to estimate selection indices is attributed to biotic traits such as pest damage, that can contribute negatively to selection. Therefore, selection criteria should consider measuring the combined effect of different components simultaneously.

Selection of high yielding genotypes based on a single parameter is therefore difficult, as increase in yield may change the other parameters such as plant height, earliness and grain size. Tesfamichael *et al.* (2013) found that in Ethiopia the criteria for farmers selection in sorghum was panicle size, seed size, grain colour and maturity date. Knowledge of heritability influences the choice of selection procedures used by plant breeders to decide which selection methods would be most useful to improve the character, to predict gain from selection and to determine the relative importance of genetic effects (Laghari *et al.*, 2010).

The choice of a selection method for plant breeding may favour identification of superior genotypes during the development of new cultivars and saves time and cost (Kurek *et al.*, 2001). The identification of superior genotypes requires selection methods capable of exploiting efficiently the available genetic material, and maximizing the genetic gain in relation to the characteristics of interest (Vivas *et al.*, 2012). Therefore, a selection index that results from a combination of certain traits that pursue simultaneous selection, allows identification of superior genotypes.

The selection of several traits at the same time is mostly facilitated by the use of a selection index based on a combination of multiple traits (Shook, 2006; Cruz, 2013). The use of the selection index allows identification of superior genotypes established by the optimal linear combination of various traits (Vittorazzi *et al.*, 2017). Selecting for traits simultaneously using an index provides useful information and a realistic response to selection for all the traits that are being combined by giving a total genetic value to the individual line (Bänziger and Lafitte, 1997). It thus results in fast genetic advance, thus reducing the breeding time required to come up with the product for the target market. Initially, Smith (1936) and Hazel (1943) reported use of selection indices in plants and animals respectively and then later other indices were proposed by Williams (1962), Pešek and Baker (1969) and Mulamba and Mock (1978). Many breeding programmes use selection indices in different crops to select superior genotypes and predict genetic gain, which leads to an appropriate performance. The limitation of selection indices in some situations is the establishment of economic weights for the various traits of interest (Pešek and Baker, 1969; Coimbra *et al.*, 1999; Vittorazzi *et al.*, 2017). For this reason, Cruz (1990) proposed the use of experimental data to estimate the economic weights.

## 2.12. Summary

From the literature reviewed, it was noted that sorghum is widely produced in the world mainly in semi-arid areas of Asia and Africa where it is one of the most important staple foods. The yield production in most of the African countries is still very low when compared to the demand. Moreover, use of hybrids in Africa is still limiting but could increase the current production and rapid growth in economic and food security of most of the African countries. This increase may start from identifying the adapted and stable hybrids that can be used for commercial production associated with other technologies. However, there is limited information available on the development of sorghum hybrids in Africa. Although yield increase is the targeted goal, there are many constraints to be taken into consideration. These constraints are biotic, abiotic, field management and socio-economic constraints whereby drought and diseases are the main constraints affecting the crop during the growth period. Diseases such as anthracnose, rusts, ergot, downy mildew, grain mould might need a good disease management and identification of sources of genetic resistance. Genetic resistance was shown to be the most effective and economic control method.  On the other hand, hybrid development on sorghum requires a good understanding of the breeding methods to be used as well as selection methods. Additionally, knowledge of consumers and producer's requirement and preferences is essential to improve the breeding strategies. Use of diverse sources of germplasm owned by farmers is used to meet complex goals of farmers' farming systems such as cultivar with tolerance to different stresses (diseases, pests, and drought and soil fertility problems). Therefore, farmers' opinions and preferences must be included in the breeding programme when defining the objectives. Variability is important for genetic gain from selection and grouping lines/cultivars into different heterotic groups. The complementarity of the lines in the crosses is crucial; therefore, the involvement of exotic material in crosses is a good step in the hybrid production process. A better understanding of the phenotypic effects is still required to relate genotypic to phenotypic variation during crop improvement. The yield stability remains an important factor in the variable African production environments where there is need of multi-environment trials analysis for selecting superior genotypes for wide or specific adaptation. Then the cost of field evaluation for grain yield and yield components can be reduced if environments are characterised. Although most of the studies reported in the literature have provided useful information for superior parents and hybrid selection, few reported the combining ability for grain yield and yield components for sorghum.

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# 3. An appraisal of sorghum farmers' trait preferences, production threats and opportunities for plant breeding in central region of Mozambique

## Abstract

Sorghum is the third most important grain cereal after maize and rice in most African countries, including Mozambique. However, despite the increase in production in Sub-Saharan region, productivity is still very low averaging 0.4 t.ha$^{-1}$ compared to a potential yield of 3.0 t.ha$^{-1}$. The present study was conducted to understand farmers' preferences and needs in sorghum varieties, production threats as well as how to involve them in breeding activities. The study covered the high potential sorghum production districts of Guro and Mussorize in central Mozambique. About 7 to 18 representative farmers were included in each discussion group resulting in 110 farmers across six locations. Data were collected through structured interviews using a structured questionnaire to guide the discussions. Data were subjected to analyses using cross-tabulation procedure, and contingency chi-square values were calculated for tests of significance. The results showed that sorghum was an important crop as maize (13.6%) in terms of production across the study locations followed by cowpea (11.4%). Sorghum production depended on many factors such as area used, crop duration in the field and yield levels in each season. All the farmers across the locations preferred white grained sorghum types, whereas 83.3% and 16.7% preferred hard and soft grain types, respectively. The attributes preferred by farmers were high grain yield, good food quality and suitability of the harvested grain for various uses. The major constraint in the production mentioned by farmers was drought. The other constraints were operational and included weeding, thinning out plants, threshing and sieving, cutting and transporting grain during and after harvest. The important constraints in sorghum commercialization were a combination of low price, unavailability of seed and weak markets. Therefore, there is a need to use improved varieties that could increase sorghum production and improve seed quality for sorghum production and marketing of sorghum products.

## 3.1. Introduction

Sorghum (*Sorghum bicolor* L.) is a staple food crop in the drier parts of Africa, Europe and Asia (Ogeto *et al.*, 2013). It is the third most important crop in terms of grain production after maize and rice in many African countries, including Mozambique. Sorghum is one of the cereal crops that are well adapted to biotic and abiotic stress factors (Hassan, 2015). Because of its tolerance to severe droughts and long dry spells during the rainy season, the crop is frequently grown in semi-arid and subtropical regions of the world (Dennes, 1990), particularly in regions where rainfall is generally low, erratic and poorly distributed.

In Mozambique, sorghum is produced and consumed mostly in the northern and central regions of the country (INTSORMIL, 2008; WorldBank, 2014). In these areas, well adapted traditional varieties have been used by farmers, but the rate of adoption of improved varieties has remained low (Benfica *et al.*, 2014). However, as the agricultural sector continues to experience challenges in production due to repeated and extended droughts, there is a need for the development of improved drought resistant crops including sorghum.

Sorghum production increased in Mozambique between 2006 and 2009, when the average annual production was estimated at 384 000 tonnes (Goodbody *et al.*, 2010). However, due to drought and other constraints, production dropped to 139 000 tonnes in 2012 but increased again due to government intervention, which involved seed distribution. Consequently, in 2014 a total of 155 164 tonnes grain sorghum was harvested (FAOSTAT, 2017). Despite the increase in production, the productivity has remained low, averaging 0.4 $t.ha^{-1}$ compared to a potential yield of 3.0 to 6.0 $t.ha^{-1}$ (Kumar *et al.*, 2008). This has been due to a number of factors including the fact that, agriculture in the Mozambican sorghum producing areas, namely the central regions of Nampula, Sofala and Manica, has remained basically under rain-fed and zero-input systems (WorldBank, 2004; Goodbody *et al.*, 2010). In view of the aforesaid, improved cultural practices such as crop rotation, timeous weeding, bird control and the inclusion of improved cultivars especially the use of hybrids by the farmers could double the current yields (WorldBank, 2004; FAO, 2013).

Although farmers tend to rely on crops such as sorghum and pearl millet when faced with unfavorable climatic conditions (Tsusaka *et al.*, 2015b), there is still remarkably low sorghum production as well as consumption among some Mozambican communities. In addition, sorghum productivity and market supply have declined in recent years due to unfavorable climatic conditions, low yields and damage by field pests (Benfica *et al.*, 2014). This suggests that households can be motivated by improving market participation, offering high prices for the product, which can help the farmers to invest in improved agricultural technologies and put more effort in increasing agricultural productivity (Benfica *et al.*, 2014). In addition, increased productivity could create higher amounts of marketable surplus, such that, with market access, could result in increased market participation leading to potential improvements in overall household welfare.

Since sorghum is the preferred cereal where maize cannot grow, it thus serves as an excellent food security crop. Therefore, the causes of the low adoption of developed and released improved varieties in Mozambique need to be determined. This could be achieved through clearly identifying what farmers prefer in a cultivar through researcher-farmer interaction and collaboration. This method involves encouraging farmers to participate in experiments using their own fields where they can learn, adopt and spread new technologies to other farmers (Leeuwis, 2013). Participatory approaches should be adopted on selection criteria of traits that are important for farmers so that they can easily accept and adopt the new cultivars. This depends on farmers' needs and it varies from location to location. Participatory plant breeding is actually a breeding method that brings farmers and researchers together and enables them to select crop varieties suitable to their specific environmental conditions.

Additionally, assessment and diagnosis are important to provide a better understanding of the farmers' needs, thereby increasing the possibility of long-term sustainability of the technology in the community. Therefore, the objectives of this study were: i) to assess farmers' preferences for traits in new sorghum varieties in central Mozambique, and ii) to identify sorghum production constraints in the region which can lead to opportunities for sorghum breeding.

## 3.2. Materials and Methods

### 3.2.1. Study locations

The study was conducted in six villages covering two selected districts of Manica province in the central part of Mozambique (Figure 3-1). The districts are Guro and Mussorize located in northern and southern parts of the province, respectively. The six villages selected constituted high potential sorghum production areas of the province (

Table 3-1).

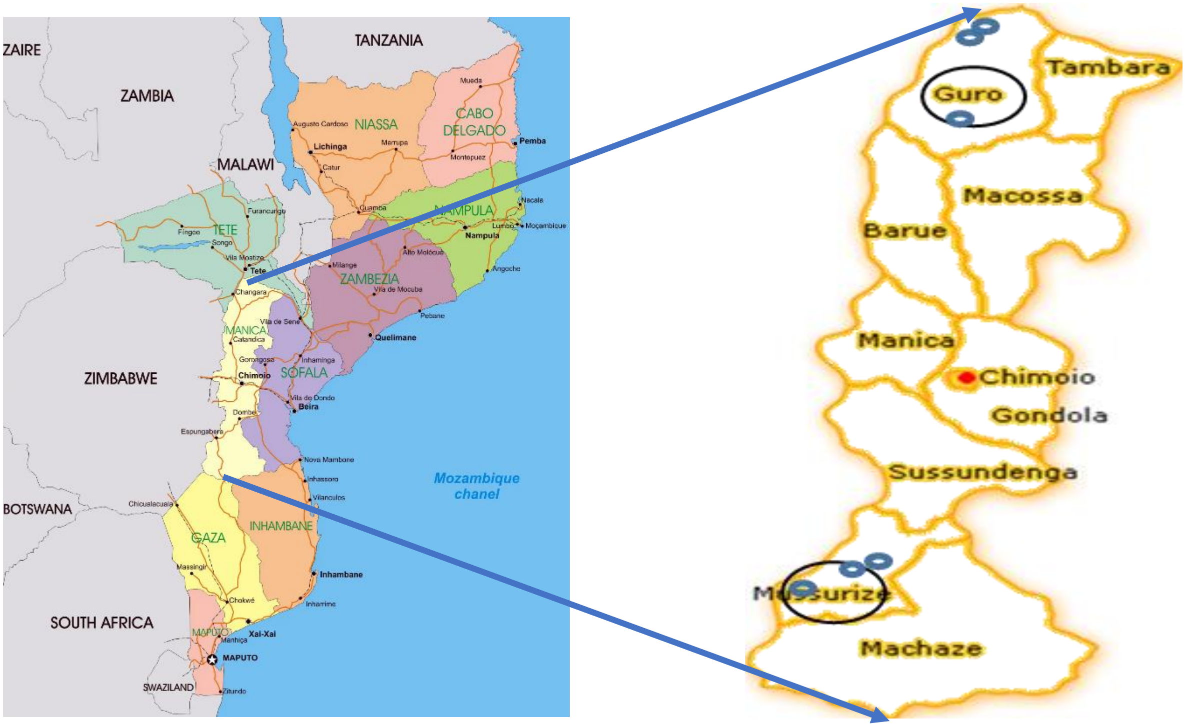

Figure 3-1 Map of the locations used in Manica Province (source: Mapsland, google)

Table 3-1 Coordinates of six the villages in two districts of Manica province where the study was conducted

| Village | District | Latitude | Longitude | Altitude (m.a.s.l) |
|---|---|---|---|---|
| Guro | Guro | 17º24.772's | 33º21.594'e | 729 |
| Mandie | Guro | 16º27.238's | 33º21.594'e | 158 |
| Dimbe | Guro | 16º26.188's | 33º34.016'e | 151 |
| Espungabera | Mussorize | 20º43.889's | 32º78.609'e | 731 |
| Mabudo | Mussorize | 20º28.545's | 32º59.285'e | 434 |
| Gunhe | Mussorize | 20º13.693's | 33º19.679'e | 188 |

The average annual rainfall in Guro town (centre of the district) is 600 mm with a maximum temperature of 30.5ºC and minimum of 17.5ºC (MAE, 2005). It is located around 729 m above sea level (m.a.s.l.). The soil type varies from red clay soil to sandy soil in the north of the district. The northern part of the district, where farmers grow mainly sorghum and pearl millet, and have livestock, is dry and the temperatures can be as high as 36-40ºC during the rainy season (November-January).

Mussorize district has an average annual rainfall of around 1500 mm with a maximum temperature of $25^{o}$C and minimum of $15.1^{o}$C (MAE, 2005). Espungabera is the town of Mussorize district and is located around 700 m.a.s.l. The maximum temperature varies between $25\text{-}27^{o}$C in January and minimum of $10\text{-}14^{o}$C in July. This district borders Zimbabwe in the west and semi-arid district of Machaze in the south east. The area where farmers produce mainly sorghum and cassava in the district is semi-arid with red clay soils and the annual rainfall is 600-800 mm.

### 3.3. Farmer participation

In each district, three villages where sorghum is produced purposively were selected. In Guro district, the selected villages were Mandie, Dimbe and Guro, while in Mussorize district they were Mabudo, Gunhe and Espungabera. The leaders of the villages who know the people assisted with the sampling of the farmers. The criteria for farmer selection was based on farmers' involvement in sorghum production or in any activity related to sorghum. About 7-18 representative farmers were included in each discussion group resulting in 110 farmers across locations. However, in Mandie and Dimbe the number of farmers were more than 15 people and were therefore, divided into two groups to answer the same questionnaire. The study could not cover more locations and farmers due to limited resources.

The locations with most participants were Mandie and Dimbe followed by Guro, Mabudo and Gunhe (Table 3-2). Espungabera had the least number of participants because many farmers were not well informed regarding the day of the interview and some farmers were not in the villages.

Table 3-2 Distribution of farmers according to location and gender

| | Location | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | Guro District | | | | | Mussorize District | | | |
| Farmers | Guro | Mandie | | Dimbe | | Espungabera | Mabudo | Gunhe | |
| Men | 5 | 8 | 7 | 6 | 5 | 5 | 12 | 10 | 58 |
| Women | 10 | 5 | 5 | 12 | 13 | 2 | 3 | 2 | 52 |
| Subtotal | 15 | 13 | 12 | 18 | 18 | 7 | 15 | 12 | |
| Total | | | | | | | | | 110 |

### 3.4. Data collection and analysis

Data were collected through interviews using a structured questionnaire to guide the discussions. The questionnaire had five components: a) general information, b) sorghum production and sales, c) farmers' preferences, d) sorghum production costs and e) farmers' constraints. The staff that facilitated the discussions in each location were a breeder, a socio-economist, an agronomist and an extension agent. The discussions were conducted in local languages (Ximanhica, Shona and Portuguese) and the collected information was translated into English on the same day.

Production cost was based on the value estimated by farmers for each activity.  Data were subjected to analyses using cross-tabulation procedure and contingency chi-square values calculated for test of statistical significance using SPSS version 16.0 (SPSS Inc., 2007). Additionally, production cost was used to estimate the profitability of producing sorghum in each district using he following formula:

$$\text{Profitability} = [\text{Grain yield (kg/ha) x selling price (Mt/kg)}] - [\text{Production cost (Mt/ha)}]$$

## 3.5. Results

### 3.5.1. Farmers' participation in farm activities

The group discussions indicated that men in all locations were responsible for clearing new land for farming while land preparation differed according to location (Table 3-3). In Guro, Mandie and Espungabera, both men and women participated in land preparation. On the other hand, in Mabudo and Gunhe, women were responsible for land preparation while in Dimbe it was done by men.

Plantings in Guro and Mandie were done by men, women and children whereas in Dimbe, Espungabera, Mabudo and Gunhe, plantings were done by men and women only. Although, thinning out and weeding were activities done by men, women and children in Guro and Mandie; in Dimbe and Espungabera these were done by women and children only. In Mabudo and Gunhe thinning and weeding were done by both men and women.

Men and women were mostly involved in harvesting in Mandie, Espungabera and Gunhe while in Guro, Dimbe and Mabudo, harvesting was done by men, women as well as children. On the other hand, threshing of the grain was done only by women in Dimbe and Espungabera. In Mandie, Mabudo and Gunhe this activity was done by both men and women whereas in Guro it was done by men, women and children. Construction of granaries was done only by men in all the locations, while milling and bird scaring were done by women and children, respectively. The transportation of the harvested crop was done by both men and women in Dimbe and Gunhe. In Guro and Mabudo, transportation of the harvest was done by men, women and children while in Mandie and Espungabera it was done by men. Moreover, in Guro, Dimbe and Espungabera women were responsible for selling farm products while in Mandie, Mabudo and Gunhe, both men and women were involved in the selling of farm products.

Table 3-3 Percentage of participation in various activities on the farm based on gender across six locations

| Activity | Guro Sede (%) | | | Mandie (%) | | | Dimbe (%) | | | Espungabera (%) | | | Mabudo (%) | | | Gunhe (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | M | W | C | M | W | C | M | W | C | M | W | C | M | W | C | M | W | C |
| Land clearing (new farm) | 100 | | | 100 | | | 100 | | | 100 | | | 100 | | | 100 | | |
| Land preparation | 50 | 50 | | 50 | 50 | | 100 | | | 50 | 50 | | | 100 | | | 100 | |
| Planting | 30 | 50 | 20 | 30 | 50 | 20 | 50 | 50 | | 50 | 50 | | 50 | 50 | | 50 | 50 | |
| Thinning and Weeding | 30 | 50 | 20 | 30 | 50 | 20 | | 70 | 30 | | 70 | 30 | 50 | 50 | | 50 | 50 | |
| Harvesting | 30 | 50 | 20 | 50 | 50 | | 30 | 50 | 20 | 50 | 50 | | 30 | 50 | 20 | 50 | 50 | |
| Threshing | 30 | 50 | 20 | 50 | 50 | | | 100 | | | 100 | | 50 | 50 | | 50 | 50 | |
| Silo building | 100 | | | 100 | | | 100 | | | 100 | | | 100 | | | 100 | | |
| Transportation of products | 30 | 50 | 20 | 100 | | | 50 | 50 | | 100 | | | 30 | 50 | 20 | 50 | 50 | |
| Sale of produce | | 100 | | 50 | 50 | | | 100 | | | 100 | | 50 | 50 | | 50 | 50 | |
| Milling | | 100 | | | 100 | | | 100 | | | 100 | | | 100 | | | 100 | |
| Bird control | | | 100 | | | 100 | | | 100 | | | 100 | | | 100 | | | 100 |

M = Men, W = Women, C = Children

### 3.5.2. Importance of sorghum in relation to the other crops produced in the region

There was a significant difference ($P \leq 0.05$) among locations in terms of the crops produced and their importance (Table 3-4). The main crops produced across locations were maize, sorghum and cowpea, corresponding to 13.6%, 13.6% and 11.4%, respectively. Pigeon pea, sweet potato, sesame and beans ranked the same in terms of importance across the locations (Table 3-5). There were other minor crops produced as indicated in Table 3-5. Maize and sorghum were produced across all the locations, but in different quantities and for different purposes.

Table 3-4 Analysis of variance for number of crop species produced

| | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Between Groups[1] | 178.440 | 2 | 89.220 | 5.474 | 0.008 |
| Within Groups | 668.287 | 41 | 16.300 | | |
| Total | 846.727 | 43 | | | |

[1] Groups are divided in subsistence crop and cash crop

The majority of the crops produced across the six locations were mainly for subsistence and sorghum was the only subsistence crop that covered all locations (Figure 3-2). About 70.5% of the crops were used for food or for other home uses while 25% were used as cash crops. Only 4.5% of the crops were used for both purposes, that is, cash and subsistence. The crops used for cash were cotton, beans, cowpea, sesame and maize.

Table 3-5 List of the crops produced and their importance for farmers across the six locations

| Crop Produced | Total Farmers* | Importance across location (%) |
|---|---|---|
| Maize | 82 | 13.6 |
| Sorghum | 110 | 13.6 |
| Peanut | 40 | 4.5 |
| Pigeon pea | 91 | 9.1 |
| Sweet potato | 78 | 9.1 |
| Sesame | 49 | 9.1 |
| Cowpea | 103 | 11.4 |
| Pearl millet | 40 | 4.5 |
| Watermelon | 36 | 2.3 |
| Cucumber | 36 | 2.3 |
| Pumpkin | 36 | 2.3 |
| Cotton | 7 | 2.3 |
| Vegetables | 7 | 2.3 |
| Beans | 83 | 9.1 |
| Cassava | 27 | 4.5 |
| Subsistence crop | 91 | 70.5 |
| Cash crop | 19 | 25.0 |
| Subsistence and cash crop | 42 | 4.5 |

*Total number of farmers growing the crop

The importance of the crops differed from one location to another. Sorghum was always within the top three important crops across the six locations, except for Espungabera where cash crops were more important. In Guro, Dimbe, Mabudo and Gunhe, sorghum was mentioned as the second important crop, after maize while in Mandie it was mentioned the third priority crop. The ranking of the other crops changed according to the use and location (Figure 3-2).

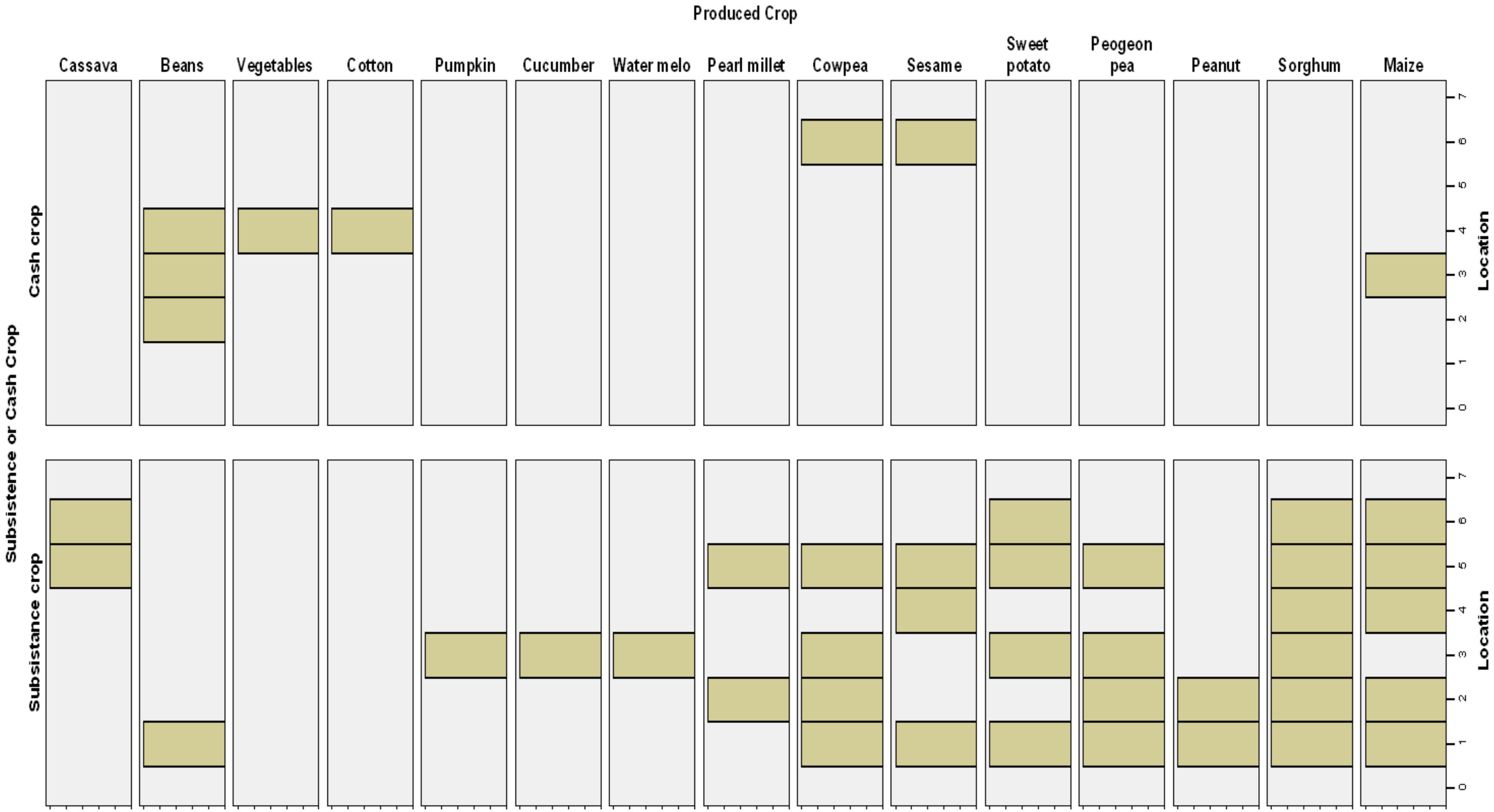

Figure 3-2 Crop production versus the importance across locations

Location legend: 1- Guro, 2- Mandie, 3- Dimbe, 4- Espungabera, 5- Mabudo and 6- Gunhe

### 3.5.3. Factors affecting sorghum production

It was observed that sorghum production across the six locations depended on many factors. Some of the factors listed by farmers were; area used, crop duration in the field and yield in each season. The minimum hectarage used for sorghum production was one hectare and a maximum of four hectares per farmer, with other farmers allocating one and half, two and three hectares to sorghum (Figure 3-3). Dimbe and Espungabera were the locations with one hectare on average while Guro, Mandie, Gunhe and Mabudo covered one and half hectares, two, three and four hectares, respectively.

The duration of the crop in the field was around six months per season in all locations. The longest sorghum cropping period was reported in Mabudo where sorghum took as long as eight months in the field and the shortest (six months) was in Guro and Mandie. The other locations had a crop season of seven months.

There was a significant difference in yield in a good season when compared to a bad season ($P<0.05$). Guro, Mandie, Gunhe and Mabudo had yields below 2.0 $t.ha^{-1}$ during good seasons while Dimbe and Espungabera produced above 2.0 $t.ha^{-1}$. These locations with yield above 2.0 $t.ha^{-1}$ showed a large difference between good seasons and bad seasons though for other locations the difference was not large.

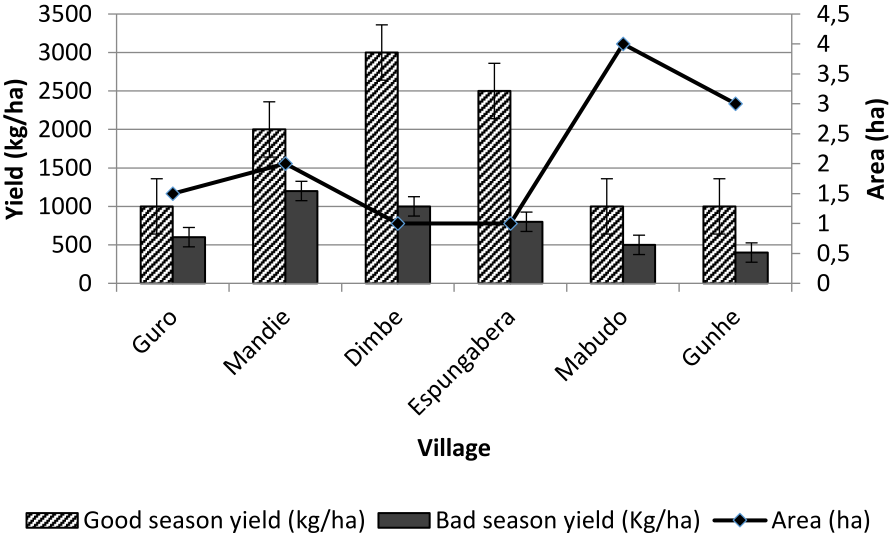

Figure 3-3 Sorghum yield under good and bad seasons across locations

The interviewees reported that during the last three years (2012 - 2014) sorghum production decreased due to many reasons including insufficient rainfall, lack of markets and lack of availability of improved seed. The majority of farmers indicated the absence of strong markets for sorghum (39.1%) and lack of improved seed (24.6%). Few interviewees highlighted insufficient rainfall (13.6%) and a combination of insufficient rainfall and unavailability of markets (22.7%) as the main factors resulting in decreased sorghum production (Table 3-6).

Table 3-6. Percentage of respondents indicating different causes of a reduction in sorghum production over the years

| Cause | Number of farmers | Percentage |
|---|---|---|
| Less rain | 15 | 13.6 |
| No market | 43 | 39.1 |
| No improved seed | 27 | 24.6 |
| Less rain and no market | 25 | 22.7 |
| Total | 110 | 100 |
| $X^2$ | | 0.667 |
| *p-value* | | 0.881 |

Respondents from Dimbe and Espungabera reported that the decrease in sorghum production was due to a lack of strong markets for sorghum and also low prices. Mabudo and Gunhe indicated that it was due to a lack of improved seed availability at the village while in Guro the main reason was insufficient rainfall. Mandie was the only location where a combination of insufficient rainfall and lack of markets was raised.

### 3.5.4. Farmers' trait preferences

The results showed that different farmers preferred different traits in a sorghum variety. These were divided into plant and grain related traits.

#### 3.5.4.1. Plant trait preferences

There was a significant difference ($p<0.05$) in plant traits preferred by farmers across all locations (Table 3-7).

Table 3-7 Test of significance for the various plant traits preferred in sorghum varieties

| Trait | Test Value = 0 | | | | | | $X^2$ |
|---|---|---|---|---|---|---|---|
| | t | df | Sig. (2-tailed) | Mean Difference | 95 percent Confidence Interval of the Difference | | |
| | | | | | Lower | Upper | |
| Plant height | 13.00 | 5 | 0.000 | 2.167 | 1.74 | 2.60 | 2.667 |
| Panicle insertion | 3.73 | 5 | 0.014 | 2.500 | 0.78 | 4.22 | 0.000 |
| Leave colour | 5.97 | 5 | 0.002 | 1.833 | 1.04 | 2.62 | 0.667 |
| Plant vigour | 4.00 | 5 | 0.010 | 1.333 | 0.48 | 2.19 | 1.000 |
| Stem size | 4.00 | 5 | 0.010 | 1.333 | 0.48 | 2.19 | 2.667 |
| Leave position | 4.57 | 5 | 0.006 | 1.833 | 0.80 | 2.87 | 2.667 |
| Plant use | 4.39 | 5 | 0.007 | 3.000 | 1.24 | 4.76 | 1.000 |

Regarding plant height, 89.1% of the farmers preferred short plants. This trait is associated with early maturing varieties. Gunhe was the only location where farmers (10.9%) chose average to tall plants (Table 3-8). For panicle insertion; big panicles were selected in Guro, Mabudo and Gunhe while in Mandie, Dimbe and Espungabera, they preferred big and long panicles. This trait is strongly associated with the harvest yield.

Leaf colour was important to the farmers because it indicates how healthy the plant is. Dark green leaves were mostly selected by farmers in Mandie, Dimbe and Espungabera and corresponded to 61.8% of all interviewed farmers. On the other hand, 24.5% of the farmers specifically in Guro and Gunhe selected a light green colour. About 13.6% of the farmers in Mabudo had no leaf colour preferences indicating any colour of leaves (dark or light green). In terms of vigour, the majority of farmers (86.4%) selected vigorous plants in the field. Mandie farmers selected average plants meaning not too much vigour (13.6%). Regarding leaf architecture, 57.3% of the farmers selected open leaves, while 20% chose any leaf position and 22.7% preferred straight leaves. Guro, Dimbe and Gunhe farmers selected open leaves, while Espungabera and Mabudo preferred any leaf position. Mandie farmers were the only ones that preferred straight leaves.

In terms of plant use, construction (20.0%), and construction and animal feed (55.5%) were the major activities that used most of the plant materials after harvesting across all the locations. On the other hand, 13.6% of the farmers left the plant materials as residue in the field while some used the materials for both construction and field residue (10.9%). Farmers in Guro and Espungabera used the plant materials for construction, while Mandie and Dimbe farmers used the materials for construction and animal feed. Mabudo farmers left the plants as residue in the field and in Gunhe they used the plant materials for both construction and residue in the field.

Table 3-8 Parameters selected by farmers in the sorghum plants

| | Parameters | Number of farmers | Percent |
|---|---|---|---|
| Plant height | Short | 98 | 89.1 |
| | Average | 12 | 10.9 |
| Panicle insertion | Big | 42 | 38.2 |
| | Big and long | 68 | 68.8 |
| Leaf colour | Light green | 27 | 24.5 |
| | Dark green | 68 | 61.8 |
| | Any | 15 | 13.6 |
| Plant vigour | Vigorous | 95 | 86.4 |
| | Average | 15 | 13.6 |
| Leaf position | Open leaves | 63 | 57.3 |
| | Straight leaves | 25 | 22.7 |
| | Any | 22 | 20.0 |
| Plant use | Construction | 22 | 20.0 |
| | Field residue | 15 | 13.6 |
| | Construction and animal feed | 61 | 55.5 |
| | Construction and field residue | 12 | 10.9 |

#### 3.5.4.2. Grain related traits preferred by farmers

The grain colour selected across locations was 100% white. Hard grain types were preferred by 83.3% of the farmers whereas 16.7% of the farmers preferred soft grain. The hard grain was selected in Guro, Dimbe, Espungabera, Mabudo and Gunhe while the soft grain was selected in Mandie.

In respect to seed size, 66.7% of the farmers in Guro, Mandie, Espungabera and Mabudo chose big size and 33.3% of the farmers in Dimbe and Gunhe chose small seeded types (Table 3-9). On the other hand, 50% of farmers chose sweet grains, 33.3% indicated any taste and 16.7% preferred bitter grain taste. Guro, Mandie and Mabudo farmers preferred sweet grains, Dimbe and Espungabera no taste preferred and Gunhe bitter taste. It was observed that 66.7% of the farmers used sorghum for brewing, food and animal feed while 16.7% used the grain for brewing or for food (Table 3-9). Farmers in Mandie, Dimbe, Espungabera and Gunhe used the grain for brewing, food and animal feed while in Guro they used it more for brewing and food and in Mabudo, only for brewing.

Grain was stored for more than a year in Dimbe, Espungabera and Gunhe (50.0%) while in Mandie and Mabudo grain was stored for a year (33.3%). However, in Guro farmers stored the grain for only three months (16.7%). Additional characteristics considered in grain selection by farmers across locations included the duration of the grain in the granary, taste for beer, and cooking time. Guro, Dimbe and Espungabera farmers reported that the shelf-life in the granary is very important while in Mandie they reported that they preferred grain with a short cooking time and longer storage/shelf-life in the granary, whereas in Mabudo and Gunhe farmers indicated that they preferred grain that was good for brewing beer (Table 3-9).

Table 3-9 Grain characteristics selected by farmers in sorghum

| Parameters | | Number of farmer | Percent |
|---|---|---|---|
| Grain colour | White | 110 | 100.0 |
| Hardness | Hard | 85 | 83.3 |
| | Soft | 25 | 16.7 |
| Size | Big | 62 | 66.7 |
| | Small | 48 | 33.3 |
| Taste | Sweet | 55 | 50.0 |
| | Bitter | 12 | 16.7 |
| | Any | 43 | 33.3 |
| Grain use | Brewing | 15 | 16..7 |
| | Brewing and food | 15 | 16.7 |
| | Brewing, food and animal feed | 80 | 66.7 |
| Storage | Three months | 15 | 16.7 |
| | One year | 40 | 33.3 |
| | More than a year | 55 | 50.0 |
| Other characteristics | Stay longer in granary (shelf-life) | 58 | 50.0 |
| | Good for beer | 27 | 33.3 |
| | Cook quickly and stay longer in granary | 25 | 16.7 |

### 3.5.4.3. Cost of producing the sorghum

The production cost was calculated based on the hired labour for activities carried out on the farm. In Mussorize district, farmers did not hire labour for some of the activities. Results showed that the cost of producing a hectare of sorghum in the two districts was higher in the southern part of the province than in the northern (Table 3-10).

Table 3-10 Cost of sorghum production activities in two districts

| Activity | Guro District cost (MZN/ha) | Mussorize District cost (MZN/ha) |
|---|---|---|
| Land preparation | 3,100.00 | 4,500.00 |
| Seedling/Planting | 600.00 | 2,500.00 |
| Pesticide | 150.00 | - |
| Thinning out | 1,250.00 | 1,250.00 |
| First weeding | 500.00 | 1,250.00 |
| Second weeding | 750.00 | - |
| Granary preparation | 500.00 | - |
| Harvesting | 875.00 | 800.00 |
| Transport | 300.00 | - |
| Threshing | 1,000.00 | - |
| **Total** | **9,025.00** | **10,300.00** |
| **Total difference (percent)** | **12.37** | |

Exchange rate 1 USD = 35 MZN (February, 2015)

The total sorghum production cost in Mussorize district was 12.37% more than in Guro district where the land preparation, planting and first weeding were the most expensive activities (Table 3-10).

In Mussorize district, some of the activities were not usually carried out using hired labour because the cost was too high. For example, pesticides were not commonly applied, and a second weeding was also not commonly practiced. In addition, granary preparation, transport and threshing were solely done by the families.

### 3.5.4.4. Estimation of profitability

The estimation of profitability was analysed assuming that family and hired labour had the same remuneration. The information used to estimate profitability is indicated below:

Cost of producing sorghum = 9,0255.00 Mt/ha (Guro district) and 10,300.00 Mt/ha (Mussorize district)

Grain selling price in 2015 = 15,00 Mt/kg

Average of production in 2015 [grain yield (kg/ha)] = 1500-2,000.00 kg/ha (Mussorize and Guro districts respectively)

$$\text{Profitability} = [\text{Grain yield (kg/ha) x selling price (Mt/kg)}] - [\text{Production cost (Mt/ha)}]$$

1. Profitability Guro district = (2000 kg/ha x 15,00 Mt/kg) – (9025.00 Mt/ha)
   Profitability Guro district = 20975.00 Mt/ha
2. Profitability Mussorize district = (1500 kg/ha x 15,00 Mt/kg) – (10,300.00 Mt/ha)
   Profitability Mussorize district = 12200.00 Mt/ha

The estimation of profitability in the two districts showed that Guro had more profit when compared to Mussorize district. Although, most activities are paid using farm products, it is still be more profitable to grow sorghum in Guro.

### 3.5.5. Constraints faced by farmers in sorghum production

The respondents in the discussion mentioned different constraints affecting sorghum during the growing season. Constraints were divided into production constraints, pest and disease constraints, commercialization constraints, varieties used and other needs to improve their farming.

#### 3.5.5.1. Production Constraints

The major constraint in the production mentioned was drought, as was experienced in the last 5 years and indicated by 11.77% of the farmers. The other production constraints had to do with field operations and weeding, thinning out plants, threshing, sieving, cutting and transporting grain during and after harvest and corresponded to 5.88% each (Table 3-11).

Table 3-11 Production constraints/challenges across locations as indicated by the farmers

| Constraint | Percent |
|---|---|
| Weeding | 5.88 |
| Thinning and weeding | 5.88 |
| Drought | 11.77 |
| Threshing and sieving | 5.88 |
| Weeding, cutting and transport | 5.88 |
| Fungi | 11.77 |

| | |
|---|---|
| Grasshoppers | 11.77 |
| Wild chickens | 5.88 |
| Rats | 5.88 |
| Low price in the market | 5.88 |
| Unavailability of improved seed | 5.88 |
| Price, seed and market | 11.77 |
| Unavailability of markets and improved seed | 5.88 |

Mandie and Dimbe were the only locations where drought was a major concern. The farmers in these locations also listed weeding and thinning as other challenges. Farmers in Mabudo, indicated that threshing and sieving were the main challenges while in Gunhe, it was cutting the plants before harvesting and transporting the harvest from the fields to the homes.

For diseases and pests; fungi and grasshoppers were the major pests with 11.77% each. The other constraints included wild chickens and rats (5.88%) which were shown to cause serious damage in some sorghum fields (Table 3-11). Apart from rats, fungi and grasshoppers, there were also birds and stem borers as reported by farmers in Mandie, Dimbe and Gunhe. The fungal diseases were not specified but from the description given, they appeared to be downy mildew (*Peronosclerospora sorghi*) and ear rot (*Fusarium graminearum*). Espungabera farmers indicated the presence of rust (*Puccinia purpurea*) and stem borer (*Chilo partellus*) apart from the pests and diseases already mentioned above.

#### 3.5.5.2. Commercialization constraints

The important constraints in sorghum commercialization were low selling prices of seed or grain, unavailability of seed and weak markets for sorghum (Table 3-11). Most farmers (11.77%) indicated a combination of price, availability of seed and markets as the most important constraints. These constraints were reported in Mandie, Guro and Mabudo. Espungabera farmers had a potential to produce sorghum but the main constraint was the low price of the grain on the market while in Gunhe farmers produced mainly for consumption and only sold when they had surplus.

#### 3.5.5.3. Sorghum varieties used

The seed used in most of the locations were a mixture of local and improved varieties (Figure 3-4). In Guro, Mandie and Dimbe farmers used a mixture of seeds while in Espungabera they used improved seeds and in Mabudo and Gunhe they used local seed only.

In Mabudo and Gunhe they were aware of the improved seed but its availability was one of the major constraints. Guro, Mandie and Dimbe farmers had acquired Macia variety about 10 years ago and this explained the reason for the mixture of improved and local seed.

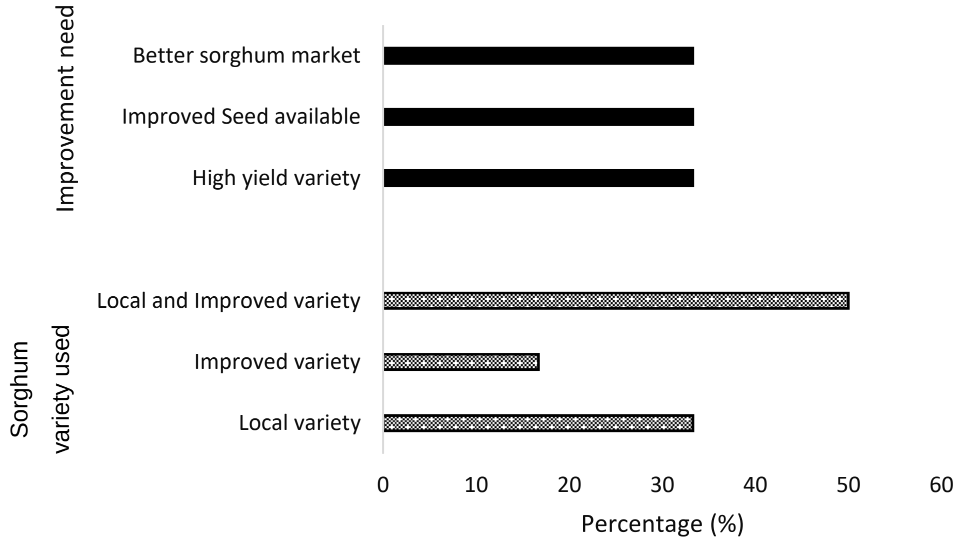

Figure 3-4 Percentage of important traits for farmers across districts

### 3.5.6. Improvement needed to increase sorghum production

The major requirement by farmers across locations was increased yields of sorghum by use of improved varieties (Figure 3-4). Guro and Dimbe farmers preferred high yielding and early maturing varieties, may be due to the harsh climatic conditions in those areas. Mandie, Mabudo and Gunhe farmers required seed of improved varieties to increase the production, as they were faced with insufficient rainfall in their location in the last 2 years. Espungabera farmers indicated that sorghum markets needed to improve, especially the price of seed and the number of grain buyers.

## 3.6. Discussion

The study showed that the level of participation by men was higher than women across locations during the interviews. Mussorize did not have many women participating in the interviews of agricultural activities and this might be due to the fact that information about interview dates did not reach them in time for them to attend. In rural areas, women are responsible for most of the farming and household activities resulting in fewer numbers participating in surveys and group discussions when the husbands are present. This is expected in these regions where there is a perception that men are responsible for cash crops and women for subsistence crops. It can also be attributed to the assumption that farm activities are a woman's job while men have more free time and can attend different meetings including focus group discussions. The results agree with Doss (1999) that women are more involved in subsistence crop production than men. WorldBank (2006) reported in a study that most farmers are women, and extension staff should therefore reach out to women groups and guarantee that suitable technology is gender-oriented. However, the findings in this study revealed that both men and women were involved in sorghum production activities.

The results also revealed that for the majority of activities, both men and women participated. However, specific activities such as clearing new lands for farming and granary building are perceived as men's activities while milling the grains is regarded as a woman's activity. In general, women participated in most of the activities, except clearing new land for farming and silo building in all districts. Men's participation in various activities varied from district to district. This differs from the results reported in other studies where women were responsible for sowing, piling up of panicles, winnowing, threshing, processing and selling, while men were responsible for ploughing, opening the holes for sowing, picking and burning of weeds, stem cutting, seed selection and construction of granaries (Dossou-Aminon *et al.*, 2014). Different results were reported by Tsusaka *et al.* (2015), where women were responsible for land preparation, harvesting and transportation of stalks while men were responsible for weeding. The involvement of women in planting, bird scaring, harvesting and post harvesting processing is common in many crops including sorghum (Muui et al., 2013). The participation of children in farm activities was to reduce labour costs for field operations and it depended on the number of children existing in the household as well as whether they were registered at school. In both districts, the selling of produce was done by men and women, but the money was kept and managed by women. Although women played a significant role in providing labour for most agricultural activities, both men and women were involved (SOFA and Doss, 2011).

In central Mozambique, the most important food crops are maize, cassava and sweet potatoes followed by sorghum, beans, millet and rice while cotton, groundnut and some cashew are the cash crops (WorldBank, 2006; Kiregyera *et al.*, 2007). Due to harsh environments in the driest areas and actual climatic conditions, farmers tend to cultivate more of sorghum and pearl millet (Tsusaka *et al.*, 2015). This study showed a diversity of crops produced in all locations but the most common were maize, sorghum, pigeon pea, cowpea, sweet potato, sesame and beans. The crops were produced for consumption as well as a source of income. The sector of cash crop farming was an important source of income growth, but there is need to develop markets and balance interest of out-growers (WorldBank, 2006). According to Barbier (1990), a cash crop is a crop that may be sold locally or abroad where it can be a food or non-food product while subsistence crop refers to domestic production of basic staples.

Farmers indicated that cereals such as sorghum, maize and pearl millet were mostly used as food security crops. These results are in agreement with findings of Benfica *et al.* (2014) that cereals are dominant among the aggregate food crops. A similar observation was made by Chipanshi *et al.* (2003) who reported that maize and sorghum are a good adaptive strategy under a changing climate and they are a food security option under farmers' conditions. A crop's importance tends to change over years due to changing climatic conditions. In 2003, sorghum was in 4th place after maize, cassava and rice (MADER, 2004). However, currently sorghum is the second most important cereal after maize in rural areas (Benfica *et al.*, 2014). Tobacco and sesame are the two crops rising in economic importance in the country, particularly after a decrease of production in Zimbabwe (Walker *et al.*, 2006). The results showed that cotton and sesame were important cash crops in the study areas. Farmers consider beans and vegetables as cash crops since they are produced and sold on the local market. According to Walker *et al.* (2006), important cash and export crops in Mozambique are tobacco, cashew, cotton, coconut, sugar cane and sesame.

The farmers also indicated that sorghum is mostly used for consumption than selling when compared to other cereals. These results are in agreement with the findings of Tsusaka *et al.* (2015) from a survey conducted in Tete province where sorghum, pearl millet, groundnut and cowpea were the most important crops for women while watermelon and pineapple were important for men. Crops such as peanuts, pigeon pea, cowpea and beans are mostly consumed fresh as vegetables. Among the crops, sorghum is one of the crops with no local markets available and it is mostly produced for consumption, thus confirming its role as a food security crop. According to Walker *et al.* (2006), sorghum has a role in food security for many farmers particularly in dry and non-maize producing areas. Groundnut is an important legume and mostly used as cash crop in more productive areas and as a subsistence crop in dry areas while cowpea and pigeon pea are mostly for subsistence (Walker *et al.*, 2006; Basavaraj *et al.*, 2015). The results of this study showed that farmers' production can be improved, nevertheless since agricultural production is rainfed, weather variability will always affect production where no adaptable crops are used.

The factors affecting sorghum production, as observed in this study, were land use, crop period in the field and grain yield. This information showed that the majority of farmers use small areas to produce sorghum and only a few of them use large hectarages. These factors affect more crops that are intercropped or mixed with other crops in each season. In terms of production volume statistics, the most commonly grown cereal crops in Mozambique are maize, sorghum, rice and pearl millet in that order (MASA, 2015). According to Tsusaka *et al.* (2015), maize and sorghum farmers assign an average of 1.4-1.5 hectares of land to each crop in harsh environments, however, maize always yields less than sorghum and pearl millet. In a good rainfall season and on a new farm, sorghum yields can go up to 3.0 $t.ha^{-1}$. This might be because the land has not been exhausted and is still endowed with enough nutrients for crop growth. This is in agreement with Taylor (2005) who reported higher yields (4.1 $t.ha^{-1}$) when improved sorghum varieties were used in the short rainy season in Kenya. Sorghum is not only associated with drought-resistance, but it can also tolerate periods of water-logging.

On the other hand, in a bad season, low yields of approximately 0.4 to 0.8 $t.ha^{-1}$ may be realised. The low yield range, observed in this study is in agreement with results by Tsusaka *et al.* (2015) that, due to low and erratic rainfall in sorghum producing areas, yields fluctuate between 0.3-0.5 $t.ha^{-1}$ (Tsusaka *et al.*, 2015). In the northern region of the country, sorghum is produced in an environment where rainfall can exceed 1200 mm per annum, whereas in the dry southern parts of the country, it is not an important crop (Walker *et al.*, 2006). Farmers reported that sorghum takes a long period in the field (6-8 months). In the northern part of Manica province, this was a major complaint from farmers; while in the southern region of the same province, it was an advantage to the farmers due to the intercropping system used. This shows that, in the south, farmers need an early maturing variety while in the north; an intermediate to late maturing variety is preferred. In the past, sorghum was the most important food crop in Mozambique but due to marketing policies, farmers have shifted production gradually from sorghum to maize (Mucavele, 1988). The increase in production in most areas might be realised through improvement of sorghum markets in terms of prices and increase in number of buyers.

It was also observed that farming practices are learned from old people or people with more experience in agricultural activities. Although, the government extension officers assist farmers with livestock farming and some crop activities such as vegetables and maize rarely do they give them information on sorghum and pearl millet. This might be due to lack of information and experience in crops such as sorghum by the young people and new extension staff.

Farmers preferred traits such as short plant height, big panicles, stay green leaves and vigorous plants for plant aspect; while for grain, they preferred white, big, hard and sweet grain. Moreover, farmers preferred grain that was hard, had long shelf-life and with a good taste for brewing as well as less cooking time. These results are similar to findings from the northern part of the country, where farmers prefer flint grain typically found in local varieties compared to the softer and sweeter grain (Tsusaka *et al.*, 2015). The storing period varies, and storage is done at the fire place and in granaries but it is infested by post-harvest insects after a short time (Muui *et al.*, 2013). In other studies, Buah *et al.* (2010) found that farmers selected varieties on the basis of good food quality, stable grain yield, brewing quality, earliness, and pest and drought tolerance. Moreover, environmental adaptability and yield stability are attributes preferred by farmers (Asrat *et al.*, 2009). The grain size, colour and shape are considered as important traits from a marketing point of view as preferred types fetch higher prices (Basavaraj *et al.*, 2015). Besides these traits, high productivity, good quality of dough and porridge, high market value, resistance to storage pests and drought are additional preferred traits (Dossou-Aminon *et al.*, 2014).

On the other hand, farmers in this study mentioned that the residues of the plants were used as animal feed and building material among other household uses. Farmers cultivate a diverse set of varieties to face stresses and meet diverse needs. Besides grain, sorghum biomass is appreciated for feed or construction (McGuire, 2008). This is also in agreement with observations by Basavaraj *et al.* (2015) who reported that farmers can use crop residues as fodder to enhance incomes through milk production. Other traits preferred by the farmers in the landraces grown are high yields, high vigour, good taste, ease of grain processing and cleaning, resistance to drought, early maturity, and resistance to birds and other pests (Muui *et al.*, 2013).

The farmers' preferences were important criteria for adoption of new and improved varieties. In addition, involving the farmers in the initial stages of a breeding programme is useful for the adoption process. Attributes such as grain and plant uses might be considered in a breeding programme. The use of sorghum grain for beer brewing may be an option for future interventions by developing varieties with good malting qualities that can lead to demand from the beer industry.

The results showed that drought was the main constraint faced by the farmers' and had severely affected them for the last five years. According to the farmers, food crop production had declined by more than 40%, however, they continued to harvest something (though small quantities) from sorghum and pearl millet every year. These results agree with the findings of Basavaraj *et al.* (2015) that the farmer's constraints are related to moisture stress, yield variability, labour scarcity, marketing and cost of production. Furthermore, Dossou-Aminon *et al.* (2014a) identified climate variability as a constraint in sorghum production. Rain fluctuation and drought were the most important factors indicated by farmers. Crop adaptation is an essential aspect that will mitigate the future severity of climate change impacts on food production and there is a need to understand possible responses of Sub-Saharan African (SSA) crops to climate change (Schlenker and Lobell, 2010).

Besides drought; pests, diseases and commercialization were among the other challenges raised. Therefore, some improvements are needed to address these challenges. Fungal diseases were the main constraint across locations and their effect is severe when there is too much rain. In the dry season, sorghum is mostly affected by birds and wild chickens. Farmers did not use any chemical inputs to control pests and diseases. Apart from snares for the wild chickens and birds, these pests are scared off by children with noise of bottles and cans. According to Tsusaka *et al.* (2015), birds are the major constraint on sorghum and pearl millet production and mitigation is done by scaring off using family labour. These findings are similar with observations in Marara (Tete) where farmers control birds by shouting and throwing stones (Muui *et al.*, 2013; Tsusaka *et al.*, 2015). In Kenya, the major farmers' constraint in sorghum production are shoot fly, birds, ants, aphids, borers, smut and honey dew (Muui *et al.*, 2013).

The commercialization of farm products is one of the farmers' targets, but it was noticed that the farmers were also involved in other off-farm activities for income generation because of poor market access and a decline in crop production levels. Poor market access could be caused by lack of infrastructure such as good roads to the villages. The engagement in activities such as off-farm activities might have an undesirable influence in sorghum farming because they are more profitable and attractive (Tsusaka *et al.*, 2015). It was observed across the six locations that both men and women were involved in selling of the products, but that women were generally less able than men to participate in economic opportunities because of their heavy workloads than men. In addition to farming activities, they have to search for water, care for the children and other household activities thus limiting their participation in economic activities (Guanziroli and Frischtak, 2011). Thus, men were more involved in business or market activities than the agricultural work itself when compared to women.

Identification of improved varieties was difficult for some farmers because they use the short stature of the plant to relate with Macia variety. It was only in Espungabera that farmers used improved sorghum seed. This was because its location is on the border town with Zimbabwe whereby the market is influenced by the neighbouring country. The government programme also once distributed improved seed of Macia variety during the driest seasons, but not all villages received it. The genetic purity of the varieties in the six locations was low probably because of seed mixtures since farmers recycle seed every season. Additionally, farmers lack of resources to buy inputs, including seed, might be the main reason for not using improved seed, and the ultimate result is decreased sorghum production. Some of the main factors responsible for decline in sorghum production were lack of seed, use of unimproved varieties and inappropriate marketing policies (Mucavele, 1988). Use of improved varieties is extremely important for sorghum to compete with many new crops that have widespread adaptability across varying conditions. Higher yields are essential, not only for rural food security but also for increasing commercialisation (Taylor, 2005). Evidently, continually increasing the farming area of sorghum will be sustainable in the long-term, particularly for semi-arid areas of Africa.

It was also observed that the profitability of sorghum production is not as high as it looks, and still challenges such as availability of stable market exist. On other hand, farmers produce sorghum more for self-consumption and very few households market their sorghum. This could be due to price and demand of sorghum in the market that is still low. The use of poor crop management, low yielding varieties and no fertilizer on the fields are factors that might influence the low productivity of the crop. These could be to unavailability and high cost of the inputs in the districts. The district of Guro had high profit than Mussorize district. This shows that farmers make profit from sorghum production although the production still low. Baiyegunhi and Fraser (2009) reported similar results when they calculated profitability in sorghum production in three villages in Nigeria. Rosenzweig and Binswanger (1992) supported the idea that profitability by farmers is influenced by aversion of risks, their capital and variability of rainfall. Risk-averse farmers prefer a combination of rotation between crops compared to planting a single crop (Willims *et al*., 2000).

## 3.7. Conclusion

Farmers select varieties based on their needs and adaption of the variety to the farming system. The important attributes preferred by farmers include high grain yield, food quality and use of the harvested products. The use of early to intermediate maturity sorghum varieties by farmers could contribute to improvement in production levels for this crop. Such varieties might have additional traits, for example, white grains that are more preferred for food and brewing. Extension staff can also advise the farmers on which technologies they can use to improve sorghum productivity and access to markets. The involvement of more women in sorghum production and marketing could help promote sorghum as an industrial and food crop in the country. This could also improve quality of seeds used in sorghum production with a market orientation point of view. Breeders could improve varieties by responding to the farmers' needs such as by incorporating resistance to pests and diseases as well as tolerance to drought. Similarly, the varieties could have good storability because it is one of the farmer's concerns.

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# 4. Identification of important morphological traits in Mozambican sorghum germplasm using multivariate analysis

## Abstract

Classification of sorghum breeding materials based on multiple crucial characters is important towards the possible formation of homogeneous groups of genotypes, and groups that can be exploited in the identification of parents for use in a breeding programme. The objective of this study was to determine the morphological characters that distinguish desirable breeding material in the National Sorghum breeding programme and group the genotypes according to similarity. Principal component analysis (PCA) and cluster analysis were used to establish the relationships among germplasm and the Shannon Diversity index was used to quantify the level of diversity. Fifteen cytoplasmic male sterile (CMS) lines and ten male fertile (restorer - R) lines were used. The experiment was conducted at Sussundenga Research Station over two seasons and laid out in a 13 x 2 alpha lattice design replicated twice. Morphological characterization was carried out based on the International Board for Plant Genetic Resources/ International Crops Research Institute for the Semi-Arid Tropics descriptor list. Cluster analysis grouped genotypes into four clusters based on days to 50% flowering, 1000 seed weight, stay green, seed size, panicle exsertion, midrib colour, leaf rolling, leaf orientation, leaf colour, inflorescence compactness, head shape, glume cover, glume colour, awn and grain colour. Five principal components cumulatively accounting for 58.5% of the total variation were observed from the PCA analysis as significant contributors, whereas the remaining components individually made a negligible contribution. The diversity index showed high diversity for seven characters, including days to 50% flowering, thousand seed weight, seed size, leaf colour, inflorescence compactness, head shape and presence of awns. The variation in morphological characteristics showed the importance of knowing the germplasm diversity, especially for characters highly preferred by farmers such as earliness, grain yield, plant height and grain colour. These results have implications in selecting parents for use in sorghum improvement through breeding.

## 4.1. Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is an important cereal crop worldwide that is used for food, feed, fibre and biofuel. There are different types of sorghum depending on intended use, *viz*. grain sorghum, dual purpose (grain and fodder) sorghum, fodder sorghum, forage sorghum, and sweet stalk sorghum (Kumar *et al.*, 2008; Reddy *et al.*, 2012). Moreover, classification of sorghum is also based on uses and importance where the relative height and grain/stover productivity are considered.

Central Africa is the origin of sorghum and is where it was domesticated (de Wet and Huckabay, 1967; House, 1985; House, 1995) and continues to be cultivated. The cultivated and wild sorghums demonstrate greatest genetic diversity of this crop (Ayana and Bekele, 1999). In Ethiopia, the centre of diversity of sorghum, 15 cultivated sorghum races have been reported (Mengesha, 1975). Within these 15 races, 5 races are primary *(bicolor*, *caudatum, guinea, durra* and *kafir*) and 10 are intermediates (Harlan and De Wet, 1972). The most cultivated race in southern and eastern Africa is *guinea* (Folkertsma *et al.*, 2005; Lacy *et al.*, 2006). However, Ramathani *et al.* (2011) reported that all five primary races are cultivated in Sub-Saharan Africa. Therefore, it is important to classify the germplasm used in breeding programmes to make it easy for plant breeders to identify and select valuable genetic resources for direct use by farmers and for use in their breeding programmes.

There are many mathematical methods that permit grouping of species according to their characteristics. The common methods are the multivariate analyses that include principal component analysis (PCA) and cluster analysis which are used to establish the relationship among germplasm and Shannon diversity index which is used to determine the level of diversity in the germplasm. The PCA is a strong tool, which reduces the dimensionality of the data before applying clustering (Derksen *et al.*, 1995; Yeung and Ruzzo, 2001). Additionally, cluster analysis is used for pattern recognition and as a discriminant method that reveals structure and relationships in the data (Anderberg, 2014). The Shannon diversity index measures unequal weights in a community through decomposing the measurements into expressive components (Jost, 2007). One of the differences between principal component analysis and cluster analysis is that the few PCs containing most of the variation certainly do not capture most of the cluster structure (Yeung and Ruzzo, 2001). This implies that the two methods can complement each other to enhance the results.

The importance of estimating genetic diversity is to identify similar groups of genotypes that facilitate conservation, evaluation and utilisation of the genetic resources. The diversity of different germplasm is used as a possible source of genes that can improve the performance of cultivars in terms of uniqueness and distinctness of the phenotypic and genetic constitution (Geleta *et al.*, 2006). The phenotypic diversity estimation may be based on agro-morphological traits to evaluate the magnitude of diversity among genotypes using multivariate approaches such as cluster and principal component analysis. These methods use the morphological characters to provide information about the similar groups and the information generated can be used to identify genotypes that have desirable characters for breeding purposes such as hybridization for pedigree breeding. Chikuta *et al.* (2015) used multivariate analysis approaches to select sorghum genotypes exhibiting high levels of grain and fodder traits from morphological and agronomic data, while Mujaju and Chakauya (2008) used multivariate analysis to categorise agro-morphological characters of sorghum landraces to explain production factors and uses of sorghum at farmers' level.

Genetic diversity studies in sorghum have been evaluated through phenotypic data (Mujaju and Chakauya, 2008; Godbharle *et al.*, 2010; Seetharam and Ganesamurthy, 2013; Chikuta *et al.*, 2015) and molecular marker data (Madu and Uguru, 2006; Ali *et al.*, 2008; Muraya, 2014). However, there is no information on the genetic diversity of sorghum germplasm in Mozambique. The objective of this present study was to identify important morphological traits that distinguish desirable breeding material in the National Sorghum breeding programme.

## 4.2. Materials and Methods

### 4.2.1. Plant material

Fifteen cytoplasmic male sterile (CMS) lines and ten male fertile (restorer- R) lines were used in this study (Table 4-1). These breeding lines were sourced from ICRISAT and from the National Sorghum programme. Maintainer lines (B-lines) were planted next to the A-lines to facilitate grain formation by male sterile lines, thereby enabling collection of data for panicle and grain traits.

Table 4-1 List of sorghum lines used in the study

| Genotype no | Line | Genotype no | Line |
|---|---|---|---|
| 1 | 150B | 14 | MA6B |
| 2 | 8607B | 15 | MACIA |
| 3 | 860IB | 16 | MZ 2R |
| 4 | A6352R | 17 | MZ 30R |
| 5 | CK 60B | 18 | MZ 37R |
| 6 | ICSA 12B | 19 | SDS 260R |
| 7 | ICSA 19B | 20 | SDS 6013R |
| 8 | ICSA 21B | 21 | SPI 38B |
| 9 | IS 14257R | 22 | SPL9B |
| 10 | IS 21458R | 23 | TX 623B |
| 11 | IS 7179R | 24 | TX 628B |
| 12 | LARSVYT 19R | 25 | TX 630B |
| 13 | LARSYT46B | 26 | TX 631B |

### 4.2.2. Location and experimental design

The experiment was conducted at Sussundenga Research Station (SRS) over two seasons. The lines were planted in January 2015 and December 2016. This location covered the mid-altitude mega-environment. Table 4-2 summarizes the location and annual average rainfall per season. The maximum temperature of 29.5°C and minimum of 17.6°C characterize the location (MAE, 2014). The majority soil type in SRS is red clay soil but sandy soils are also found in some areas.

Table 4-2 Characteristics of the location and season used for evaluation of germplasm

| Location | Season | Code | Latitude (°S) | Longitude (°E) | Altitude (m) | Rainfall* (mm) |
|---|---|---|---|---|---|---|
| Sussundenga | 2015/16 | Sus16 | 19°18’ | 33°15’ | 635 | 522 |
| Sussundenga | 2016/17 | Sus17 | 19°18’ | 33°15’ | 635 | 989 |

*Rainfall referred to the amount received during the crop growing season

The trial was laid out in a 13 x 2 alpha lattice design with two replications. Each plot had four rows that were 4 m long and spaced 80 cm apart, with an in-row spacing of 25 cm**.** The crop management was according to recommended practices.

### 4.2.3. Data collection

Morphological characterization was done using International Board for Plant Genetic Resource (IBPGR) and International Crops Research Institute for the Semi-Arid Tropics ICRISAT (1993) descriptor list. The characteristics used for phenotypic characterization are described in Table 4-3. The data were collected and recorded from the two middle rows of each plot. Six plants per accession were randomly selected for observations and measurements.

### 4.2.4. Data analysis

The analysis of variance for the parameters was used to estimate the mean squares effects using the GLM procedures in SAS software 9.3 version (SAS, 2011), according to the model:

$$P_{ijk} = \mu + g_i + r_j + b_k + \varepsilon_{ijk}$$

Where: $P_{ijk}$ is the phenotypic value of the $i^{th}$ accession, µ the grand mean, $g_i$ the genetic effect for the $i^{th}$ accession, $r_j$ the replication effect, $b_k$ the block effect in each replication and $e_{ijk}$ the residual error.

Cluster analysis was performed using unweighted pair-group method with arithmetic average (UPGMA) and dendrogram constructed using the GenStat statistic software version $18^{th}$ (Payne *et al.*, 2016). Principal component analysis (PCA) was performed using the R statistics software (R Team, 2014) where the biplot of multivariate data was constructed.

The diversity among germplasm was determined from morphological frequencies using the method suggested by Grenier *et al.* (2000). The characters observed were used to calculate Shannon-Weaver index of diversity (H') from the frequency distribution for the accessions and grouped into different classes according to Perry and McIntosh (1991). The calculation was done as: $H' = 1\text{-}\sum_{i=1}^{n} \mathrm{pi}\ loge\,pi$

Where: *H'* is Shannon Diversity Index; $p_i$ is the proportion of accessions in the $i^{th}$ class of n-class character; n is the number of phenotypic classes of traits.

The H' estimates were done using GenStat statistic software version $18^{th}$ (Payne *et al.*, 2016) and Microsoft Excel.

Table 4-3 Descriptors used for morphological characterization of sorghum germplasm.

| Characteristic | Descriptor and code |
|---|---|
| **Stay green** | Very slight senescent (1), leaves senescent 25% (2), leaves senescent 50% (3), leaves senescent 75% (4) and complete senescent (5) at harvest stage |
| **Seed size** | Small< 5mm (1), medium< 5-10mm (2), large> 10mm (3) |
| **Leaf rolling** | Non- rolled leaf (1), 25% leaves rolled (2), 50% leaves rolled (3), 75% leaves rolled (4) and all leaves rolled (5) |
| **Panicle exsertion** | Slightly exserted <2cm (1), exserted 2-10cm (2), well exserted >10cm (3), peduncle re-curved (4) |
| **Leaf colour** | Dark green (1) and light green (2) |
| **Leaf orientation** | Erect (1) and dropping (2) |
| **Inflorescence compactness** | Very loose erect (1), very loose dropping (2), loose erect (3), loose dropping (4), semi loose erect (5), semi loose dropping (6), semi compact elliptic (7), compact elliptic (8), compact oval (9), half broom corn (10) and broom corn (11) |
| **Head shape** | Elliptical (1), oblong (2), round (3), semi-loose (4) and loose (5) |
| **Midrib colour** | White (1), dull green (2), yellow (3), brown (4) and purple (5) |
| **Grain colour** | Red (1), yellow (2), brown (3), white (4), light orange (5), white with orange (6) and white and red (7), cream (8) |
| **Awns** | Absent (1) and present (2) |
| **Glume colour** | White (1), red (2), purple (3), black (4), grey (5), brown (6), dark brown (7) |
| **Glume cover** | 25% grain covered (1), 50% grain covered (2), 75% grain covered (3), 100% grain covered (4) and glume longer than grain (5) |

Source: adapted from IBPGR/ICRISAT, 1993

## 4.3. Results

### 4.3.1. Analysis of variance

Analysis of variance showed highly significant differences (P≤0.01) among genotypes for most of the characters measured except for the grain colour, glume colour and presence of awns (Table 4-4).

Table 4-4 Mean squares and variability parameters for various characters of sorghum genotypes

| Characters | MS | GV | PV | $h^2_b$ | H' |
|---|---|---|---|---|---|
| Days to 50% flowering | $764.79^{***}$ | 182.66 | 216.83 | 84.2 | 3.25 |
| 1000 seed weight (g) | $27.99^{***}$ | 5.37 | 11.88 | 45.2 | 3.25 |
| Stay green | $2.25^{***}$ | 0.56 | 0.58 | 96.2 | 3.21 |
| Grain colour | 7.43 | 1.73 | 2.24 | 77.2 | 3.21 |
| Seed size | $1.55^{***}$ | 0.35 | 0.50 | 69.1 | 3.24 |
| Panicle exertion | $3.66^{***}$ | 0.87 | 1.06 | 81.3 | 3.20 |
| Midrib colour | $3.62^{***}$ | 0.90 | 0.92 | 97.4 | 3.19 |
| Leaf rolling | $2.01^{***}$ | 0.46 | 0.64 | 71.1 | 3.21 |
| Leaf orientation | $1.79^{***}$ | 0.44 | 0.47 | 92.8 | 3.21 |
| Leaf colour | $1.08^{***}$ | 0.23 | 0.37 | 63.2 | 3.23 |
| Inflorescence | $13.36^{***}$ | 3.16 | 3.90 | 81.0 | 3.24 |
| Awn | 1.78 | 0.19 | 1.23 | 15.1 | 3.25 |
| Head shape | $3.83^{***}$ | 0.90 | 1.12 | 80.1 | 3.23 |
| Glume colour | 16.06 | 3.76 | 4.79 | 78.5 | 3.21 |
| Glume cover | $1.76^{***}$ | 0.43 | 0.47 | 92.8 | 3.21 |

$^{***}$, $^{**}$, $^{*}$ significant at 0.1, 1 and 5% respectively. MS= mean square, GV= genotypic variance, PV= phenotypic variance, $h^2_b$= Heritability broad sense and H'= Shannon-Weiner Diversity index

### 4.3.2. Morphological characterization

Days to 50% flowering ranged from 81 days to 116 days. Line 150B had the least number of days (81) while the lines A6352R and MA6B had the highest number of days (116). For the thousand-seed weight, line ICSA21B had a weight of 13.7 g representing the lowest whereas IS 7179B and SP 9B recorded 21.5 g and 21.1 g, respectively, representing the highest values (Table 4-5).

Regarding the stay green character, 65.4% of the lines had 25% of their leaves senesced, 30.8% of the lines had very slight senescence, whereas 3.8% had 50% of their leaves senesced. The most senesced genotype was IS 7179R where by harvesting time, 50% of the leaves were senesced. The majority of lines (65%) had white grain colour, 11% had creamy grains, while the remaining lines had red (8%), brown (8%) and light orange (8%) grains. In respect to seed size, most lines were medium size although lines SDS 6013R, SPL 38B, MZ 2R and IS 7179R were on average, large seeded. Panicle exsertion was mostly between 2 and 10 cm (42.3%), however, some had more than 10 cm (34.6%), and fewer exserted below 2 cm (23.1%).

Furthermore, midrib colour presented dull green colour in the majority of lines (53.8%), while white midrib colour was present in 42.3% of the lines and 3.8% were brown. Similar percentages were observed for leaf rolling characteristic, where 53.8% had their leaves rolled by 25%, 42.3% non-rolled leaves, and 3.8% had leaves rolled by 50%. Likewise, regarding leaf orientation and colour, the majority of genotypes had dark green leaves and dropping (61.5%) whilst some had erect and light green leaves (38.5%).

For inflorescence compactness (Figure 4-1), the compact elliptic form was the most abundant (46.2%), followed by the semi compact elliptic (26.9%), compact oval (15.4%); and semi loose dropping, semi loose erect and loose erect each with 3.8%. On the other hand, 42.3% of the lines had round shaped heads, followed by semi loose shape (38.5%) and oblong shape (19.2%). About 96.2% lines in this study had no awns whereas 3.8% displayed awns as observed in line IS 7179R. Furthermore, different glume colours and glume covering percentages were observed. Most of the lines displayed grey glume colour (73.1%) while other lines presented red glumes (11.5%), black glumes (7.7%) and brown glumes (7.7%). The grain glume covering was 25% for the majority (53.8%) of lines, and other lines (46.2%) had 50% covering.

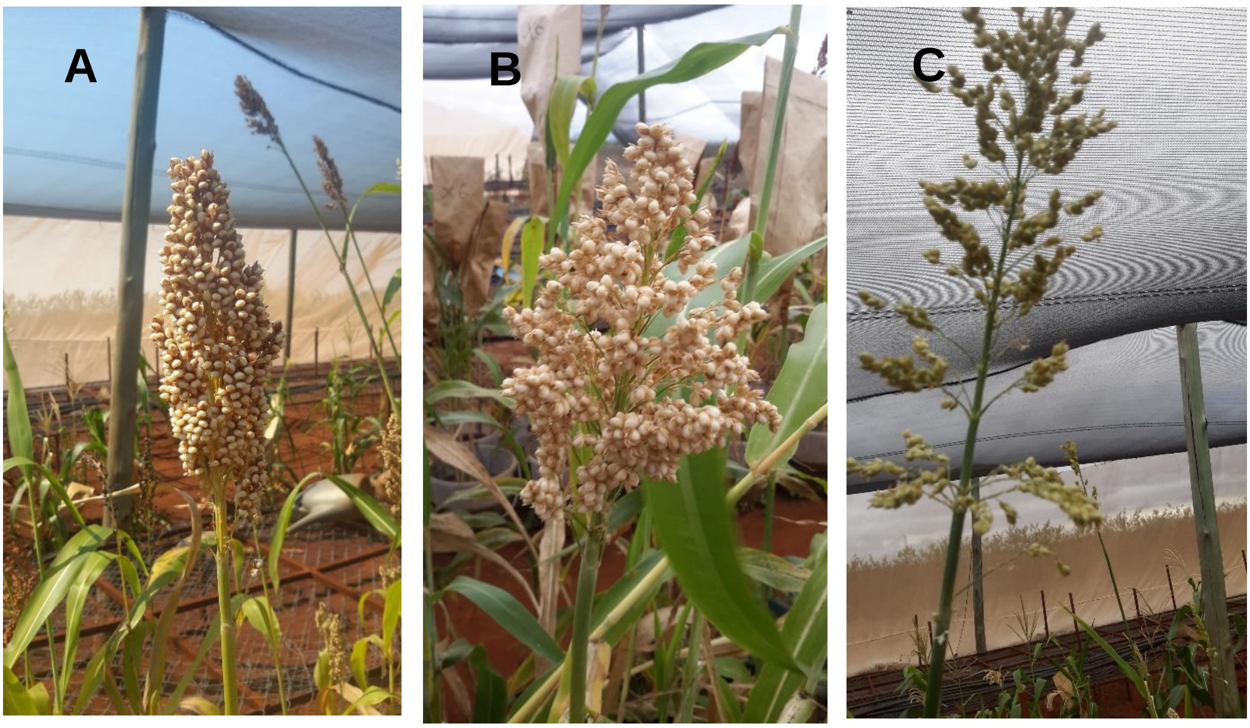

Figure 4-1 Inflorescence compactness of different genotypes. Compact elliptic (a), semi compact elliptic (b) and semi loose erect (c)

Table 4-5 Means for the morphological characters used in the study for each genotype

| Line | DF | SW | SS | PE | MC | LR | LO | LC | IF |
|---|---|---|---|---|---|---|---|---|---|
| 150 B | 81 | 18.1 | 2 | 3 | 2 | 2 | 2 | 2 | 8 |
| 8607 B | 101 | 17.1 | 3 | 2 | 1 | 1 | 2 | 1 | 7 |
| 860I B | 88 | 16.1 | 2 | 3 | 2 | 2 | 1 | 2 | 8 |
| A6352 R | 115 | 20.9 | 2 | 3 | 2 | 2 | 1 | 2 | 8 |
| CK 60 B | 107 | 17.6 | 2 | 2 | 2 | 2 | 1 | 1 | 5 |
| ICSA 12 B | 106 | 19.1 | 2 | 3 | 2 | 2 | 2 | 1 | 7 |
| ICSA 19 B | 114 | 16.7 | 2 | 3 | 2 | 1 | 2 | 2 | 7 |
| ICSA 21 B | 104 | 13.7 | 2 | 3 | 2 | 1 | 2 | 2 | 8 |
| IS 14257 | 87 | 17.2 | 3 | 1 | 2 | 2 | 2 | 2 | 8 |
| IS 21458 | 107 | 20.1 | 2 | 2 | 1 | 2 | 2 | 2 | 6 |
| IS 7179 | 94 | 21.5 | 3 | 3 | 1 | 1 | 1 | 2 | 8 |
| LARSVYT 19 R | 97 | 16.4 | 2 | 2 | 1 | 2 | 2 | 1 | 8 |
| LARSYT46 B | 87 | 20.3 | 2 | 2 | 1 | 2 | 2 | 2 | 8 |
| MA6 B | 116 | 18.2 | 2 | 2 | 1 | 1 | 1 | 1 | 7 |
| MACIA | 94 | 16.4 | 2 | 3 | 1 | 1 | 1 | 2 | 8 |
| MZ 2 | 106 | 18.4 | 3 | 2 | 2 | 1 | 2 | 1 | 9 |
| MZ 30 | 112 | 16.5 | 2 | 1 | 1 | 2 | 1 | 1 | 8 |
| MZ 37 | 101 | 16.8 | 1 | 2 | 2 | 1 | 2 | 2 | 7 |
| SDS 260 R | 94 | 18.7 | 2 | 2 | 4 | 2 | 1 | 1 | 3 |
| SDS 6013 R | 106 | 16.8 | 3 | 1 | 1 | 2 | 2 | 2 | 7 |
| SPI 38 B | 98 | 18.2 | 3 | 3 | 2 | 1 | 1 | 2 | 7 |
| SPL9 B | 104 | 21.1 | 2 | 2 | 2 | 1 | 2 | 1 | 8 |
| TX 623 B | 103 | 20.3 | 2 | 1 | 1 | 1 | 2 | 2 | 8 |
| TX 628 B | 105 | 20.2 | 2 | 2 | 2 | 3 | 2 | 1 | 9 |
| TX 630 B | 88 | 19.2 | 2 | 1 | 2 | 2 | 1 | 2 | 9 |
| TX 631 B | 87 | 17.6 | 2 | 1 | 1 | 2 | 2 | 2 | 9 |
| LSD | 5.8 | 2.5 | 0.4 | 0.4 | 0.2 | 0.4 | 0.2 | 0.4 | 0.8 |
| CV (%) | 5.8 | 14.0 | 17.9 | 22.0 | 9.4 | 27.9 | 11.8 | 24.1 | 11.6 |
| SED | 2.9 | 1.3 | 0.2 | 0.2 | 0.1 | 0.2 | 0.1 | 0.2 | 0.4 |

DF= days to flowering, SW= 1000 seed weight, SS= seed size, PE= panicle exsertion, MC= midrib colour, LR= leaf rolling, LO= leaf orientation, LC= leaf colour, IF= inflorescence compactness.

### 4.3.3. Variability and heritability of the characters

The genetic variance, phenotypic variance and heritability estimates are presented in Table 4-4. The phenotypic variance was higher than the genetic variance for all characters. Higher estimates were observed for days to 50% flowering, thousand seed weight, glume colour and inflorescence compactness. The other characters such as stay green, seed size, leaf rolling, leaf colour and glume cover presented lower estimates.

Very high heritability estimates were obtained for stay green and midrib colour with 96.2% and 97.4%, respectively. Glume cover and leaf orientation also had very high heritability estimates of 92.8% each. The characters with heritability estimates below 50% were thousand seed weight and presence of awns with 45.2% and 15.1%, respectively.

### 4.3.4. Cluster analysis

The results of cluster analysis are presented in Figure 4-2 (genotypes names in Table 4-1). Lines 8 (ICSA 21B), 23 (TX 623B), 22 (SPL 9B), 20 (SDS 6013R), 24 (TX 628B), 10 (IS 21458R), 16 (MZ 2R), 6 (ICSA 12B) and 5 (CK 60B) were grouped together (Cluster I). The second group (cluster II) constituted lines 17 (MZ 30R), 7 (ICSA 19B), 14 (MA 6B) and 4 (A6352R). The third group (Cluster III) included lines 19 (SDS 260R), 15 (Macia), 11 (IS 7179R), 21 (SPL 38B), 12 (LARSVYT 19R), 18 (MZ 37R) and 2 (8607R). The fourth group (Cluster IV) comprised of lines 25 (TX 630B), 13 (LARSVYT 46B), 26 (TX 631B), 9 (IS 14257R), 3 (8601B) and 1 (150B). Cluster I contained the largest number of B and R lines from different groups, followed by Cluster III which was made up of only R lines. Cluster IV grouped the majority of B lines and only one IS 14257R line.  The least number of lines was found in Cluster II.

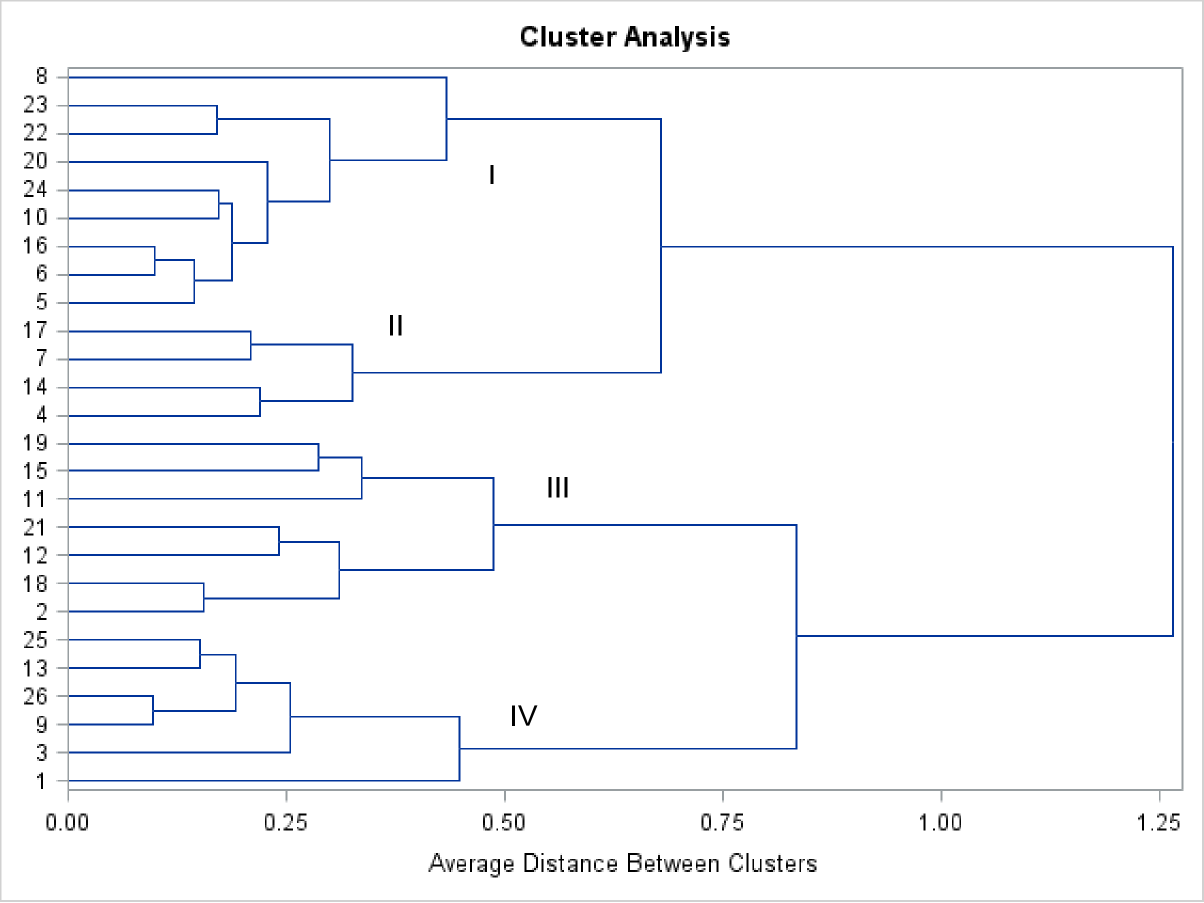

Figure 4-2 Dendrogram of 26 sorghum lines showing genetic similarity based on morphological characters (genotypes names are presented in Table 4-1)

Table 4-6 presents cluster means for the various characters that were measured or observed. Cluster I had lines with an average of 105 days for 50% flowering. Average seed weight in this cluster was 18.6 g per thousand grains, with medium seed size and plants with 25% senesced leaves at harvest maturity. Panicle exsertion was 2-10 cm with dark green and dropped leaves. The leaves were 25% rolled and midrib colour was dull green. The head was round, semi-compact elliptic inflorescence, awn less with white grains. The grains were 25% covered with purple glumes.

Cluster II contained lines with a longest duration to 50% flowering. The lines had an average of 114 days for flowering and a mean of 18.1 g for thousand seed weight. The stay green character rating was on average 25% leaves senesced at harvesting maturity. Seed size was medium and panicle was exserted between 2 cm and 10 cm. Additional characters included non-rolling and erect leaves with a dull green midrib. The leaves were dark green and inflorescence compactness was the semi compact elliptic category. Head shape was on average round with white grains, awn less with purple glumes covering 25% of the grain.

Days from planting to 50% flowering averaged 97 in Cluster III and plants produced medium sized seed weighing on average 17.9 g per thousand grains. The plants stayed green until harvest maturity (25% senesced leaves) with dull green midrib and no rolling leaves, erect oriented and light green. The panicles were 2-10 cm exserted with semi compact elliptic inflorescence that was round in shape. The grains were white with no awns but covered 25% with black glumes.

Cluster IV consisted of early flowering group with an average of 86 days to 50% flowering. The size of seeds was medium with an average weight of 18.1 g per thousand grains and plants having 25% senesced leaves at harvest maturity. The leaves were light green, 25% rolled, dropped with a dull green midrib. The panicles were exserted 2-10 cm with round and compact elliptic inflorescence, and awn less. The grains were light orange and covered 50% with grey glumes

Table 4-6 Cluster means for morphological characters measured in the 26 sorghum genotypes

| | Cluster | | | |
|---|---|---|---|---|
| | I | II | III | IV |
| Character | n = 9 | n= 4 | n=7 | n=6 |
| Days to 50% flowering | 105 | 114 | 97 | 86 |
| 1000 seed weight (g) | 18.6 | 18.1 | 17.9 | 18.1 |
| Stay green | 2 | 2 | 2 | 2 |
| Seed size | 2 | 2 | 2 | 2 |
| Panicle exsertion | 2 | 2 | 2 | 2 |
| Midrib colour | 2 | 2 | 2 | 2 |
| Leaf rolling | 2 | 1 | 1 | 2 |
| Leaf orientation | 2 | 1 | 1 | 2 |
| Leaf colour | 1 | 1 | 2 | 2 |
| Inflorescence compactness | 7 | 7 | 7 | 8 |
| Head shape | 3 | 3 | 3 | 3 |
| Glume cover | 1 | 1 | 1 | 2 |
| Glume colour | 5 | 3 | 4 | 5 |
| Grain colour | 4 | 4 | 4 | 5 |
| Awn | 1 | 1 | 1 | 1 |

### 4.3.5. Principal component analysis

The PCA analysis showed that 58.5% of the total variation was accounted for by five components (Table 4-7) and the first component had the major contribution of 15% to the variation. Variation in the first component was mainly from the positive eigenvector loadings of head shape, days to 50% flowering and negative loadings of leaf colour, leaf orientation and inflorescence compactness. The second component contributed 13% to the variation mainly from the positive loadings of head shape, panicle exsertion, midrib colour, glume colour and negative loadings of leaf rolling and inflorescence compactness.

The variation in the third component (12.2%) was due to positive loadings of midrib colour, grain colour and days to 50% flowering while the negative eigenvector loadings were due to stay green and presence of awns. Positive loadings of days to 50% flowering and the thousand-seed weight contributed 9.5% to the total variation of the fourth component with high negative loadings of seed size. The fifth component variation (7.9%) was due to positive loadings of glume colour, glume cover and negative loadings of inflorescence compactness and leaf colour.

Table 4-7 Principal components and eigenvector loadings for the morphological characters

| Principal Components | Component 1 | Component 2 | Component 3 | Component 4 | Component 5 |
|---|---|---|---|---|---|
| Eigen vectors (loadings) | | | | | |
| Head shape | 0.35 | 0.33 | -0.25 | 0.15 | 0.11 |
| Stay green | -0.17 | -0.48 | -0.37 | -0.33 | 0.11 |
| Leaf rolling | -0.22 | -0.63 | 0.20 | -0.26 | 0.14 |
| Panicle exsertion | 0.13 | 0.38 | 0.11 | -0.40 | -0.14 |
| Leaf colour | -0.41 | 0.23 | 0.18 | -0.12 | 0.37 |
| Leaf orientation | -0.36 | 0.11 | 0.26 | 0.15 | -0.20 |
| Inflorescence compactness | -0.35 | -0.34 | 0.18 | -0.16 | -0.30 |
| Midrib colour | 0.28 | 0.30 | 0.31 | -0.27 | 0.17 |
| Grain colour | -0.28 | 0.24 | 0.38 | -0.25 | -0.19 |
| Awn | -0.28 | 0.30 | -0.43 | -0.15 | -0.14 |
| Glume colour | -0.28 | 0.36 | 0.21 | 0.19 | 0.41 |
| Glume cover | -0.24 | 0.20 | -0.18 | 0.16 | 0.46 |
| Seed size | -0.20 | -0.17 | 0.27 | -0.77 | 0.20 |
| Days to 50% flowering | 0.31 | -0.26 | 0.30 | 0.62 | 0.17 |
| 1000 seed weight (g) | -0.18 | 0.19 | -0.18 | 0.53 | 0.17 |
| Proportion of variance (%) | 0.150 | 0.139 | 0.122 | 0.095 | 0.079 |
| Cumulative proportion (%) | 0.150 | 0.289 | 0.410 | 0.506 | 0.585 |

Characters such as head shape, midrib colour, panicle exsertion, glume colour, presence of awns, grain colour, glume cover, and thousand seed weight were positively correlated. Negative correlations were found between the characters days to 50% flowering, leaf colour, seed size, stay green, grain colour, thousand seed weight, awn presence, glume colour and inflorescence compactness (Figure 4-3). A strong positive correlation was found between the characters glume cover, glume colour, presence of awns and thousand seed weight. On the other hand, there was a strong correlation between the characters head shape, midrib colour and panicle exsertion. A strong negative correlation was found between inflorescence compactness, head shape, midrib colour and panicle exsertion. The negative correlations were found between the characters head shape and inflorescence compactness as well as between days to 50% flowering and seed size. These results showed that there is a correlation between some morphological characters measured in the study.

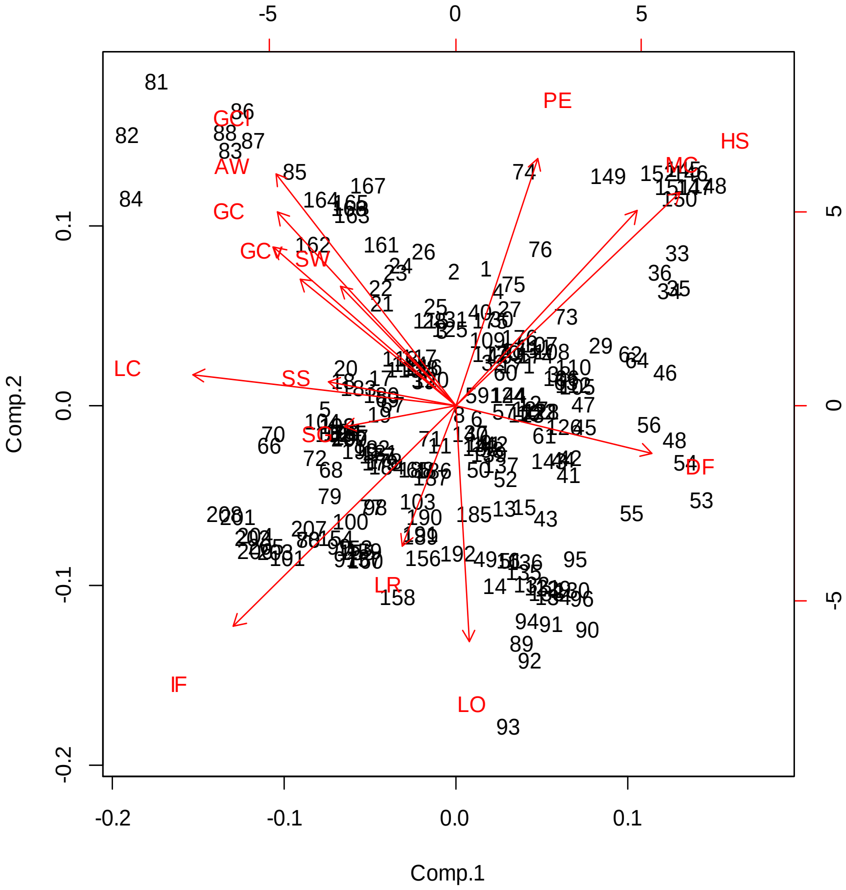

Figure 4-3 Biplot of the first and second principal components (Comp. 1 and Comp. 2) of morphological characters in the study.

DF= days to flowering, SW= 1000 seed weight, SG= stay green, GC= grain colour, SS= seed size, PE= panicle exsertion, MC= midrib colour, LR= leaf rolling, LO= leaf orientation, LC= leaf colour, IF= inflorescence compactness, Aw= presence of awns, HS=head shape, GCl= glume colour, GCv= glume cover

### 4.3.6. Diversity index

The Shannon Diversity Index (H’) was estimated to compare the morphological characters used in the study (Table 4-4). The mean of Shannon Diversity index of the characters was 3.22. The H’ of stay green, panicle exsertion, midrib colour, leaf rolling, leaf orientation, glume colour, glume cover and grain colour were on par with the mean. Days to 50% flowering, thousand seed weight, seed size, leaf colour, inflorescence compactness, head shape and presence of awns were found to have H’ greater than mean. The last seven characters showed high diversity when compared to the first eight characters.

## 4.4. Discussion

The results showed highly significant differences among genotypes for most of the characters measured except for grain colour, glume colour and presence of awns. Days to 50% flowering ranged from 81 for line 150B to 116 days recorded for A6352R and MA 6B. The flowering period among genotypes was almost a month and this might be attributed to a mixture of genotypes with different genetic backgrounds and different responses to environmental conditions. A study by Craufurd and Peacock (1993) characterised genotypes on responses to temperature and photoperiod, and they found that variation in flowering period was affected by photoperiod and environment adaptation. Water stress also has an influence on days to flowering in as much as it increased the period between panicle initiation and flowering by retarding the rate of panicle development (Craufurd *et al.*, 1993). Seed size in this study was mostly medium, although some lines had large seeds. For thousand seed weight, ICSA21B had the lowest weight (13 g), whereas IS 7179B and SP 9B had the highest weights of 21.5 g and 21.1 g, respectively. The fact that most of the genotypes were medium sized imply lack of variation in seed size. There is, therefore, no evidence in this study to suggest that seed weight was influenced by seed size. Seed weight has been reported to be positively correlated to seed size and yield (Evans and Bhatt, 1977; Ezeaku and Mohammed, 2006). Seed size may be considered as an important factor when selecting seed due to plasticity associated with the seed to complete different growth stages (Sadras, 2007).

As far as leaf orientation and leaf rolling are concerned, the majority of lines had dropped orientation and rolled leaves. These characteristics might be influenced by a short period of drought during the growth season. On the other hand, some lines did not change the leaf orientation and rolling. Water deficit, high air temperature and sunlight affect leaf rolling in plants (Kadioglu and Terzi, 2007). Regarding the stay green character, 65.4% of the lines had low levels of senescence (25% of their leaves senesced) under optimal growing conditions. Additionally, Burke *et al.* (2010) found that the best way to identify stay green line (BTx642) is to evaluate in well-watered environments. However, stay green trait could be affected by pre-flowering or post-flowering drought stress (Burke *et al.*, 2013). The stay green trait is an important component when breeding for drought tolerant crop and photosynthesis components (Thomas and Smart, 1993). It also improves adaptation to drought and respond to yield under different agro-ecological conditions of sorghum (Borrell *et al.*, 2000). The majority of grain exhibited white colour and it was observed as one of the preferred characteristics by farmers in a PRA study (Mulima, unpublished). White grain colour was indicated by farmers to be associated with preferences of porridge colour and taste (Vom Brocke *et al.*, 2010). Seed size and seed colour are the important traits to farmers during variety selection (Odendo *et al.*, 2001). Therefore, selection of a variety has to meet specific farmer requirements in order to cater for local food industrial requirements as preferred by the final consumer (Dicko *et al.*, 2006).

Inflorescence compactness was dominated by the compact elliptic type with round head shape. The inflorescence structure is an essential element for breeders due to the contribution of it to the yield, stability and quality of the grain (Brown *et al.*, 2006). Additionally, it was observed that most lines had no awns and seed were covered 25% by grey glumes. The presence of strong awns in the seed may be used as a protection against bird's attack. According to Upadhyaya *et al.* (2010), glume cover and glume colour may be utilized to screen for grain mould resistance. Panicle compactness is used as a racial indicator and it is influenced not only by a number of branches and elongation but also by abortions in a branch (Brown *et al.*, 2006).

### 4.4.1. Variability and heritability of the characters

The phenotypic variance was higher than the genotypic variance for all characters. Higher phenotypic estimates were observed for days to 50% flowering, thousand seed weight, glume colour and inflorescence compactness. The other characters such as stay green, seed size, leaf rolling, leaf colour and glume cover presented lower estimates. The phenotypic expression could be influenced by rainfall and temperature differences between the seasons as recorded with 522 mm during 2016 and 989 mm in 2017. Similar findings from Chikuta *et al.* (2015) and Ayana *et al.* (2000) indicate that gradient of rainfall, temperature and growing sites are important for genotype variation. The phenotypic expression can infer genetic variability and consequences of phenotypic variation due to changes in the environment (Abubakar and Bubuche, 2013). Similarly, Seetharam and Ganesamurthy (2013) found that a narrow difference between the phenotypic and genetic variation are an indication of little environmental influence. Variability in characters such as stay green, leaf rolling, and leaf orientation implies that the traits can be used to exploit drought tolerance. An extensive collection of genetic variability can be used in the improvement of drought tolerance in grain sorghum (Abdalla, 2014; Idris *et al.*, 2015).

High heritability estimates were obtained for stay green, midrib colour, glume cover and leaf orientation. The characters such as thousand seed weight and presence of awns had heritability estimates below 50%. The low heritability estimates have implication in breeding because phenotypic selection cannot be based on those traits with low heritability values. Similar results of low heritability were observed in sorghum for panicle length and breadth (Arunkumar, 2013). According to Bello *et al.* (2007), traits that are related to grain yield and yield components might have low heritability due to direct or indirect effects of the several components while Obilana and Fakorede (1981) reported that heritability estimates tend to be low for the traits that are influenced by the environment (quantitative traits).

It is said that the characters with higher heritability estimates may reflect the utility of the characters in a breeding strategy. This result is in agreement with Warkad *et al.* (2008) who observed low heritability estimates for grain and fodder yield, thousand seed weight and presence of awns in sorghum. Similar results were obtained by Seetharam and Ganesamurthy (2013) for 50% flowering and Liang *et al.* (1972) for 50% flowering, plant height and seed weight. The inflorescence has higher heritability in the primary branch than secondary and tertiary branches (Brown *et al.*, 2006). High heritability suggests that the main genes for those characters may have an additive gene effect and consequently indicate the importance of those characters for selection.

### 4.4.2. Cluster analysis

Cluster I contained the largest number of lines which also were from different sets (B and R lines) followed by Cluster III which contained only R lines. The Cluster IV grouped majority of B lines and only one R line. Cluster II consisted of the fewest number of lines. Cluster analysis was able to group the lines according to flowering period, with Cluster II having members taking longest time to flowering; Cluster I and III were intermediate flowering groups and Cluster IV was the earliest to flower. This grouping revealed that information about flowering period among the lines may be useful in order to identify parents for different maturity groups. The success of any crop breeding programme is based on the knowledge and availability of genetic variability for efficient selection (Ali *et al.*, 2008). The characters, thousand seed weight, stay green, seed size, panicle exsertion, midrib colour, head shape and presence of awns showed similar characteristics in all clusters. Characters such as leaf rolling, leaf orientation, leaf colour, inflorescence compactness, glume covering, glume colour and grain colour were the most distinguishing traits between the clusters. Leaf rolling, and leaf orientation were clustered in the same pattern in cluster I and IV as well as II and III. The clusters that were paired together were I and II, III and IV for leaf colour. Inflorescence compactness, glume cover and grain colour clustered together I, II and III. Grouping the genotypes according to the characteristics might reveal that the lines have similarity in one or more traits. Seetharam and Ganesamurthy (2013) reported that promising genotypes can be identified from cluster means recorded for each trait. A better understanding of genetics of morphological characteristics is required by the breeder to increase the efficiency of selection of more diverse and adapted parents for crop improvement (Billot *et al.*, 2013). These clusters suggested that there is a large amount of allelic diversity in the germplasm in this study, assuming that it could be divided into four groups.

### 4.4.3. Principal component analysis

Principal component analysis showed that 58.5% of the total variation was explained by five principal components. The first principal component had the major contribution (15%) to the total variation. In the first component, maximum weight should be given to the traits with high magnitude and positive Eigenvector loadings, namely head shape and days to 50% flowering and traits with high magnitude negative loadings *viz*. leaf colour, leaf orientation and inflorescence compactness. In a separate study, days to 50% flowering was found as one of the most important characters contributing to the first principal component (Ayana and Bekele, 1999), hence its importance has been confirmed in this study. The second principal component explained 13.9% of the variation, and in this component maximum importance should be attached to traits with high positive loadings specifically head shape, panicle exsertion, midrib colour and glume colour and those with high magnitude negative loadings *viz.* leaf rolling and inflorescence compactness. In the third component, maximum importance should be attached to traits with high positive loadings, namely, midrib colour, grain colour and days to 50% flowering; and those traits with high negative loadings, that is, stay green and presence of awns. The traits, days to 50% flowering and the thousand seed weight (with positive loadings), and stay green, panicle exsertion and seed size (with negative loadings) should be given maximum importance in the fourth principal component. Ayana and Bekele (1999) also observed that thousand seed weight was one of the important traits in the fourth principal component. In the fifth component, maximum weight should be attached to positive loadings, namely, leaf colour, glume colour and glume cover and those with negative loadings, specifically, inflorescence compactness and leaf colour. The dull green midrib colour and dark green leaf colour were suggested to be associated with pithy stems, meaning juicy stems

(Ngugi and Maswili, 2010), while days to 50% flowering was found to be strongly correlated with 95% maturity (El Naim *et al.*, 2012).

Positive and strong correlations were found between the characters glume cover and glume colour, presence of awns and thousand seed weight. Also, there was a strong correlation between the head shape, midrib colour and panicle exsertion. Negative and strong correlations were found between inflorescence compactness, head shape, panicle exsertion and midrib colour. The opposite correlations were found between the characters head shape and inflorescence compactness as well as between the days to 50% flowering and seed size. These results aligned with PCA result, whereby the positively correlated characters are the same with positive contribution under PCA. Additionally, the negatively correlated characters were also similar to PCA results. This suggested that those characters should be taken into consideration when doing the selection for crop improvement. Grouping morphologically similar germplasm is useful for selecting parents for crossing (Ayana and Bekele, 1999; Iannucci *et al.*, 2011) and evaluating the $F_1$. According to Rahim *et al.* (2010), $F_1$ hybrids from genotypes with maximum distance result in high yield, achieving maximum heterosis.

### 4.4.4. Diversity index

The Shannon Diversity index (H') values for stay green, panicle exsertion, midrib colour, leaf rolling, leaf orientation, glume colour, glume cover and grain colour were on par with the mean. This indicated that the traits were less diverse. Days to 50% flowering, thousand seed weight, seed size, leaf colour, inflorescence compactness, head shape and presence of awns were found to have H' greater than the mean. A low H' shows lack of genetic diversity and an extremely unbalanced frequency classes for an individual trait (Upadhyaya *et al.*, 2010). Highly diverse genotypes are important in a breeding programme as they may be useful in predicting the potential of hybrid progenies when combined with other genotypes (Seetharam and Ganesamurthy, 2013). Additionally, it would be interesting and fruitful to see the extent of segregation for different traits generated by those crosses (Upadhyaya *et al.*, 2010).

## 4.5. Conclusion

The results of the Mozambican sorghum germplasm diversity study have provided interesting information that is useful in improvement of the genotypes. The traits that are not strongly related could be exploited in recombination breeding in future. The multivariate analyses clearly showed the grouping of the genotypes according to the characters outlined in the study. Diversity index additionally confirmed the range in the traits which can be explored in hybridization. Therefore, these results have implications in selection of parents for use in sorghum improvement programme. For example, genotypes that are early in maturity, 150B, IS 14257R, LARSVYT 46B, TX 631B, TX 630B and 8601B could be used for improving earliness, while for late maturity genotypes MA 6B, A 6352R, ICSA 19B and MZ 30R could be used when late cultivars are desired. Moreover, grain yield can be increased using genotypes that produce seed with good weight such as IS 7179R, SPL 9B and A 6353R and those associated with large seed size as observed in lines SPL 38B, SDS 6013R and MZ 2R. On the other hand, lines ICSA 21B, 8610B, MZ 37R, 150B and MZ 2R can be exploited for drought tolerance variety deployment due to the intense stay green character. The line IS 7179R can be used for hybridization to reduce the bird attack due to the presence of awns. Additionally, for mould resistance, lines 8601B and TX 630B can be used. Morphological characteristics identified will assist breeders in understanding the importance of the germplasm diversity, and help identify important characters that are highly preferred by farmers such as earliness, grain yield, plant height and grain colour.

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# 5. Combining ability and heterosis for sorghum grain yield and secondary traits across lowland and midland Mozambique

## Abstract

Low sorghum grain yield in Mozambique makes production of the crop less attractive and unsustainable, ultimately leaving many households food insecure. Development of improved cultivars with increased grain yield coupled with farmers' preferred traits is thus desired. This study aimed at evaluating the combining ability and heterosis of sorghum crosses relative to current commercial cultivars. Nine cytoplasmic male sterile genotypes (designated as lines) and four cytoplasmic male fertile genotypes (designated as testers) were crossed in a line x tester mating scheme. The resultant 36 hybrids were evaluated and compared to two checks in respect of grain yield and secondary traits across six test environments. Testers showed a significant GCA effect for grain yield, days to 50% flowering and plant height. The GCA values for grain yield were positive for IS 14257R and MZ 37R. The days to 50% flowering were highly significant ($P \leq 0.01$) with negative GCA effects in testers IS 14257R and MZ 37R while plant height was significant and negative in tester SDS 6013R. Three lines, LARSVYT46A, SPL38A and TX631A had significant and positive GCA effects for grain yield, and negative but significant GCA effects for other traits except for panicle length. Testers IS14257R and MZ 37R had positive GCA values for grain yield while some hybrids based on the two parents also had positive SCA effects. Lines 8601A, ICSA12A, TX631A and LARSVYT46A had highly significant negative GCA effect for days to 50% flowering. For plant height, line TX631A, ICSA12A, ICSA21A and TX628A had negative and significant GCA effects while panicle length showed positive significant GCA effect for the lines LARSVYT46A, SPL38A and TX631A. For disease resistance: hybrids ICSA12A x MZ2R, ICSA12A x SDS6013R and TX631A x SDS6013R were resistant to rust while moderate resistance was found in LARSVYT46A x IS14257R, LARSVYT46A x SDS6013R and 8601A x MZ37R. In addition, most of the hybrids were classified as resistant to moderately resistant to *Cercospora spp,* whereas all hybrids were classified as resistant to anthracnose. The parents involved in the crosses can be used as sources of resistance in future studies. The heterosis over the trial mean and the best check ranged from 1.2 to 22.6% and 0.1 to 37.2% respectively. The hybrid TX 631A x MZ 37R had better performance over the best check, check mean and over the best parents for grain yield. Therefore, lines and testers with good general combining ability for grain yield associated with low level of disease may be exploited in new combinations to develop new sorghum hybrids.

## 5.1. Introduction

Agriculture in southern Africa has been affected by erratic rainfall accompanied with harsh climatic conditions for most growing seasons. During the 2015-2016 rainy season, Mozambique was affected by two consecutive El Nino phenomena that induced droughts. This situation led to unprecedented levels of food insecurity (Tadross, 2009; Vam, 2017). Although drought has been affecting crop production, sorghum performed better during these conditions as an indication of its ability to withstand drought in semi-arid regions of Africa (Machado and Paulsen, 2001), particularly central and north Mozambique. However, it was reported that the use of low grain yielding varieties has not changed substantially over the past five years in Mozambique with average yields ranging from 0.4 t.ha$^{-1}$ to 0.6 t.ha$^{-1}$ (Tsusaka *et al.*, 2015). Low productivity in sorghum has been linked to a lack of modern farming technologies including low use of improved varieties. Therefore, development of cultivars with high grain yield potential more than the current commercial and local cultivars with farmers' preferable characteristics is desired. Although local cultivars are adapted to multi-factor effects of biotic and abiotic constraints, grain yield is still considered a major trait that requires improvement.

Many studies have proven that grain yield can be improved through the use of potential sorghum hybrids (House, 1995). The potential hybrids are those with inherited traits such as grain yield, plant height, maturity, tillering and disease resistance. It is, therefore, essential for sorghum breeders to study the combining ability among parents for grain yield and some of these secondary traits for improvement of grain yield potential which is the most important trait in sorghum breeding (Reddy *et al.*, 2012). The use of adapted parents may enhance farmers' food security and income through increased yield (Rattunde *et al.*, 2013). Sorghum is known for its potential heterosis for grain yield that can be exploited for hybrid development. According to Ashok Kumar *et al.* (2011), newly developed hybrid varieties showed 30-40% heterosis for grain yield over the best known commercial hybrid checks. Furthermore, Mahdy *et al.* (2011) recorded heterosis for sorghum grain yield over the best parent of between 9 to 97% and lower estimates were obtained in crosses with adapted parent lines.

Therefore, for the plant breeder it is essential to study the combining ability of the parents during the development of new improved varieties. Understanding of the inheritance of characters comes through knowledge of the combining ability of the lines. Bertan *et al.* (2007) indicated that this helps in selection of the best lines for use in a breeding programme. Several studies on combining ability and heterosis in sorghum have been conducted (Kenga *et al.*, 2005; Makanda *et al.*, 2010; Menezes *et al.*, 2014; Mindaye *et al.*, 2016). Kenga *et al.* (2005) reported significant positive general combining ability (GCA) and specific combining ability (SCA) effects for most of the traits. They also observed that the male lines were capable of transmitting high yielding potential to the offspring and female lines effectively transmitted earliness and medium to tall height. Makanda *et al.* (2010) indicated that heterosis explained the high grain yield obtained for hybrids when compared to the parents and check varieties. Furthermore, Menezes *et al.* (2014) reported that crossing two parents that exhibited highest GCA could possibly produce the best performing cross due to an increasing frequency of favourable genes. According to Thomas *et al.* (2017), one of the strategies to increase the yield potential is manipulation of heterosis.

Heterosis studies in sorghum have shown that grain yield is dependent on the contribution of various components such as increased plant height (Jain and Patel, 2013; Ringo *et al.*, 2015), harvesting index (Can *et al.*, 1997), larger leaf area, higher number of grains per panicle (Beil and Atkins, 1967; Liang *et al.*, 1972), and photosynthesis process and transpiration (Kirby and Atkins, 1968; Blum *et al.*, 1977; Blum *et al.*, 1990). Although studies have been done on combining ability and heterosis for sorghum grain yield there is still no information available on combining ability of the germplasm in Mozambique and the potential for exploiting heterosis for hybrid development. Furthermore, information regarding parents potential for grain yield is limiting. The main objectives of this study were to estimate combining ability of the lines used in the National Sorghum programme and estimate the heterosis of the hybrids over the commercial cultivars for grain yield and yield component traits.

## 5.2. Materials and Methods

### 5.2.1. Plant materials

The sorghum genotypes used in this study were obtained from the Sorghum National Breeding programme and some were originally from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). The two standard checks used during evaluation were varieties widely grown in the country with good grain yield performance and stability. The hybrids which produced a full set of seed after crossing were used for the evaluation (Figure 5-1). This procedure is used for hybrid development as well as in identifying male sterile seed parents (House, 1985). The parental lines were divided into two groups: cytoplasmic male sterile lines (CMS) designated as females and cytoplasmic male fertile lines (CMF) as males (Table 5-1). The CMS lines facilitated the hybrid development in sorghum improvement (Reddy *et al.*, 2008a). Nine female lines (lines) and four male lines (testers) were used in a Line x Tester mating scheme. All crosses were successful and the resultant 36 hybrids together with two checks were evaluated in yield trials across six test environments (combination of year-location) during 2015/16 and 2016/17 seasons (Table 5-2). The 13 parents were also evaluated in four of the six test environments.

Figure 5-1 Sorghum hybridization in a greenhouse (left) and sorghum head of one hybrid during field evaluation (right) at Sussundenga Research Station.

Table 5-1 Parents used in the line by tester crossing block for hybrid development

| Parent | Group | Designation | Group | Origin |
|---|---|---|---|---|
| LARSVYT 46A | CMS | Female | Line | NAR/ICRISAT |
| 8601A | CMS | Female | Line | NAR/ICRISAT |
| SPL 38A | CMS | Female | Line | NAR/ICRISAT |
| ICSA 19A | CMS | Female | Line | NAR/ICRISAT |
| TX 628A | CMS | Female | Line | NAR/ICRISAT |
| ICSA 21A | CMS | Female | Line | NAR/ICRISAT |
| ICSA 12A | CMS | Female | Line | NAR/ICRISAT |
| CK 60A | CMS | Female | Line | NAR/ICRISAT |
| TX 631A | CMS | Female | Line | NAR/ICRISAT |
| IS 14257R | CMF | Male | Tester | NAR/ICRISAT |
| SDS 6013R | CMF | Male | Tester | NAR/ICRISAT |
| MZ 2R | CMF | Male | Tester | NAR |
| MZ 37R | CMF | Male | Tester | NAR |

NAR = National Research Sorghum Programme; cytoplasmic male sterile lines (CMS) and cytoplasmic male fertile lines (CMF)

### 5.2.2. Field evaluation sites

The trials were conducted at Chókwè and Maniquenique in the southern region, Sussundenga in the central region and Mapupulo in the northern region. These sites cover from low to mid-altitude environments (Table 5-2).

Table 5-2 Locations used for evaluation of entries over two seasons and rainfall received during the evaluation period

| Location | Season | Code | Latitude (ºS) | Longitude (ºE) | Altitude (m) | Rainfall* (mm) |
|---|---|---|---|---|---|---|
| Sussundenga** | 2015/16 | Sus16 | 19º18’ | 33º15’ | 635 | 522 |
| Chókwè** | 2015/16 | Chk16 | 24º52’ | 33º00’ | 33 | 380 |
| Sussundenga** | 2016/17 | Sus17 | 19º18’ | 33º15’ | 635 | 989 |
| Chókwè** | 2016/17 | Chk17 | 24º52’ | 33º00’ | 33 | 650 |
| Maniquenique | 2016/17 | Man17 | 24º73’ | 33º53’ | 13 | 468 |
| Mapupulo | 2016/17 | Map17 | 13º19’ | 38º86’ | 534 | 1050 |

*Rainfall refers to the amount received during the crop growing season, **Parents evaluation sites

### 5.2.3. Experimental design and field management

The 36 experimental hybrids, along with two check hybrids were laid out in a 19 x 2 alpha lattice design with three replications in each environment. The 13 parents were also evaluated in the same field adjacent to the hybrids and were laid out in a randomized complete block design with three replications in four of the six environments. Individual plots consisted of two rows which were 5 m long, spaced 0.75 m apart and the distance between plants in a row was 0.25 m. Fertilizer was applied at recommended rates of 250 kg ha$^{-1}$ NPK (12-24-12) basal fertilizer, and 150 kg ha$^{-1}$ Urea (46% N) as a top-dressing fertilizer. Other cultural practices such as ploughing, disking, hand planting, hand weeding and herbicides and pesticide application were carried out at each site.

Ten plants were randomly selected from each hybrid in each replication to measure the characters such as days to 50% flowering, plant height, panicle length, number of tillering plants, number of panicles and panicle aspect. Grain yield, biomass and disease scoring were done at on per plot basis. Adjusted harvest grain yield was determined following the standard practices used by CIMMYT (CIMMYT, 1985) as presented:

$$\text{Grain yield (t.ha}^{-1}\text{)} = [\text{Grain weight (kg/plot)} \times 10 \times (100\text{-MOI}^{*}) / (100\text{-}12.5) / (\text{Plot Area})]$$

*MOI = Grain Moisture Content

Due to high amounts of rainfall received in the 2016/17 season, three diseases severely affected some entries in four experimental sites. The diseases were *Cercospora spp* (similar to grey leaf spot (GLS) in maize), *Puccinia purpurea* (rust) and *Colletotrichum graminicola* (Cesati) Wilson (anthracnose). The disease severity was recorded based on visual assessment of the degree of damaged leaf area on scale of 1 to 5, where 1 = no disease, 2 = 1 to 5% leaf area damaged, 3 = 6 to 20% leaf area damage, 4 = 20 to 40% leaf area damaged, and 5 = severe disease with more than 40% leaf area damaged. The scores were further classified according to disease reaction type, where less than 5% leaf damage = resistant (R), 6 to 10% leaf damage = moderate resistant (MR), 10 to 20% leaf damage = moderately susceptible (MS) and more than 20 % leaf damage = susceptible (S).

### 5.2.4. Data analysis

The individual and combined season data were analysed using PROC GLM procedure in SAS 9.3 (SAS, 2011). Analyses of variance (ANOVA) were done first by environment with genotypes as the main effect, then a combined analysis across environments was conducted to evaluate the effect of environment, genotypes and their interactions. The calculation of combining ability effect was done only for the 36 hybrids tested. The data analysis followed a fixed effects model:

$$Yijkl = \mu + li + rj(li) + bij + mk + fi + (m * f)kl + (l * m)ik + (l * f)il + (l * m * f)ikl + \varepsilon ijkl$$

Where: $Y_{ijkl}$ = observed hybrid response; µ = overall mean of the population; $l_i$ =effects of the $i^{th}$ environment; $r_j$ ($l_i$) = effects of the $j^{th}$ replication in the $i^{th}$ environment; $b_{ij}$ = effects of the blocks in the $j^{th}$ replication in the $i^{th}$ environment; $m_k$ = effects of the $k^{th}$ male parent; $f_l$ = effects of the $l^{th}$ female parent; $m*f_{kl}$ = effects of the interaction between $k^{th}$ male and $l^{th}$ female parents; $l_i*m_k$ = interaction effects of the $i^{th}$ environment in $k^{th}$ male parent; $li*f_l$ = interaction effects of the $i^{th}$ environment in $l^{th}$ female parent; $l_i*m*f_{kl}$ = interaction effects of the $i^{th}$ environment and the interaction between the $k^{th}$ male and $l^{th}$ female parents; $\varepsilon_{ijkl}$ = experimental error.

Estimation of general combining ability (GCA) and specific combining ability (SCA) effects were done according to Dabholkar (1999):

$$kj(tester) = \frac{Y.j.}{rl} - \frac{Y...}{rlt};$$

$$fi\ (line) = \frac{Yi..}{rt} - \frac{Y...}{rlt} \text{ and}$$

$$Sij = \frac{Yij}{r} - \frac{Yi..}{rt} - \frac{Y.j.}{rl} + \frac{Y\ldots}{rlt}$$

where $k_{(tester)}$ and $f_{(line)}$ represent the estimates of GCA effects $i^{th}$ lines and $j^{th}$ tester, respectively. Sij represents the SCA effects of i x $j^{th}$ cross. $Y_{i..}$, $Y_{.j.}$ and $Y_{\ldots}$ represent the sum of lines, testers and grand total of the grain yield respectively.

The "t" test was used to estimate the significance of the GCA and SCA, and standard errors were calculated as follows:

$$SEkj = (\frac{Me}{rl})^{\frac{1}{2}}, j = 1, \ldots, j$$

$$SEfi = (\frac{Me}{rt})^{1/2}, i = 1, \ldots, i$$

$$SEij = (\frac{Me}{r})^{1/2}$$

Where SEs are the standard errors for testers ($SEk_j$), lines ($SEf_i$) and crosses ($SE_{ij}$). Me - is the mean square of the error. Thus, *t* test:

$$tg = \frac{g - 0}{SEg}$$

$$ts = \frac{sij - 0}{SEij}$$

Where tg – test significance for GCA effects and ts – test significance for SCA effects. The *t* test was considered significant at probability of 5% if the value was greater than 1.96 and significant at 1% if it was greater than 2.58.

Heterosis (H) analysis was performed to compare the hybrids with their parents and identify hybrid performance that exceeds the average parental performance (House, 1985). The heterosis was calculated using the following formulas:

1) Heterosis over the mid-parent:

(MPH) = [($F_1$ – MP)/*MP]*100, where $F_1$ = hybrid mean performance, MP = average predicted performance for the two parents.

2) Standard heterosis:

(HBP) = [($F_1$ – MT)/*MT]*100, where $F_1$ = hybrid mean performance, MT = best check mean, checks mean, best parents mean or trial mean

## 5.3. Results

The results from the analysis of variance showed that hybrids differed in grain yield performance across environments ($P \leq 0.01$). Secondary traits such as days to 50% flowering, plant height, panicle length and number of tillering plants per plot were also highly significant; however, there was no significant variation for number of panicles (Table 5-3). The environments exhibited highly significant differences ($P \leq 0.01$) for all traits. Testers were significant ($P \leq 0.05$) for grain yield and plant height, and highly significant ($P \leq 0.01$) for days to 50% flowering. There were significant differences for panicle length, number of tillering plants and number of panicles. On the other hand, lines exhibited highly significant differences ($P \leq 0.01$) for all traits except number of panicles that were significant at $P \leq 0.05$. The line x tester interaction effect was highly significant ($P \leq 0.01$) for all traits except number of panicles. The environment x hybrids interaction was highly significant ($P \leq 0.01$) for all traits while environment x line interaction did not show significant differences for panicle length and number of panicles but was highly significant ($P \leq 0.01$) for grain yield, and significant for number of panicles ($P \leq 0.05$). Environment x tester interaction effects and the environment x line x tester were highly significant ($P \leq 0.01$) for all traits.

The line effects and environment x hybrid interaction effects were highly significant ($P \leq 0.01$) for *Cercospora spp*, rust, anthracnose and biomass (Table 5-4). Testers showed highly significant differences for biomass but did not show significant differences for the three diseases. Although the line x tester interaction effect was significant ($P \leq 0.01$) for all the diseases, it was not significant for biomass. The environment x hybrids interaction effect was highly significant ($P \leq 0.01$), and the environment x line interaction effect was significant ($P \leq 0.05$). Furthermore, the environment x line x tester interaction was highly significant for rust, anthracnose and biomass but not significant for *Cercospora spp*.

### 5.3.1. Grain yield and other Agronomic traits

The results from analysis of variance of grain yield across six test environments showed that the main effects (genotypes and environments) and their interaction were highly significant ($P<0.001$, Table 5-3). The mean grain yields of the parents and hybrids were 1.23 $t.ha^{-1}$ and 2.63 $t.ha^{-1}$, respectively. There were highly significant differences ($P<0.001$) among environments for all traits. The grain yields in the different environment ranged from 3.5 $t.ha^{-1}$

to 0.6 t.ha$^{-1}$ where the highest yields were from environment Map17 followed by Sus17, Sus16, Man17, Chk17 and Chk16 had the lowest yields (Figure 5-2).

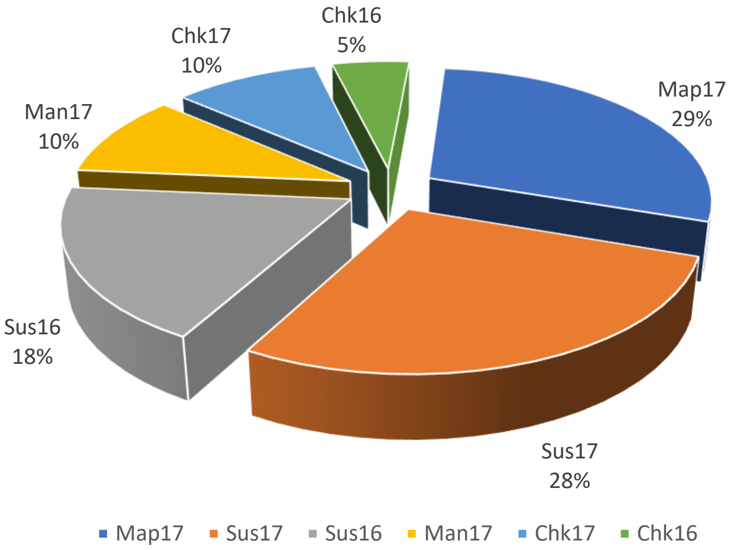

Figure 5-2 Hybrids performance for grain yield at different environments.

Table 5-3 Mean squares for grain yield and secondary traits across six environments

| **Source of Variation** | **DF** | **Grain yield (t.ha$^{-1}$)** | **Days to flowering (days)** | **Plant height (cm)** | **Panicle length (cm)** | **Number of tillering plants** | **Number of panicles** |
|---|---|---|---|---|---|---|---|
| Environment (Env.) | 5 | 128.63$^{***}$ | 2808.51$^{***}$ | 30899.37$^{***}$ | 1241.82$^{***}$ | 513.39$^{***}$ | 2825.94$^{***}$ |
| Block (Rep x Env.) | 3 | 0.54 | 3.64$^{***}$ | 1329.33$^{***}$ | 53.20$^{***}$ | 36.28$^{***}$ | 66.48$^{*}$ |
| Hybrids | 35 | 1.46$^{***}$ | 64.68$^{***}$ | 3010.23$^{*}$ | 125.45$^{**}$ | 47.87$^{***}$ | 60.94 |
| Tester (GCA) | 3 | 1.25$^{*}$ | 92.72$^{***}$ | 1407.18$^{***}$ | 27.11 | 15.17 | 15.68 |
| Line (GCA) | 8 | 2.00$^{***}$ | 106.48$^{***}$ | 5020.67$^{***}$ | 342.17$^{***}$ | 78.34$^{***}$ | 93.89$^{*}$ |
| Line x Tester (SCA) | 24 | 1.43$^{***}$ | 52.47$^{***}$ | 2438.94$^{***}$ | 72.63$^{***}$ | 44.93$^{***}$ | 57.55 |
| Env. X Hybrids | 175 | 1.50$^{***}$ | 86.29$^{***}$ | 3060.51$^{***}$ | 143.64$^{***}$ | 45.12$^{***}$ | 86.83$^{***}$ |
| Env. X Tester | 15 | 1.48$^{***}$ | 53.79$^{***}$ | 3263.75$^{***}$ | 35.25 | 18.49 | 75.90$^{*}$ |
| Env. X Line | 40 | 1.82$^{**}$ | 129.61$^{***}$ | 5523.80$^{***}$ | 394.97$^{***}$ | 80.57$^{***}$ | 140.41$^{***}$ |
| Env. X Line x Tester | 120 | 1.35$^{**}$ | 77.28$^{***}$ | 2206.93$^{***}$ | 59.46$^{***}$ | 33.64$^{***}$ | 68.51$^{***}$ |
| Error | 402 | 0.48 | 1.90 | 519.71 | 26.03 | 17.15 | 43.91 |
| Overall mean | | 2.04 | 66.62 | 139.59 | 31.76 | 18.60 | 20.80 |
| $R^2$ (%) | | 85.54 | 98.09 | 80.50 | 80.32 | 67.88 | 68.75 |

$^{*, **, ***}$ Data is significant at $P \le 0.05$, $P \le 0.01$ and $P \le 0.001$ respectively

Table 5-4 Mean squares for disease scores and biomass across four environments

| **Source of Variation** | **DF** | **Csp**¥ | **Rust**¥ | **Anth**¥ | **Bio** |
|---|---|---|---|---|---|
| Environment (Env.) | 5 | 6.70*** | 5.68*** | 4.04*** | 570.69*** |
| Block (Rep x Env.) | 3 | 0.33 | 0.32 | 0.49 | 5.81 |
| Hybrids | 35 | 0.51** | 0.96*** | 1.32*** | 7.90** |
| Tester (GCA) | 3 | 0.17 | 0.25 | 0.12 | 13.89** |
| Line (GCA) | 8 | 0.43** | 1.14*** | 1.03** | 13.21*** |
| Line x Tester (SCA) | 24 | 0.59*** | 0.57*** | 0.96*** | 5.92 |
| Env. X Hybrids | 175 | 0.38*** | 0.90*** | 1.21*** | 7.65*** |
| Env. X Tester | 15 | 0.24 | 0.70*** | 1.56*** | 14.28*** |
| Env. X Line | 40 | 0.58*** | 0.81*** | 1.27*** | 7.85*** |
| Env. X Line x Tester | 120 | 0.27 | 0.79*** | 0.88*** | 6.97*** |
| Error | 402 | 0.21 | 0.24 | 0.40 | 4.33 |
| Overall mean | | 2.02 | 2.30 | 1.68 | 6.44 |
| $R^2$ (%) | | 64.06 | 72.26 | 65.22 | 74.69 |

*, **, *** Data is significant at $P \leq 0.05$, $P \leq 0.01$ and $P \leq 0.001$ respectively; Csp = *Cercospora spp*, Rust = *Puccinia purpurea*, Anth = Anthracnose and Bio = Biomass; ¥ disease rating scores (1=symptomless and 5=severe leaf damage).

### 5.3.2. Hybrid reaction to the foliar diseases

Among the three diseases observed [*Cercospora spp*, *Puccinia purpurea* (leaf rust) and *Colletotrichum graminicola* (anthracnose)], anthracnose was less severe with average leaf damage area between 1 to 5%. Rust was the most severe disease with 10 to 30% leaf area damage. *Cercospora spp* was rated between 6% and 10% leaf area damage. The checks Macia and Sima had moderate resistance (MR) for both anthracnose and *Cercospora spp* but Macia showed susceptibility to rust. The rust resistant hybrids were ICSA 12A x MZ 2R, ICSA 12A x SDS 6013R and TX 631A x SDS 6013R while moderately resistant were LARSVYT 46A x IS 14257R, LARSVYT 46A x SDS 6013R and 8601A x MZ 37R. For *Cercospora spp,* most of the hybrids were rated as either resistant or moderately resistant whereas for anthracnose all hybrids were resistant.

### 5.3.3. General combining ability estimates

The line GCA mean squares were highly significant (P≤0.01) for all traits except for number of tillering plants which was significant at P≤0.05 (Table 5-3). The tester GCA mean squares were highly significant for days to 50% flowering and plant height biomass but not significant for grain yield. Non- significant GCA mean squares were observed in testers for number of tillering plants, number of panicles, *Cercospora spp*, rust and anthracnose (Table 5-5). On the other hand, SCA mean squares were significant (P≤0.05) for number of panicles and biomass but highly significant (P≤0.01) for grain yield, days to 50% flowering, plant height, panicle length, number of tillering plants, *Cercospora spp*, rust and anthracnose (Table 5-5). The desirable direction for selection based on GCA and SCA effects was positive for grain yield and panicle length and negative for days to 50% flowering, plant height, number of tillering plants, disease score and biomass. For grain yield, testers MZ 2R and SDS 6013R showed negative GCA values while IS 14257R and MZ 37R showed non-significant positive values. The lines with significant positive (P≤0.01) GCA effects for grain yield were LARSVYT 46A, SPL 38A and TX 631A while 8601A, ICSA 19A and TX 628A showed significant (P≤0.01) negative GCA effects. Days to 50% flowering were highly significant (P≤0.01) with negative GCA effects in testers IS 14257R and MZ 37R while plant height was significant and negative in tester SDS 6013R. The lines that showed highly significant (P≤0.01) negative GCA effects for days to 50% flowering were 8601A, ICSA 12A and TX 631A and those significant (P≤0.05) were LARSVYT 46A. For the plant height, lines TX 631A, ICSA 21A and TX 628A had significant negative GCA effects (P≤0.05). Panicle length showed a positive significant (P≤0.01) GCA effect for the lines LARSVYT 46A, SPL 38A and TX 631A, while the negative but significant (P≤0.01) GCA effects were obtained for the lines 8601A, ICSA 19A, ICSA 21A and ICSA 12A. The desirable direction for number of tillering plants were shown by line

ICSA21A and was highly significant (P≤0.01) while the opposite direction significant (P≤0.01) GCA effects were found in SPL 38A. Negative significant (P≤0.01) GCA values for rust disease scores were observed for lines ICSA 12A and TX 631A while other lines had positive GCA values for the rest of the diseases.

Table 5-5 General combining ability estimates of parents for grain yield and secondary traits across six environments

| **Parent line** | **GY (t.ha$^{-1}$)** | **DF (days)** | **PH (cm)** | **PL (cm)** | **NP** | **Csp¥** | **RUST¥** | **ANTH¥** |
|---|---|---|---|---|---|---|---|---|
| **(Testers)** | | | | | | | | |
| MZ 2R | -0.09 | $0.73^{**}$ | 0.54 | 0.48 | -0.12 | -0.02 | 0.03 | -0.02 |
| IS 14257R | 0.09 | $-0.78^{**}$ | -0.96 | -0.44 | 0.40 | 0.00 | 0.02 | -0.01 |
| SDS 6013R | -0.06 | $0.65^{**}$ | $-4.36^{*}$ | 0.16 | -0.04 | 0.04 | -0.04 | 0.02 |
| MZ 37R | 0.05 | $-0.60^{**}$ | $4.78^{**}$ | -0.20 | -0.23 | -0.01 | -0.01 | 0.01 |
| SE | 0.10 | 0.10 | 1.80 | 0.40 | 0.30 | 0.04 | 0.04 | 0.10 |
| **(Lines)** | | | | | | | | |
| LARSVYT 46A | $0.29^{**}$ | $-0.35^{*}$ | $11.99^{**}$ | $3.59^{**}$ | $1.10^{*}$ | -0.02 | -0.05 | -0.08 |
| 8601A | -0.01 | $-2.14^{**}$ | 3.29 | $-2.30^{**}$ | 0.35 | 0.02 | -0.01 | 0.00 |
| SPL 38A | $0.16^{**}$ | $1.55^{**}$ | 2.86 | $3.00^{**}$ | $1.88^{**}$ | -0.05 | 0.06 | -0.04 |
| ICSA 19A | -0.09 | $1.11^{**}$ | $6.18^{*}$ | $-1.45^{*}$ | 0.12 | -0.02 | -0.05 | -0.09 |
| TX 628A | $-0.16^{**}$ | $1.01^{**}$ | $-5.75^{*}$ | -0.54 | -0.24 | -0.05 | $0.21^{**}$ | $0.22^{**}$ |
| ICSA 21A | $-0.19^{**}$ | $1.01^{**}$ | $-5.33^{*}$ | $-1.73^{**}$ | $-1.63^{**}$ | $0.01^{*}$ | 0.00 | -0.03 |
| ICSA 12A | -0.08 | $-0.85^{**}$ | -0.40 | $-1.58^{**}$ | -0.34 | $0.11^{*}$ | $-0.11^{*}$ | 0.09 |
| CK 60A | -0.08 | 0.08 | 3.04 | -0.64 | -0.81 | -0.07 | 0.09 | -0.05 |
| TX 631A | $0.17^{**}$ | $-1.43^{**}$ | $-15.88^{**}$ | $1.66^{**}$ | -0.42 | 0.07 | $-0.13^{*}$ | -0.01 |
| SE | 0.10 | 0.20 | 2.70 | 0.60 | 0.50 | 0.05 | 0.06 | 0.07 |

$^{*, **, ***}$ Significant at P≤0.05, P≤0.01 and P≤0.001, respectively; GY =Grain yield (t.ha$^{-1}$), DF = Days to 50% flowering, PH =Plant height, PL = Plant length, NP = Number of tillering plants, Csp = *Cercospora spp*, Rust = *Puccinia purpurea*, and Anth = Anthracnose. ¥ Disease rating scores (1=symptomless and 5=severe leaf damage).

### 5.3.4. Specific combining ability estimates

The line SCA mean squares were highly significant (P≤0.01) for all traits except for number of panicles and biomass that were not significant (Table 5-3). For SCA effects, most of the hybrids showed significant effects in the desirable direction for selection for each trait. The cross TX 631A x MZ 37R had significant (P≤0.01) positive SCA effects for grain yield (Table 5-7). The other crosses showed a negative SCA effects for grain yield. About 14 hybrids showed significant (P≤0.05) and negative SCA effects for days to 50% flowering, while 10 hybrids showed significant (P≤0.05) positive SCA effects. The highest negative SCA values for days to 50% flowering were recorded for hybrids 8601A x IS 14257R, 8601A x SDS 6013R, ICSA 12A x MZ 2R, TX 631A x IS 14257R and TX 631A x MZ 37R. Most of the hybrids showed significant (P≤0.05) negative SCA effects for plant height while all the positive SCA effects for panicle length were not significant. Fifteen hybrids involving lines TX 631A, CK 60A, ICSA 12A, ICSA 21A, TX 628A and 8601A showed a significant (P≤0.05) negative SCA effects for number of tillering plants. Most of the SCA effects for the three diseases were not significant except for the hybrids LARSVYT 46A x MZ 37R and CK 60A x MZ 2R that showed significant (P≤0.05) negative SCA effects.

### 5.3.5. Correlation among grain yield and secondary traits

Correlation coefficients among GCA and SCA effects of the different traits were determined (Table 5-6). Most of the correlation coefficients among the traits were very low (r<0.5) apart from the significant coefficients. A significant positive correlation coefficient (P≤0.05) was observed between the parent GCA effects for grain yield and number of tillering plants and between number of tillering plants and panicle length. Besides, a negative and significant (P≤0.05) correlation was found between *Cercospora spp* disease scores and rust disease scores. Significant correlation coefficients (P≤0.05) between SCA effects were obtained for the following pairs of traits: grain yield and panicle length; grain yield and number of tillering plants, as well as panicle length and number of panicles.

Table 5-6 Pearson correlation coefficients among SCA effects (below diagonal) of the hybrids and GCA effects (above diagonal) of the parents for grain yield and secondary traits across six environments

| | **GY** | **DF** | **PH** | **PL** | **NP** | **Csp** | **RUST** | **ANTH** |
|---|---|---|---|---|---|---|---|---|
| **GY** | | -0.35 | 0.23 | 0.80 | 0.69$^{**}$ | 0.02 | -0.36 | -0.41 |
| **DF** | -0.29 | | 0.08 | 0.18 | 0.05 | -0.53 | 0.47 | -0.01 |
| **PH** | 0.33 | -0.14 | | 0.13 | 0.47 | -0.44 | 0.07 | -0.42 |
| **PL** | 0.43$^{**}$ | 0.02 | 0.05 | | 0.64$^{**}$ | -0.22 | -0.06 | -0.27 |
| **NP** | 0.71$^{***}$ | -0.07 | 0.39 | 0.41$^{**}$ | | -0.24 | 0.03 | -0.20 |
| **Csp** | 0.02 | -0.19 | -0.06 | 0.01 | -0.03 | | -0.78$^{**}$ | 0.16 |
| **RUST** | -0.17 | 0.15 | 0.12 | 0.01 | -0.11 | -0.14 | | 0.44 |
| **ANTH** | -0.10 | 0.04 | -0.15 | -0.09 | 0.06 | -0.13 | 0.33 | |

$^{*, **, ***}$ Significant at P≤0.05, P≤0.01 and P≤0.001 respectively; GY =Grain yield ($t.ha^{-1}$), DF = Days to 50% flowering, PH =Plant height, PL = Panicle length, NP = Number of tillering plants, Csp = *Cercospora spp*, Rust = *Puccinia purpurea* and Anth = Anthracnose.

### 5.3.6. Genotype superiority

The performance of the top ten experimental hybrids was compared to the checks. The earliest flowering hybrids were TX 631A x IS 14257R and 8601A x IS 14257R with 62 days. Macia (check) was also part of the early genotypes with 65 days to flowering. On the other hand, Macia (check) was amongst the shortest genotypes with 120 cm after TX 631A x MZ 2R with 117 cm. The hybrids LARSVYT 46A x MZ 2R, LARSVYT 46A x SDS 6013R, SPL 38A x MZ 2R, TX 631A x SDS 6013R, SPL 38A x IS 14257R, SPL 38A x MZ 37R and TX 631A x IS 14257R displayed large panicle sizes of 35 cm to 38 cm compared to Sima (check) and Macia with 34 cm and 30 cm respectively. The hybrids ICSA 21A x MZ 37R, ICSA 12A x IS 14257R and TX 628A x MZ 37R were the top three in respect to number of tillering plants per plot with 16 plants. Few number of panicles were recorded from the check Macia and hybrids 8601A x SDS 6013R, ICSA 21A x MZ 2R and TX 628A x MZ 37R. None of the checks appeared in the top 10 genotypes for grain yield performance. However, when raking the top 20, Sima came at position 16 while Macia came at position number 20. The hybrids with the highest average grain yield across environments were TX 631A x MZ 37R followed by SPL 38A x SDS 6013R and LARSVYT 46A x IS 14257R (Figure 5-3).

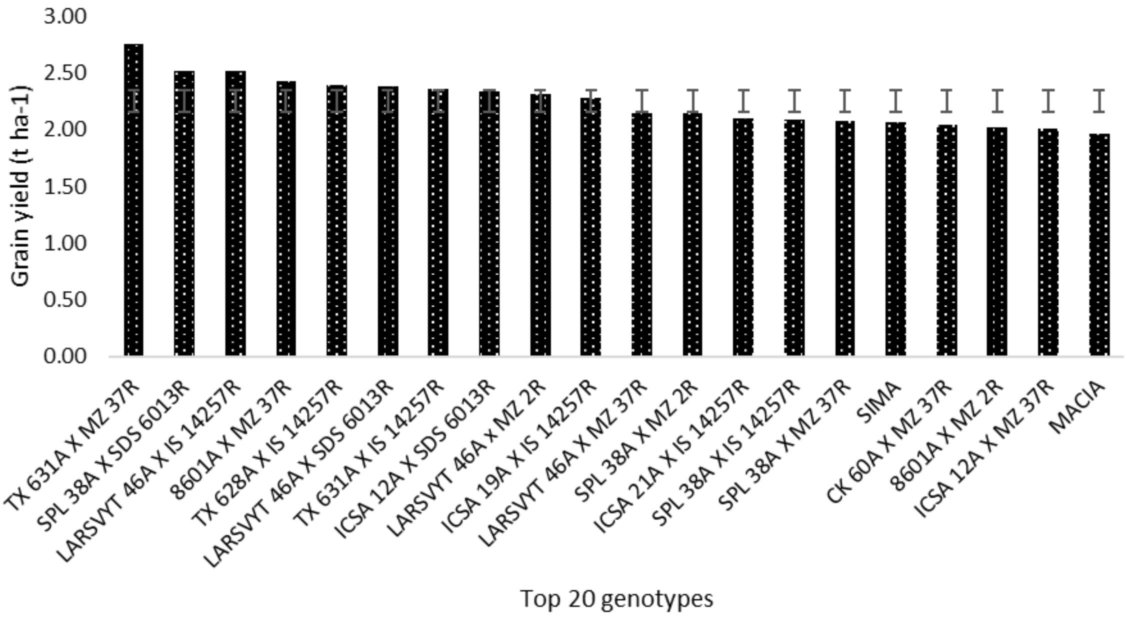

Figure 5-3 Top 20 genotypes performance for grain yield across six locations

Table 5-7 Specific combining ability estimates of the 36 hybrids for grain yield and secondary traits across six environments

| **Hybrids** | **GY (t.ha$^{-1}$)** | **DF (days)** | **PH (cm)** | **PL (cm)** | **NP** | **GLS$^{¥}$** | **RUST$^{¥}$** | **ANTH$^{¥}$** |
|---|---|---|---|---|---|---|---|---|
| LARSVYT 46A x MZ 2R | 0.06 | 0.10 | 6.37 | 1.83 | -1.04 | 0.00 | 0.04 | -0.10 |
| LARSVYT 46A X IS 14257R | 0.26 | -1.01$^{**}$ | 7.08 | -1.41 | 2.69$^{**}$ | 0.19 | 0.18 | 0.09 |
| LARSVYT 46A X SDS 6013R | 0.13 | -1.18$^{**}$ | -7.94 | 0.90 | 1.13 | 0.11 | -0.15 | 0.18 |
| LARSVYT 46A X MZ 37R | -0.10 | -0.84$^{**}$ | -7.65 | -3.25$^{**}$ | -2.31$^{**}$ | -0.23$^{*}$ | -0.18 | -0.07 |
| 8601A x MZ 2R | -0.22 | -0.95$^{**}$ | 1.18 | -5.24$^{**}$ | -1.54 | 0.00 | 0.15 | 0.09 |
| 8601A x IS 14257R | -0.31 | -4.90$^{**}$ | 1.15 | -7.54$^{**}$ | -0.15 | -0.17 | -0.07 | 0.29$^{*}$ |
| 8601A x SDS 6013R | -0.51$^{**}$ | -4.51$^{**}$ | -25.26$^{**}$ | -7.14$^{**}$ | -2.09$^{**}$ | 0.30$^{**}$ | 0.07 | -0.02 |
| 8601A x MZ 37R | 0.18 | 0.27 | -14.02$^{**}$ | -5.58$^{**}$ | 1.24 | 0.11 | -0.12 | 0.04 |
| SPL 38A x MZ 2R | -0.11 | 1.71$^{**}$ | -17.54$^{**}$ | 0.53 | 1.13 | -0.09 | -0.01 | -0.07 |
| SPL 38A x IS 14257R | -0.16 | 1.55$^{**}$ | -27.70$^{**}$ | -0.21 | 0.74 | 0.05 | 0.02 | 0.21 |
| SPL 38A x SDS 6013R | 0.27 | 1.66$^{**}$ | 18.38$^{**}$ | -4.04$^{**}$ | 2.13$^{**}$ | 0.02 | 0.07 | 0.04 |
| SPL 38A x MZ 37R | -0.17 | -0.23 | -11.80$^{*}$ | -0.57 | -0.42 | -0.06 | 0.27$^{*}$ | 0.07 |
| ICSA 19A x MZ 2R | -0.53$^{**}$ | 1.82$^{**}$ | -6.78 | -4.20$^{**}$ | -0.26 | 0.19 | -0.01 | -0.10 |
| ICSA 19A x IS 14257R | 0.03 | -0.12 | -7.93 | -6.17$^{**}$ | -0.87 | -0.03 | 0.04 | 0.07 |
| ICSA 19A x SDS 6013R | -0.40$^{*}$ | 1.05$^{**}$ | -10.49 | -2.36$^{*}$ | -0.70 | -0.09 | 0.02 | -0.07 |
| ICSA 19A x MZ 37R | -0.29 | 0.16 | -0.20 | -9.37$^{**}$ | -1.65 | 0.00 | -0.15 | 0.15 |
| TX 628A x MZ 2R | -0.30 | -0.23 | -16.95$^{**}$ | -3.98$^{**}$ | -1.26 | 0.02 | 0.57$^{**}$ | 0.76$^{*}$ |
| TX 628A x IS 14257R | 0.15 | 0.10 | -17.80$^{**}$ | -3.77$^{**}$ | 2.24$^{**}$ | -0.17 | 0.07 | 0.32$^{*}$ |
| TX 628A x SDS 6013R | -0.83$^{**}$ | 2.38$^{**}$ | -31.04$^{**}$ | -6.89$^{**}$ | -2.70$^{**}$ | -0.11 | 0.13 | 0.21 |

| **Hybrids** | **GY (t.ha$^{-1}$)** | **DF (days)** | **PH (cm)** | **PL (cm)** | **NP** | **GLS¥** | **RUST¥** | **ANTH¥** |
|---|---|---|---|---|---|---|---|---|
| TX 628A x MZ 37R | -0.49$^{**}$ | 0.27 | -7.31 | -3.81$^{**}$ | -3.20$^{**}$ | 0.22$^{*}$ | 0.15 | -0.02 |
| ICSA 21A x MZ 2R | -0.48$^{**}$ | 1.88$^{**}$ | -12.97$^{*}$ | -4.92$^{**}$ | -3.04$^{**}$ | 0.02 | 0.04 | 0.04 |
| ICSA 21A x IS 14257R | -0.15 | -1.01$^{**}$ | -16.85$^{**}$ | -7.91$^{**}$ | -2.37$^{**}$ | 0.05 | 0.07 | -0.18 |
| ICSA 21A x SDS 6013R | -0.39$^{*}$ | 2.27$^{**}$ | -20.46$^{**}$ | -6.04$^{**}$ | -1.48 | 0.08 | -0.12 | 0.15 |
| ICSA 21A x MZ 37R | -0.58$^{**}$ | -0.62 | -21.13$^{**}$ | -4.36$^{**}$ | -3.59$^{**}$ | 0.02 | 0.10 | 0.26 |
| ICSA 12A x MZ 2R | -0.40$^{*}$ | -3.51$^{**}$ | -4.09 | -5.78$^{**}$ | -0.37 | 0.14 | -0.18 | -0.04 |
| ICSA 12A x IS 14257R | -0.61$^{**}$ | 1.05$^{**}$ | -23.37$^{**}$ | -7.46$^{**}$ | -3.54$^{**}$ | -0.09 | 0.10 | 0.26 |
| ICSA 12A x SDS 6013R | 0.09 | -0.73$^{*}$ | -18.92$^{**}$ | -3.84$^{**}$ | -0.76 | 0.27$^{*}$ | -0.18 | 0.18 |
| ICSA 12A x MZ 37R | -0.24 | -1.73$^{**}$ | -5.34 | -5.55$^{**}$ | -0.65 | 0.25$^{*}$ | -0.10 | 0.37$^{*}$ |
| CK 60A x MZ 2R | -0.28 | 0.10 | -21.38$^{**}$ | -4.61$^{**}$ | -0.92 | -0.25$^{*}$ | -0.07 | 0.07 |
| CK 60A x IS 14257R | -0.33$^{*}$ | -0.79$^{*}$ | -5.54 | -5.14$^{**}$ | -1.98$^{*}$ | 0.25$^{*}$ | 0.04 | -0.07 |
| CK 60A x SDS 6013R | -0.34$^{*}$ | 1.21$^{**}$ | -25.39$^{**}$ | -5.72$^{**}$ | -3.15$^{**}$ | -0.03 | 0.24$^{*}$ | 0.09 |
| CK 60A x MZ 37R | -0.20 | -1.73$^{**}$ | 14.35$^{**}$ | -3.38$^{**}$ | -1.15 | -0.11 | 0.24$^{*}$ | 0.09 |
| TX 631A x MZ 2R | -0.37$^{*}$ | 2.21$^{**}$ | -35.75$^{**}$ | -5.95$^{**}$ | -2.65$^{**}$ | 0.14 | -0.10 | 0.04 |
| TX 631A x IS 14257R | 0.10 | -5.34$^{**}$ | -30.42$^{**}$ | -1.02 | -2.09$^{**}$ | 0.19 | -0.10 | -0.13 |
| TX 631A x SDS 6013R | -0.38$^{*}$ | 0.21 | -30.84$^{**}$ | -0.09 | -1.65 | 0.08 | -0.18 | 0.32$^{*}$ |
| TX 631A x MZ 37R | 0.51$^{**}$ | -4.34$^{**}$ | -16.63$^{**}$ | -2.57$^{*}$ | 0.74 | 0.00 | -0.07 | 0.12 |
| SE | 0.20 | 0.30 | 5.40 | 1.20 | 1.00 | 0.11 | 0.12 | 0.15 |

$^{*, **, ***}$ Significant at P≤0.05, P≤0.01 and P≤0.001 respectively; GY =Grain yield (t.ha$^{-1}$), DF = Days to 50% flowering, PH =Plant height, PL = Plant length, NP = Number of tillering plants, Csp = *Cercospora spp*, Rust = *Puccinia purpurea*, Anth = Anthracnose and Bio = Biomass. ¥ Disease rating scores (1=symptomless and 5=severe leaf damage).

### 5.3.7. Heterosis estimates for grain yield across environments

The heterosis over the mid-parent (MPH) and standards heterosis (SH) are outlined in Table 5-8. The heterosis was highly significant ($P<0.01$) over the mid-parent, trial mean, best check and best parents. The grain yield mean of the parent lines and hybrids was 1.23 $t.ha^{-1}$ and 2.63 $t.ha^{-1}$, respectively. Across all the environments, hybrids showed superior grain yield over all parents, with the mean heterosis over the mid-parent of 194% and mean heterosis over the best check of 76% (Table 5-8). The MPH was positive and ranged from 52 to 194% over the mid-parent. Twenty-six hybrids had heterosis over the mid-parent with more than 100% and the remaining 10 were below 100%. The top five hybrids were: TX 631A x MZ 37R, followed by SPL 38A x SDS 6013R, LARSVYT 46A x IS 14257R, 8601A x MZ 37R and TX 628A x IS 14257R. Most of the hybrids had heterosis from 5 to 57% above the trial mean. The hybrids 8601A x SDS 6013R, ICSA 19A x MZ 2R, ICSA 21A x MZ 37R, ICSA 12A x IS 14257R, TX 628A x SDS 6013R had heterosis below the trial mean.

The hybrid TX 631A x MZ 37R had better performance over the best check, check mean and over the best parent for grain yield. The heterosis over the best check ranged from 5 to 76%. Two testers (IS 14257R and MZ 37R) and one line (LARSVYT 46A) were selected based on their positive and significant GCA effects for grain yield when compared with hybrids. The hybrids generated from the selected testers or lines exhibited high level of heterosis, whereas lines TX 631A and 8601A combined with tester MZ 37R also displayed high levels of heterosis of 182% and 148%, respectively. The combination of the selected line LARSVYT 46A with tester IS 14257R displayed a level of heterosis of 141% (Table 5-8). Among the top 10 hybrids, the lines that combined with tester MZ 37R displayed high levels of heterosis with TX 631A and 8601A, while the lines; LARSVYT 46A, TX 628A, TX 631A and ICSA 19A resulted in hybrids with high levels of heterosis when combined with tester IS 14257R. On the other hand, the hybrids from testers SDS 6013R and MZ 2R with line LARSVYT 46A also displayed a high level of heterosis.

Table 5-8 Standard heterosis for grain yield (t.ha$^{-1}$) of 36 hybrids across six environments

| **Genotypes** | **MPH (%)** | **SH to trial mean (%)** | **SH to best check (%)** | **SH to check mean (%)** | **SH to P2 (%)** | **SH to P4 (%)** | **SH to P5 (%)** |
|---|---|---|---|---|---|---|---|
| TX 631A x MZ 37R | 293.9 | 156.8 | 175.5 | 176.4 | 265.2 | 282.2 | 203.9 |
| SPL 38A x SDS 6013R | 268.8 | 143.4 | 160.5 | 161.3 | 242.5 | 258.1 | 186.5 |
| LARSVYT 46A x IS 14257R | 267.6 | 142.7 | 159.7 | 160.5 | 241.4 | 256.9 | 185.6 |
| 8601A x MZ 37R | 258.6 | 137.9 | 154.4 | 155.2 | 233.3 | 248.3 | 179.4 |
| TX 628A x IS 14257R | 255.1 | 136.1 | 152.3 | 153.1 | 230.2 | 244.9 | 177.0 |
| LARSVYT 46A x SDS 6013R | 253.4 | 135.2 | 151.3 | 152.1 | 228.7 | 243.3 | 175.8 |
| TX 631A x IS 14257R | 250.7 | 133.7 | 149.7 | 150.4 | 226.2 | 240.7 | 173.9 |
| ICSA 12A x SDS 6013R | 250.3 | 133.5 | 149.4 | 150.2 | 225.8 | 240.3 | 173.6 |
| LARSVYT 46A x MZ 2R | 246.5 | 131.5 | 147.1 | 147.9 | 222.4 | 236.6 | 171.0 |
| ICSA 19A x IS 14257R | 243.9 | 130.1 | 145.6 | 146.4 | 220.1 | 234.2 | 169.2 |
| CK 60A x MZ 37R | 241.6 | 128.8 | 144.2 | 144.9 | 218.0 | 231.9 | 167.6 |
| SPL 38A x MZ 2R | 229.5 | 122.4 | 137.0 | 137.7 | 207.1 | 220.3 | 159.2 |
| LARSVYT 46A x MZ 37R | 227.2 | 121.2 | 135.6 | 136.3 | 205.0 | 218.1 | 157.6 |
| ICSA 21A x IS 14257R | 223.1 | 119.0 | 133.2 | 133.8 | 201.3 | 214.1 | 154.7 |
| SPL 38A x MZ 37R | 222.6 | 118.7 | 132.9 | 133.6 | 200.9 | 213.7 | 154.4 |
| SPL 38A x IS 14257R | 221.5 | 118.1 | 132.2 | 132.9 | 199.8 | 212.6 | 153.6 |
| 8601A x MZ 2R | 217.0 | 115.7 | 129.6 | 130.2 | 195.8 | 208.3 | 150.5 |
| ICSA 12A x MZ 37R | 214.8 | 114.6 | 128.2 | 128.9 | 193.8 | 206.2 | 149.0 |
| ICSA 19A x MZ 37R | 211.1 | 112.6 | 126.0 | 126.7 | 190.5 | 202.7 | 146.5 |
| CK 60A x MZ 2R | 209.1 | 111.5 | 124.9 | 125.5 | 188.7 | 200.8 | 145.1 |
| 8601A x IS 14257R | 208.0 | 110.9 | 124.2 | 124.8 | 187.7 | 199.7 | 144.3 |
| TX 628A x MZ 2R | 206.7 | 110.2 | 123.4 | 124.0 | 186.5 | 198.4 | 143.4 |
| CK 60A x IS 14257R | 205.0 | 109.3 | 122.4 | 123.0 | 184.9 | 196.8 | 142.2 |
| CK 60A x SDS 6013R | 202.2 | 107.8 | 120.7 | 121.3 | 182.4 | 194.1 | 140.2 |
| ICSA 19A x SDS 6013R | 202.0 | 107.8 | 120.6 | 121.2 | 182.3 | 194.0 | 140.1 |
| TX 631A x SDS 6013R | 200.6 | 107.0 | 119.8 | 120.4 | 181.0 | 192.6 | 139.2 |
| TX 631A x MZ 2R | 199.5 | 106.4 | 119.1 | 119.7 | 180.0 | 191.5 | 138.4 |
| ICSA 12A x MZ 2R | 198.2 | 105.7 | 118.3 | 118.9 | 178.8 | 190.2 | 137.5 |
| ICSA 21A x SDS 6013R | 197.7 | 105.4 | 118.0 | 118.6 | 178.4 | 189.8 | 137.1 |
| ICSA 21A x MZ 2R | 188.3 | 100.5 | 112.4 | 113.0 | 169.9 | 180.8 | 130.6 |
| TX 628A x MZ 37R | 188.2 | 100.4 | 112.4 | 112.9 | 169.8 | 180.7 | 130.5 |
| 8601A x SDS 6013R | 185.8 | 99.1 | 110.9 | 111.5 | 167.6 | 178.4 | 128.9 |
| ICSA 19A x MZ 2R | 183.7 | 98.0 | 109.7 | 110.2 | 165.8 | 176.4 | 127.4 |
| ICSA 21A x MZ 37R | 178.6 | 95.2 | 106.6 | 107.2 | 161.1 | 171.4 | 123.9 |
| ICSA 12A x IS 14257R | 175.9 | 93.8 | 105.0 | 105.5 | 158.7 | 168.9 | 122.0 |
| TX 628A x SDS 6013R | 152.4 | 81.3 | 91.0 | 91.4 | 137.5 | 146.3 | 105.7 |
| Error MS | 5288.8 | 1504.5 | 1885.2 | 1904.1 | 4305.6 | 4874.4 | 2544.7 |
| Critical Value of Studentized Range | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 |
| Minimum Significant Difference | 94.3 | 50.3 | 56.3 | 56.6 | 85.1 | 90.5 | 65.4 |

SH-Standard Heterosis, Checks = Macia and Sima, P2 = IS 14257R, P4 = MZ 37R and P5 = LARSVYT 46A

## 5.4. Discussion

### 5.4.1. Grain yield performance and genotype superiority

From the results, it was observed that, in general, the grain yield for the hybrids involving testers MZ 37R and SDS 6013R was higher than those involving testers IS 14257R and MZ 2R. However, the same hybrids involving IS 14257R were ranked in third and fifth position of the top ten high yielding hybrids across the environments. This suggests that the two testers IS 14257R and MZ 2R were more adapted to those environments. The contribution of the four testers to grain yield of the top ten hybrids was between 11 and 35% yield increase than the trial mean (data not shown). Among the top 10 hybrids, four were crosses with tester IS 14257R, three with SDS 6013R, two with MZ 37R and one with MZ 2R, but the superiority over the trial mean were 35% from MZ 37R, 23% from SDS 6013R and IS 14257R each and 13% from MZ 2R. The magnitude of GCA effects of the testers suggested that IS 14257R was the best tester for yield improvement although MZ 37R demonstrated superiority over the other testers in contributing to grain yield increase. These results align with the findings of Mindaye *et al.* (2016) where using adapted and non-adapted groups of sorghum hybrids for increased productivity  revealed hybrids that were superior to local checks by 10 and 52% for grain yield. According to Farshadfar *et al.* (2012), genotypes with high mean yield across tested environments are regarded as ideal genotypes. For the secondary traits, hybrids involving IS 14257R performed better for days to 50% flowering, MZ 2R and Macia for plant height, MZ 2R and SDS 6013R for panicle length, MZ 37R and IS 14257R for number of tillering plants, SDS 6013R and MZ 2R for number of panicles. In a study by Thakare *et al.* (2014) involving line x tester crosses, plant height showed a high significant contribution to grain yield. In addition, in this current study, analysis of the environments showed that environments Map17, Sus17 and Sus16 had the highest yield performance. This implies that Mapupulo and Sussundenga locations could be used to identify potentially high yielding hybrids, but additional testing is needed.

Among the three diseases observed, rust was the most severe disease followed by *Cercospora spp* and anthracnose. The checks Macia and Sima had moderate reaction (MR) to anthracnose and *Cercospora spp* but Macia showed susceptibility to rust. The hybrids classified as resistant to rust were ICSA 12A x MZ 2R, ICSA 12A x SDS 6013R and TX 631A x SDS 6013R, while moderately resistant were LARSVYT 46A x IS 14257R, LARSVYT 46A x SDS 6013R and 8601A x MZ 37R. For *Cercospora spp,* most of the hybrids were classified as resistant to moderately resistant whereas for anthracnose, all hybrids were classified as resistant. This suggested that the source of resistance to anthracnose and *Cercospora spp* were from the parents. Similar results were found by Wang *et al.* (2006) where accessions from South Africa and Mali showed high resistance to anthracnose. Although rust disease itself has insignificant effects on sorghum grain yield (Wang *et al.*, 2006), it can predispose plants to other major diseases. Deployment of resistance to anthracnose has been used to control the disease in many hybrids and lines (Frederiksen, 2000). Although the weather conditions were favorable for disease development and spread, further studies using artificial inoculation are recommended.

### 5.4.2. Combining ability effects

The GCA mean squares for testers were significant to highly significant for grain yield, days to 50% flowering, plant height and biomass but not significant for panicle length, number of panicles, *Cercospora spp*, rust and anthracnose. Traits with significant GCA effects were influenced by additive gene action, and breeding progress could be achieved through selection of good parents (Makanda *et al.*, 2010). The interaction of line x tester with the environment was highly significant except for *Cercospora spp*. It also suggests that the hybrids performed differently for the same trait in a different environment. These findings are important for the breeding strategy especially in breeding for specific adaptation. Therefore, grain yield could be improved using methods such as hybridization or pure line selection when SCA is important (Reddy *et al.*, 2008b).

The testers were highly significant for days to 50% flowering, plant height, panicle length and biomass but not significant for grain yield. Significant GCA mean squares for number of tillering plants, number of panicles, *Cercospora spp*, rust and anthracnose were also observed. Significant GCA effects suggested the importance of additive genetic variance for the expression of the traits. Tadesse *et al.* (2008) found similar results of additive genes controlling plant height while Kenga *et al.* (2004) reported additive genes for both plant height and flowering days. Days to 50% flowering were highly significant with negative GCA effects in testers IS 14257R and MZ 37R, while plant height was significant with a negative GCA effect in tester SDS 6013R. The other traits did not show any significant GCA effects. Parents with significant positive GCA effects might be valuable for integration of delayed maturity when needed. A positive direction for selection was desirable for grain yield and panicle length and negative for days to 50% flowering, plant height, number of tillering, plants disease scores and biomass. The GCA effects in the desired direction deliver support in a selection system and parents having greater GCA in the desired direction for traits of interest can be selected for further hybridization and assessment programmes (Tariq *et al.*, 2014). The lines with significant positive GCA effects for grain yield were LARSVYT 46A, SPL 38A and TX 631A while 8601A, ICSA 21A and TX 628A which showed significant negative GCA effects. For plant height, lines TX 631A, ICSA 12A, ICSA 21A and TX 628A were significant for SCA effects. For panicle length, lines LARSVYT 46A, SPL 38A and TX 631A showed positive significant GCA effects while the negative but significant GCA effects were obtained for the lines 8601A, ICSA 19A, ICSA 21A and ICSA 12A. The undesirable GCA effect direction for number of tillering plants (positive) was shown by line ICSA21A and the effect was highly significant. In the opposite direction, significant GCA effects were recorded for line SPL 38A. Negative and significant GCA effects for disease scores were found in lines ICSA 12A and TX 631A for rust disease and other lines had positive GCA effects values for other diseases. A significant interaction amongst the environment and GCA (testers) for all traits indicated the differences between the genotypes in environment responses for these traits while significant GCA (lines) indicated that genotype were more constant in expression over environments (Kenga *et al.*, 2005). These results also indicated the importance of the yield components during the yield assessment for stability and adaptability of genotypes.

SCA mean squares were significant for number of panicles, biomass, days to 50% flowering, plant height, panicle length, number of tillering plants, *Cercospora spp*, rust and anthracnose. This indicated that non-additive gene effects contributed to variation in expression of the traits. Kenga *et al.* (2005) reported that lack of significant SCA mean squares indicate that genes which contributed in variation are additive. For SCA effects, most of the hybrids showed significant effects in the desired direction for each trait (positive or negative). Grain yield showed significant positive SCA effects for the cross TX 631A x MZ 37R (Table 5-7). Other crosses showed negative SCA effects for grain yield. Negative SCA effects for days to 50% flowering were observed in hybrids 8601A x IS 14257R, 8601A x SDS 6013R, ICSA 12A x MZ 2R, TX 631A x IS 14257R and TX 631A x MZ 37R. Most of the hybrids showed significant negative SCA effects for all traits except for number of panicles and biomass. The hybrids LARSVYT 46A x MZ 37R, 8601A x SDS 6013R, TX 628A x SDS 6013R, TX 628A x MZ 37R, ICSA 21A x MZ 2R, ICSA 21A x IS 14257R, ICSA 21A x MZ 37R, ICSA 12A x IS 14257R, CK 60A x IS 14257R, CK 60A x SDS 6013R, TX 631A x MZ 2R and TX 631A x IS 14257R showed significant negative SCA effects for number of tillering plants. While the SCA effects for diseases *Cercospora spp*, rust and anthracnose were not significant except the hybrids LARSVYT 46A x MZ 37R and CK 60A x MZ 2R that showed significant negative SCA effects. None of the best five hybrids with respect to grain yield were early maturing. This trait is usually linked to low yielding in sorghum. Efficient breeding strategies should be effective to improve grain yield and earliness by exploiting superior high yield and earl maturity hybrids (Hayes and Rooney, 2014). The non-additive gene action for grain yield indicates that when high yielding improved lines are selected, then additional yield improvement might be achieved in a hybrid programme (Singhania, 1980).

The significance of GCA and SCA mean squares for the lines and testers is an indication of the importance of both additive and non-additive gene action in controlling the expression of the various traits. Performance of the hybrids across the six environments was also different. This might be due to differences in trial management as well as differences in soil moisture and rainfall at each site and season. Chapman *et al.* (2000) have reported similar factors causing complication of genotype x environment interaction of sorghum hybrids over location and years. High yielding lines and testers may appear as poor combiners for hybrid development and this behaviour could be from intra and/or inter allelic interaction of genes concerned with the character (Dabholkar, 1999). This explains why not all superior hybrids had parents showing good per se performance in respect of the concerned characteristic. In addition, Tariq *et al.* (2014) explained that the mean performance of the parents and their hybrids is assumed to be one of the important features for their evaluation and parents with high mean values may or may not convey their high performance to their hybrids. This performance over the parents may be either over-dominance at some quantitative trait loci (QTL) involved in the traits and/or there may be some dominance, not necessarily complete but with the increasing alleles disseminated to some extend between the two parents (Mackay, 2011).

The correlation between the performance of the parents (GCA) and hybrids (SCA) was significant for some traits and not significant for other traits. Correlation coefficients among GCA and SCA effects were significant for grain yield, days to 50% flowering, plant height, panicle length, number of tillering plants and the diseases. For GCA effects, significant and positive correlation between grain yield and number of tillering plants (r=0.69) and between number of tillering plants and panicle length (r=0.64) were observed. This revealed that number of tillering plants and panicle length had minor but significant contribution to grain yield. Smith (1986) explained that the correlation between the line per se and testcross performance are expected to be less than 0.5 due to masking effects of favourable dominant alleles in the tester. Additionally, panicle length was strongly associated with the number of tillering plants existing in a plot. Similar results were reported where panicle length exhibited the least association with grain yield (Ezeaku and Mohammed, 2006). A significant but negative correlation between *Cercospora spp* and rust diseases were observed. Therefore, depending on the environmental conditions, an increase in one disease could reduce the impact of the other disease. SCA effects showed significant and positive correlations between grain yield and panicle length, as well as grain yield and number of tillering plants. In addition, a significant and positive correlation between panicle length and number of panicles was also observed. It suggests that the contribution of these traits to grain yield should be considered simultaneously when selecting for yield improvement in sorghum. The relationship among the traits may differ from environment to environment as Heinrich *et al.* (1983) indicated that the environment is an important factor affecting yield and its components.

### 5.4.3. Estimates of heterosis

The combination of cytoplasmic male sterile lines with cytoplasmic male fertile lines produced hybrids that exhibited higher mean grain yield compared to the high parent grain yield and best check. These results revealed the potential to increase sorghum productivity of hybrids resulting from crosses involving locally adapted genotypes. Across the environments, hybrids showed superior grain yield over the parents and checks. This superiority was also reported by Mindaye *et al.* (2016) and Kenga *et al.* (2005) in crosses involving male sterile lines and restorer lines. The highest amount of heterosis over the mid-parent was observed in hybrid TX 631A x MZ 37R. The highest amount of heterosis over the mid-parent observed in the hybrids revealed the genetic potential of the involved lines in breeding for grain yield improvement. Hayes and Rooney (2014) reported a high grain yield potential of parental lines in six black sorghum hybrids that performed 172% more than parents. The significant combining ability for the lines showed that additive genes were more important than non-additive genes for most of the traits, suggesting a preliminary selection of the parents that produce hybrid combinations having wide and/or specific adaption to different environments would be possible. Similar results have been reported by Premalatha *et al.* (2006), where estimates of GCA and SCA indicated presence of both additive and non-additive gene action for all traits under study. The hybrid with significant and positive SCA effects for grain yield also had high heterosis level for the same trait. Significant positive heterosis was also associated with higher SCA effects in most of the hybrids (Umakanth *et al.*, 2012). The exploitation of heterosis might be one of the possible methods for improvement of grain yield in sorghum (Premalatha *et al.*, 2006).

Among the lines, TX 631A, ICSA 12A and SPL 38A performed well for most of the characters compared to mid parent heterosis. On the hand, MZ 37R and IS 14257R testers had better performance and exhibited high levels of heterosis for most of the characters that contribute to grain yield. Premalatha *et al.* (2006) suggested that heterosis over the check or local variety could be considered as the best criteria for evaluation of hybrids.

## 5.5. Conclusion

The testers IS 14257R and MZ 37R had desired GCA effects for grain yield and days to 50% flowering while lines LARSVYT 46A, SPL 38A and TX 631A had desired GCA effects for grain yield. Lines 8601A, ICSA 12A, TX 631A and LARSVYT 46A had desired GCA effects for days to 50% flowering. For plant height, lines TX 631A, ICSA 12A, ICSA 21A and TX 628A had desired GCA effects while for panicle length, lines LARSVYT 46A, SPL 38A and TX 631A had desired GCA effects. The lines ICSA 12A and TX 631A showed desired GCA effects for rust disease. The hybrid with highest average of grain yield across environments was TX 631A x MZ 37R followed by SPL 38A x SDS 6013R and LARSVYT 46A x IS 14257R. The early maturing hybrids were TX 631A x IS 14257R, 8601A x IS 14257R and Macia (check). None of the checks were ranked in the top 10 genotypes for grain yield. The hybrids resistant to rust were ICSA 12A x MZ 2R, ICSA 12A x SDS 6013R and TX 631A x SDS 6013R, while moderately resistant hybrids were LARSVYT 46A x, IS 14257R, LARSVYT 46A x SDS 6013R and 8601A x MZ 37R. The parents involved in these crosses can be used as sources of resistance in future breeding programmes.  The heterosis over the mid-parent and over best check ranged from 52 to 194% and 5 to 76%, respectively. The parents IS 14257R, MZ 37R and LARSVYT 46A were selected for grain yield. The hybrids containing the selected testers or lines exhibited high levels of heterosis whereas lines TX 631A and 8601A combined with tester MZ 37R displayed level of heterosis of 182% and 148% respectively. The line LARSVYT 46A exhibited heterosis of 141% when combined with tester IS 14257R.

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# 6. Influence of genotype x environment interaction on grain yield performance of sorghum genotypes across lowlands and midlands of Mozambique

## Abstract

For an efficient selection of desirable genotypes, genotype by environment interaction components have to be understood, after which they can either be ignored, minimized or exploited. Therefore, it is essential for plant breeders to study the genotype by environment interactions during development and selection of improved varieties. The present study evaluated grain yield adaptability and stability of sorghum hybrids to identify the best performing genotypes across and within specific environments using the genotype, genotype by environment (GGE) biplot analysis. A total of 38 entries, which included 36 experimental hybrids and 2 checks were evaluated across six test environments during 2015/16 and 2016/17 seasons, with three replications in each environment. The experimental hybrids were generated in a Line x Tester mating design involving nine cytoplasmic male sterile (CMS) lines and four restorer lines. In addition, the 13 parents were also evaluated. The hybrid main effects and hybrid x environment interactions for grain yield were highly significant ($P<0.001$) indicating differences among hybrids and environments. Although checks performed well in some environments, their potential yields were lower compared to the experimental hybrids (1.23 $t.ha^{-1}$ and 2.63 $t.ha^{-1}$, respectively). Based on the mean performance and stability P12 (CK 60A) and P5 (LARSVYT46A) were the high yielding and stable parents whereas the hybrids GS9 (SPL 38A x MZ 2R), GS36 (TX 631A x MZ 37R), GS1 (LARSVYT46A x MZ 2R) and GS34 (TX 631A x IS 14257R) were high yielding and stable. Hybrids GS9 and GS36 showed general adaptation across environments while GS2 (LARSVYT46A x IS 14257R), GS11 (SPL 38A x SDS 6013R), GS38 (SIMA), GS7 (8601A x SDS 6013R), GS32 (CK 60A x MZ 37R) had specific adaptation to different environments. The recommended environment for testing new genotypes were Mapupulo and Sussundenga where LARSVYT46A x IS 14257R is recommended for Mapupulo and SPL 38A x SDS 6013R for Sussundenga. These results will assist the breeder in recommending hybrids according to performance and adaption as well as selection of the best environment to test new genotypes.

## 6.1. Introduction

In Mozambique, agriculture plays a vital role in the development of the country and is one of the pillars for economic growth. According to USAID (2017), agriculture remains the backbone of Mozambique's economy, employing more than 80% of its labour force and contributing more than a quarter of its GDP. The existing vast potential for crop production makes the country suitable for farming and for improved agricultural productivity. Unfortunately, farmers are still using unimproved varieties that are low yielding and susceptible to adverse effects of climate changes. Sorghum is amongst the crops grown for food security by families in smallholder farms. The crop responds well to a wide range of environments (Machado and Paulsen, 2001), and it has considerable potential to be used as both human food and a beverage source (Reddy *et al.*, 2012). It is also an important source of nutraceuticals such as antioxidants, phenolics and cholesterol-lowering waxes (Taylor *et al.*, 2006). In terms of production, grain yield remains the most important trait considered by farmers (Reddy *et al.*, 2012).

Sorghum has potential for heterosis for grain yield which can be exploited for hybrid development. According to a study by Ashok Kumar *et al.* (2011), new hybrid varieties gave 30-40% heterosis for grain yield compared to the best hybrid checks under rainfed conditions. Therefore, for the plant breeder it is essential to study the genotype x environment interactions (GEI) effects on grain yield during the development of improved varieties. Mohammadi and Amri (2008) reported that the identification of superior genotypes is complicated by genotype by environment interactions. Although several statistical methods facilitate interpretation of the GEI, very few explain adequately the genotype performance across environments. Eberhart and Russell (1966) suggested that the means to reduce GEI was to use genetic mixtures rather than homogeneous or pure lines. In contrast, other researchers found that evaluation based on several years and locations is a good strategy to pursue in breeding under varying environments (Mohammadi and Amri, 2008; Dehghani *et al.*, 2013). Selection for high yielding and stable genotypes requires a preliminary evaluation that ranks varieties according to their adaptation. Evaluation of potential genotypes from crosses is the first step before implementation of selection.

Different procedures have been developed to evaluate crop adaptability and stability. These procedures are based on analysis of variance, multivariate analysis, linear regression, non-linear analysis and biplot analysis. There are several approaches for analysis and interpretation of GEI based on biplots. However, the additive main effects and multiplicative interaction (AMMI) analysis was found to be the most useful because of the larger number of practical explanations it provides (Duarte and Vencovsky, 1999) compared to other methods.

Additionally, Yan *et al.* (2000) proposed a modification on the conventional AMMI analysis and called it GGE biplot (genotype and genotype-environment interaction) analysis. The advantage of GGE biplot analysis over AMMI analysis lies in the fact that biplots explain an intermediate fraction of sum of squares of genotypes + genotypes by environments (G + GE), making the graphical illustration more accurate and more practical (Yan *et al.*, 2007). Sibiya (2009) compared the two methods and found AMMI and GGE biplot analysis to depict similar results for maize hybrid selection. On the other hand, Balestre *et al.* (2009) found GGE2 biplot being superior to AMMI1 and graphical accuracy was higher in representing the proportion of G + GE. On other hand, Ma *et al.* (2004) suggested that GGE biplot stands for genotype main effects plus GEI and it was confirmed by Yan *et al.* (2007) that GGE biplot had many visual interpretations than AMMI, including the visualization of crossover GEI. Therefore, for this study, GGE biplot was selected to analyze and interpret the genotype by environment interaction for experimental hybrids across several environments in Mozambique. The aims of the present study were to evaluate the grain yield adaptability and stability of sorghum hybrids and to identify the best performing genotypes across environments and in specific environments using the GGE biplot methodology.

## 6.2. Materials and Methods

### 6.2.1. Plant materials

Thirteen sorghum genotypes used as parents in this study were obtained from the Sorghum National Programme but were originally bred by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). The two standard checks used during evaluation are varieties widely used in the country with high grain yield performance and stability. The parent lines were divided into two groups; nine cytoplasmic male sterile (CMS) designated as females and four cytoplasmic male fertile (CMF) as males (Table 6-1).

Table 6-1 Parental material used in the line by tester crossing block to develop the sorghum hybrids

| Line | Group | Designation | Parent code | Origin |
|---|---|---|---|---|
| LARSVYT 46A | Line | Female | P5 | NAR/ICRISAT |
| 8601A | Line | Female | P6 | NAR/ICRISAT |
| SPL 38A | Line | Female | P7 | NAR/ICRISAT |
| ICSA 19A | Line | Female | P8 | NAR/ICRISAT |
| TX 628A | Line | Female | P9 | NAR/ICRISAT |
| ICSA 21A | Line | Female | P10 | NAR/ICRISAT |
| ICSA 12A | Line | Female | P11 | NAR/ICRISAT |
| CK 60A | Line | Female | P12 | NAR/ICRISAT |
| TX 631A | Line | Female | P13 | NAR/ICRISAT |
| IS 14257R | Tester | Male | P2 | NAR/ICRISAT |
| SDS 6013R | Tester | Male | P3 | NAR/ICRISAT |
| MZ 2R | Tester | Male | P1 | NAR |
| MZ 37R | Tester | Male | P4 | NAR |

*NAR = National Research Sorghum Programme;

### 6.2.2. Line x tester crosses and field evaluation sites

The nine females and four male lines were crossed in a line x tester mating scheme to produce 36 experimental hybrids at Sussundenga Research Station. The 36 experimental hybrids along with two check hybrids were grown for evaluation in six test environments (combination of year-location) during 2015/16 and 2016/7 seasons (Table 6-2). The thirteen parents were also evaluated in four test environments during the same seasons (designated with an asterisk in Table 6-2).

### 6.2.3. Evaluation sites

The trials were conducted at four sites in Mozambique: Chókwè, Maniquenique (South), Sussundenga (Central), Mapupulo (North). These locations covered from low to mid-altitude mega-environments. Table 6-2 summarizes the geographic locations of each of the sites used and their annual average rainfall.

Table 6-2 Locations used for evaluation of parents, hybrids and checks

| Location | Season | Code | Latitude (ºS) | Longitude (ºE) | Altitude (m) | Rainfall[*] (mm) |
|---|---|---|---|---|---|---|
| Sussundenga** | 2015/16 | Sus16 | 19º18’ | 33º15’ | 635 | 522 |
| Chókwè** | 2015/16 | Chk16 | 24º52’ | 33º00’ | 33 | 380 |
| Sussundenga** | 2016/17 | Sus17 | 19º18’ | 33º15’ | 635 | 989 |
| Chókwè** | 2016/17 | Chk17 | 24º52’ | 33º00’ | 33 | 650 |
| Maniquenique | 2016/17 | Man17 | 24º73’ | 33º53’ | 13 | 468 |
| Mapupulo | 2016/17 | Map17 | 13º19’ | 38º86’ | 534 | 1050 |

[*] Rainfall refers to the amount received during the crop growing season, ** Parents included at these sites only

### 6.2.4. Experimental design

The experimental layout in each environment was a 19 x 2 alpha lattice design with three replications. Each plot consisted of two rows that were 5 m long with a spacing of 0.75 m inter-row spaced 0.25 m between plants. A blended NPK (12-24-12) fertilizer was applied at a rate of 250 kg ha$^{-1}$ (basal application) at planting. Urea (46% N) was applied as a top dressing at a rate of 150 kg ha$^{-1}$ at 30 days and a week before flowering. Other cultural practices such as ploughing, disking, hand planting, hand weeding and herbicides application were carried out at each site.

### 6.2.5. Data analysis

Combined data were analysed using PROC GLM procedure in SAS 9.3 (SAS, 2011). ANOVA was performed separately for each environment with genotypes as the main effect, then a combined analysis across environments was conducted to evaluate the effect of years, genotypes, and environments and their interactions. Genotype means were ranked and compared using Tukey test at 5% probability level.

Adjusted harvest grain yields were calculated according to CIMMYT (1985):

Grain yield (t.ha$^{-1}$) = [Grain weight (kg/plot) x 10 x (100-MOI)/ (100-12.5) / (Plot Area)]

### 6.2.6. GGE biplot analysis

The GGE biplot analysis was performed using GenStat 14 (Payne *et al.*, 2011) and R software (R Team, 2014). This method is based on the principal component analysis (PCA) to effectively explore the multi-environment trial data (Yan *et al.*, 2000; Farshadfar *et al.*, 2012).

The following model for GGE biplot based on singular value decomposition (SVD) of first two principal components was used (Yan and Tinker, 2006):

$$Y(ij) - \mu - \beta_i = \kappa_1 \lambda_{i1} \xi_{j1} + \kappa_2 \lambda_{i2} \xi_{j2} + \varepsilon_{ij}$$

Where: $Y_{ij}$ = Yield mean of $i^{th}$ genotype in $j^{th}$ environment; μ = grand mean; $\beta_j$ = main effect of environment j; $\mu + \beta_j$ = mean yield across all genotypes in environment j; $\kappa_1$ and $\kappa_2$ = singular values (SV) for the first and second Principal component (PC1 and PC2), respectively, $\lambda_{i1}$ and $\lambda_{j2}$ = eigen vectors of hybrid i for PC1 and PC2, respectively, $\xi_{i1}$ and $\xi_{i2}$ = eigen vectors of environment j for PC1 and PC2, respectively, $\varepsilon_{ij}$ = residual associated with genotype i in environment j.

## 6.3. Results

The results from the analysis of variance of grain yield across six test environments showed that the main effects of the genotypes, environment and their interaction were highly significant ($P<0.001$, Table 6-3). The means for the parents and hybrids were 1.23 $t.ha^{-1}$ and 2.63 $t.ha^{-1}$ respectively. The environment effect was highly significant ($P<0.001$). Yields ranged from 7.1 $t.ha^{-1}$ to 0.51 $t.ha^{-1}$ and the environment with highest grain yield was Map17 and Sus17, while Man17 and Chk16 had the lowest yields.

Table 6-3 Analysis of variance for grain yield of hybrids and parents tested across six environments

| Source | DF | Type III SS | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Hybrids | | | | | |
| Environment | 5 | 852.338659 | 170.4677318 | 357.21 | <.0001 |
| BLK(REP*Env) | 30 | 16.227678 | 0.5409226 | 1.13 | 0.2898 |
| ENTRY | 37 | 53.8708812 | 1.4559698 | 3.05 | <.0001 |
| Hybrids | 35 | 53.1202041 | 1.5177201 | 3.08 | <.0001 |
| ENTRY*Env | 185 | 277.258879 | 1.4986966 | 3.14 | <.0001 |
| Env*Hybrids | 175 | 257.467671 | 1.4712438 | 2.99 | <.0001 |
| Error | 426 | 203.293122 | 0.477214 | | |
| Corrected total | 683 | 1406.23541 | | | |
| Parents | | | | | |
| Environment | 3 | 24.9563436 | 8.3187812 | 143.46 | <.0001 |
| BLK(REP*Env) | 8 | 1.03171795 | 0.12896474 | 2.22 | 0.032 |
| Parent | 12 | 13.7083359 | 1.14236132 | 19.7 | <.0001 |
| Env*Parent | 36 | 3.72435641 | 0.10345434 | 1.78 | 0.0136 |
| Error | 96 | 5.56661538 | 0.05798558 | | |
| Corrected Total | 155 | 48.9873692 | | | |
| Means | | | | | |
| Hybrids | | | 2.63 | | |
| Parents | | | 1.23 | | |

### 6.3.1. Genotype ranking within and across test environments

The ranking of the top 15 hybrids and two checks based on the mean grain yields within and across environments is presented in Table 6-4. The hybrids that appeared in more than 2 environments in the top 15 were GS36 (5 env), GS32 (5 env), GS14 (4 env), GS11 (4 env), GS3 (4 env), GS6, GS8, GS10, GS22, GS31, GS33, GS34 and GS35. The other two hybrids appeared in two environments (GS5 and GS30). The checks appeared in only one (MACIA) and two (SIMA) environments. Hybrid GS36 had an average mean grain yield of 3.68 t.ha$^{-1}$ in five environments followed by GS8 with 3.57 t.ha$^{-1}$ in two environments consecutively. These hybrids were followed by GS1 (4 env) with 3.13 t.ha$^{-1}$ and GS34 (3 env) yielding 3.02 t.ha$^{-1}$. The yield of the other hybrids ranged from 2.84 t.ha$^{-1}$ (5 env) to 1.5 t.ha$^{-1}$ (3 env).

Table 6-4 Ranking of the top 15 hybrids based mean grain yield across environments

| Rank | Sus 15/16 | Chk 15/16 | Man 16/17 | Sus 16/17 | Chk 16/17 | Map 16/17 | Overall (mean yield- t.ha$^{-1}$) |
|---|---|---|---|---|---|---|---|
| 1 | GS36 | GS15 | GS4 | GS36 | GS27 | GS2 | GS36 (2.76) |
| 2 | GS11 | GS3 | GS32 | GS18 | GS32 | GS3 | GS8 (2.52) |
| 3 | GS3 | GS4 | GS33 | GS38 | GS36 | GS1 | GS11 (2.51) |
| 4 | GS8 | GS7 | GS23 | GS8 | GS29 | GS36 | GS34 (2.43) |
| 5 | GS5 | GS9 | GS31 | GS7 | GS6 | GS34 | GS10 (2.40) |
| 6 | GS32 | GS25 | GS34 | GS28 | GS13 | GS9 | GS3 (2.38) |
| 7 | GS14 | GS16 | GS36 | GS27 | GS14 | GS37 | GS31 (2.35) |
| 8 | GS1 | GS35 | GS13 | GS22 | GS35 | GS17 | GS32 (2.34) |
| 9 | GS10 | GS14 | GS10 | GS2 | GS28 | GS10 | GS5 (2.31) |
| 10 | GS33 | GS6 | GS22 | GS16 | GS4 | GS18 | GS14 (2.28) |
| 11 | GS31 | GS2 | GS3 | GS32 | GS30 | GS21 | GS30 (2.15) |
| 12 | GS34 | GS33 | GS9 | GS14 | GS12 | GS11 | GS35 (2.14) |
| 13 | GS30 | GS26 | GS1 | GS31 | GS25 | GS8 | GS33 (2.10) |
| 14 | GS22 | GS23 | GS5 | GS35 | GS15 | GS27 | GS22 (2.09) |
| 15 | GS6 | GS32 | GS38 | GS11 | GS22 | GS29 | GS6 (2.08) |
| Mean(t.ha$^{-1}$) | 1.98 | 0.58 | 1.28 | 2.98 | 1.16 | 3.53 | 1.91 |
| LSD (0.05) | 0.77 | 0.15 | 0.15 | 1.13 | 0.40 | 2.20 | 0.15 |
| MSe | 0.23 | 0.01 | 0.01 | 0.49 | 0.06 | 1.79 | 0.01 |
| CV | 24.01 | 15.00 | 7.05 | 23.54 | 20.22 | 38.00 | 15.51 |
| *P* | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.007 | 0.000 |
| *P* | *** | *** | *** | *** | *** | *** | *** |
| Min | 0.62 | 0.23 | 0.60 | 1.88 | 0.34 | 1.66 | 0.94 |
| Max | 4.67 | 1.41 | 2.64 | 5.14 | 3.05 | 5.68 | 3.58 |

### 6.3.2. Analysis of the parents using GGE biplot

The results of the GGE biplot of grain yield of 13 parents used in the development of hybrids showed that the two PCs explained 100% (PC1 = 81.2% and PC2 = 18.81%) of the variation (Figure 6-1).

#### 6.3.2.1. Relationship among test environments

Environment vectors were drawn from the biplot origin to respective environments. The environments for each location in the two seasons were overlaid showing the similar conditions to the genotypes. The angle between the vectors of two environments showed the correlation between them. A smaller angle less (than 90$^{o}$) showed high correlations and was observed for the four environments (Figure 6-1).

The angle between environments Sus16, Sus17 and environments Chk16 and Chk17 were less than 90$^{o}$ (Figure 6-1). The environments Chk16 and Chk17 were positive and strongly correlated and so were environments Sus16 and Sus17. Additionally, the Chk and Suss locations were positive and strongly correlated.

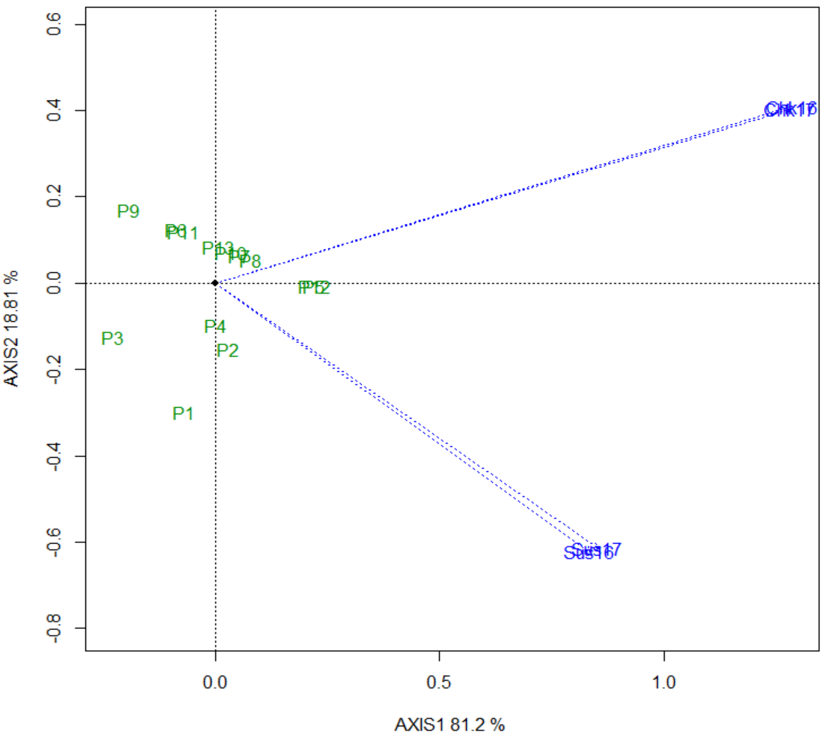

Figure 6-1: GGE biplot based on grain yield (t.ha$^{-1}$) for parents in 4 environments showing the relationship among them.
Where environments are Sus16 = Sussundenga first season; Chk16 = Chókwè first season; Sus17 = Sussundenga second season; Chk 17 = Chokwe second season

### 6.3.2.2. Discriminating ability and representativeness of test environments

The visualization of vector length of the environmental vector is proportional to the standard deviation within the respective environments and it is measures the discriminating ability of the environments. Therefore, all four environments showed good discriminating ability for parents.

Representativeness of a test environment uses the Average Environment Axis (AEA) line that passes through the average environments and the biplot origin (Figure 6-2).

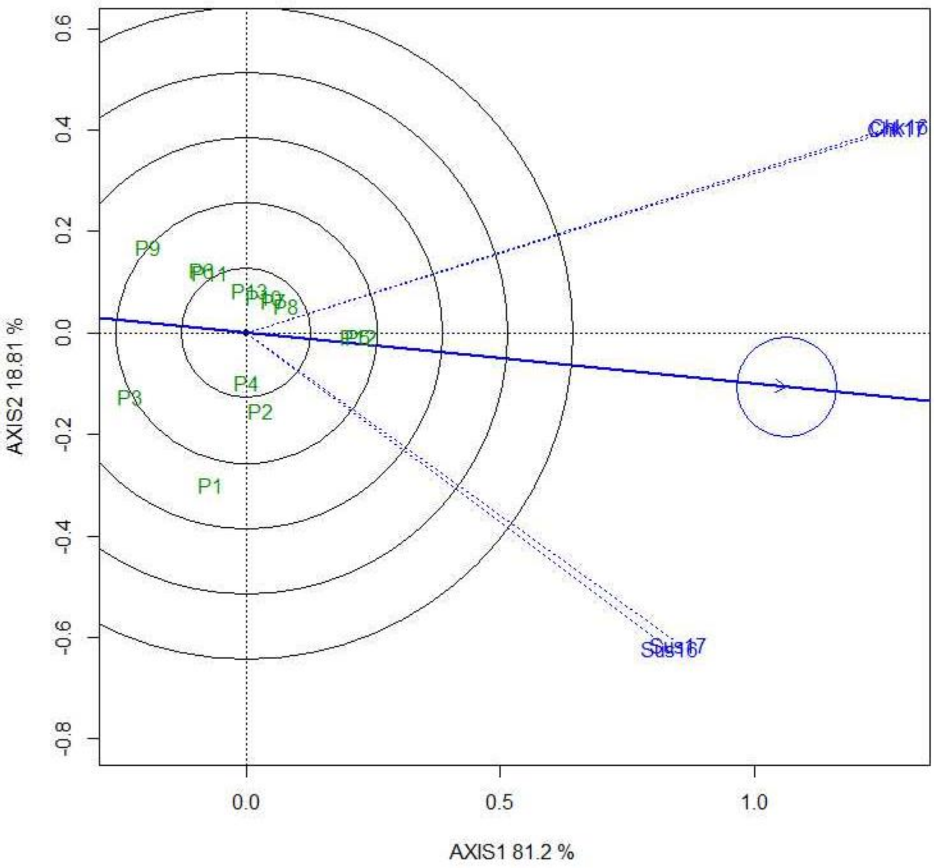

Figure 6-2: The discriminating and representativeness view of the test environments. The environments described in environments were P5 and P12. The other parents (P1, P3 and P9) on the vertex were poor in the test envronments.

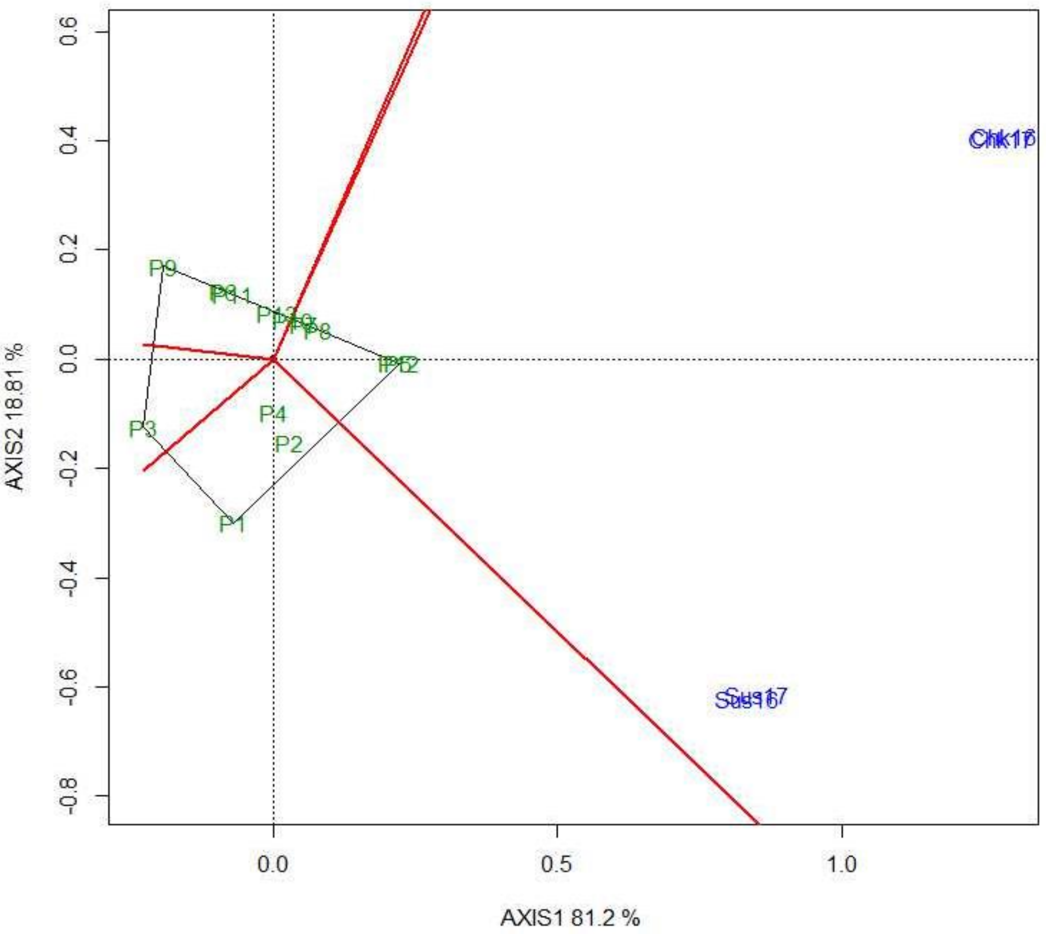

Figure 6-3: Polygon view of the GGE biplot based on grain yield (t.ha-1) for the parents across four environments. The environments are described in Figure 6-1.

Thus Figure 6-2 shows that none of the environments was representative for the parents' selection. Although the environments were discriminating, they were non-representative of the environments. These environments are useful for selecting unstable genotypes because they all fell in a single mega-environment (Figure 6-3).

### 6.3.3. Mega-environment identification and "which-won-where" genotype selection

Figure 6-3 shows a polygon view divided into four sectors based on the rays of the biplot and the four environments were grouped in one sector. Consequently, the results showed the presence of one mega-environment covering all four environments and that P12 and P5 were the best parents in the mega-environment. The vertex for each quadrant represents the parent with the highest or lowest yield in a particular environment. The highest yielding parents in the mega-environments were P5 and P12. The other parents (P1, P3 and P9) on the vertex were poor in the test envronments.

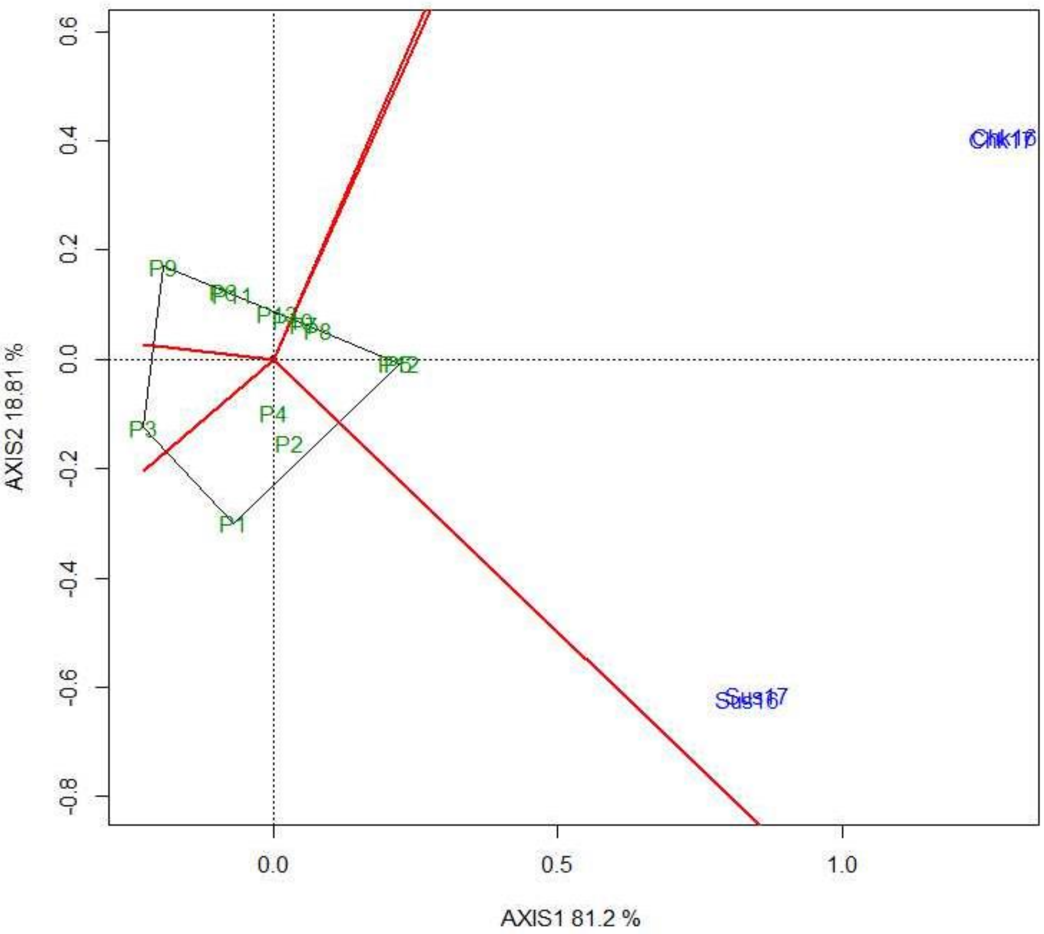

Figure 6-3: Polygon view of the GGE biplot based on grain yield (t.ha$^{-1}$) for the parents across four environments. The environments are described in Figure 6-1.

### 6.3.3.1. Mean performance and stability of the genotypes

The parents that were furthest from the origin in the positive direction of the average environmental coordinate (AEC) and with shortest perpendicular distance from AEC were defined as high yielding and stable (Figure 6-4). The AEC abscissa pointed to higher mean yield across environments. Thus, P12 and P5 had the highest mean yield followed by P8, P7, P2, P4, P10 and P13. For stability, P12 and P5 had the shortest distance from AEC, meaning that they were the most stable parents. The parents P1, P3 and P9 were the worst in terms of yield and stability. Their PC1 values were below zero and had longest vectors from AEC.

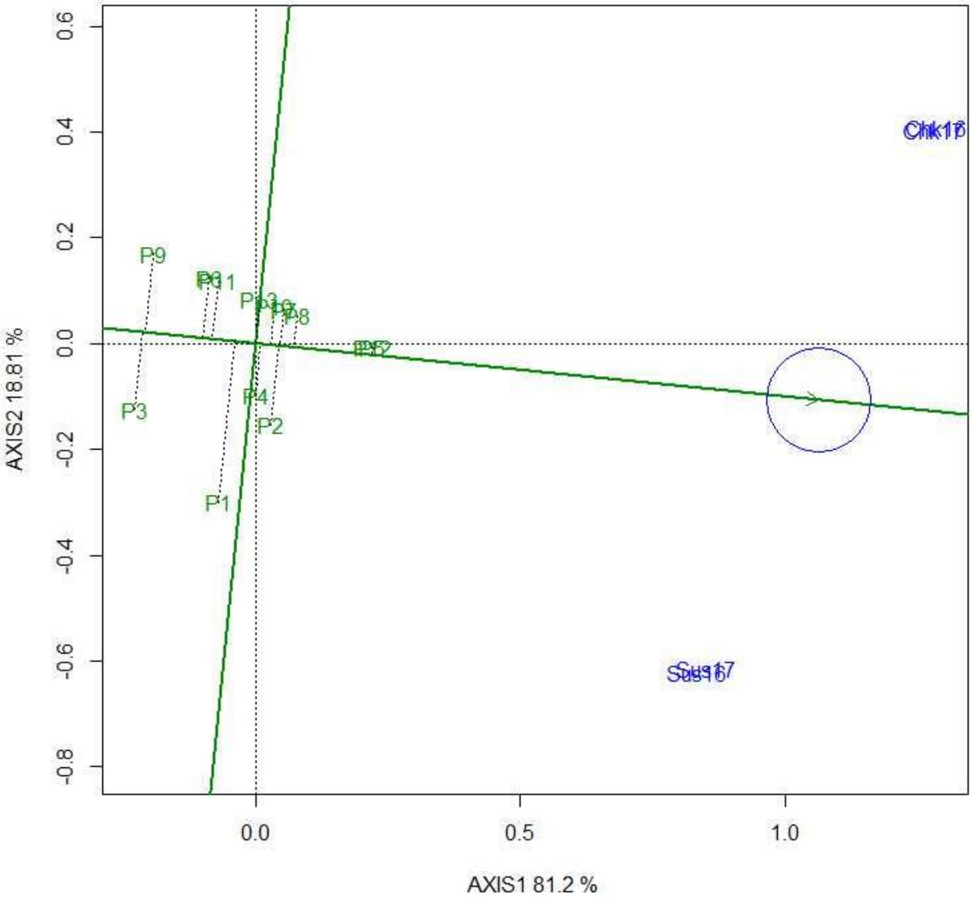

Figure 6-4: GGE biplot based on grain yield (t.ha$^{-1}$) for four environments ranking parents based on both the mean grain yield (t.ha$^{-1}$) and stability. The environments are described in Figure 6-1.

The parents P8, P7, P13 and P10 are located on the line that connects P12 and P9, meaning that the rank was P12 > P5 > P8 > P7 > P13 and P10.

## 6.3.4. Analysis of the hybrids using GGE biplot across locations

### 6.3.4.1. Relationships among test environments

From the analysis of GGE biplot, the first two PCs explained 63.88% (Axis 1= PC1 = 37.11% and Axis 2 = PC2 = 26.77%) of the total GGE variation. The relationships among the environments is shown by vectors drawn from the biplot origin to the environments (Figure 6-5). The environments Map17 and Sus17, Map17 and Sus 16 were positively correlated (acute angle) while Map17 and Man17, Map17 and Chk17 were slightly negatively correlated (obtuse angle). The environments Map17 and Chk16 were not correlated (right angle). The negatively correlated environments provide information of presence of crossover genotype by environment.

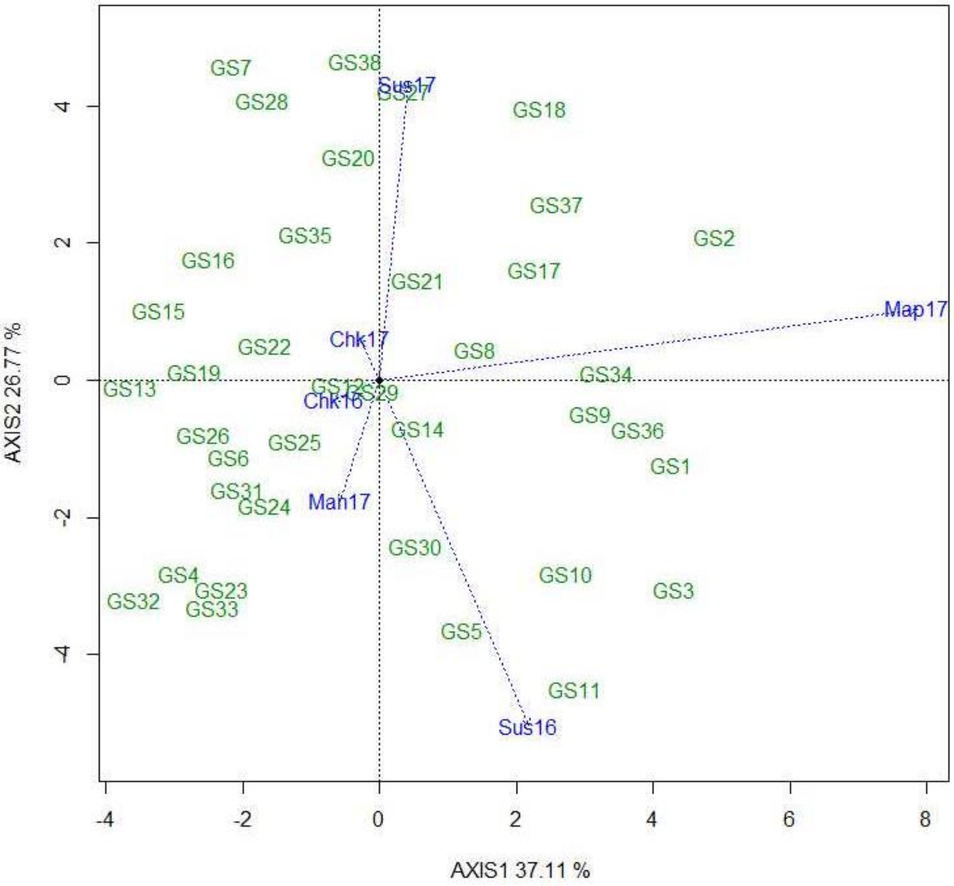

Figure 6-5 Relationships among the environments for hybrids evaluation
Environments are Sus16 = Sussundenga 2015/6; Chk16 = Chókwè season 2015/6; Sus17 = Sussundenga season 2016/7; Chk 17 = Chokwe season 2016/7, Man17 = Maniquineque season 2016/7 and Map17 = Mapupulo season 2016/7.

#### 6.3.4.2. Discriminating ability and representativeness of test environments

Among the six environments, Map17, Sus16 and Sus17 were most discriminating (informative) environments while the least discriminating environments were Chk16, Chk17 and Man17 (Figure 6-6). The result for representativeness of the test environments showed that Map17 was the most representative environment than the others due to the small angle between the environmental vector and AEC. Although Map17 was slightly representative, it was not the best test environment for selecting generally adapted genotypes. The environment Sus16 and Sus17 were discriminating but non-representative.

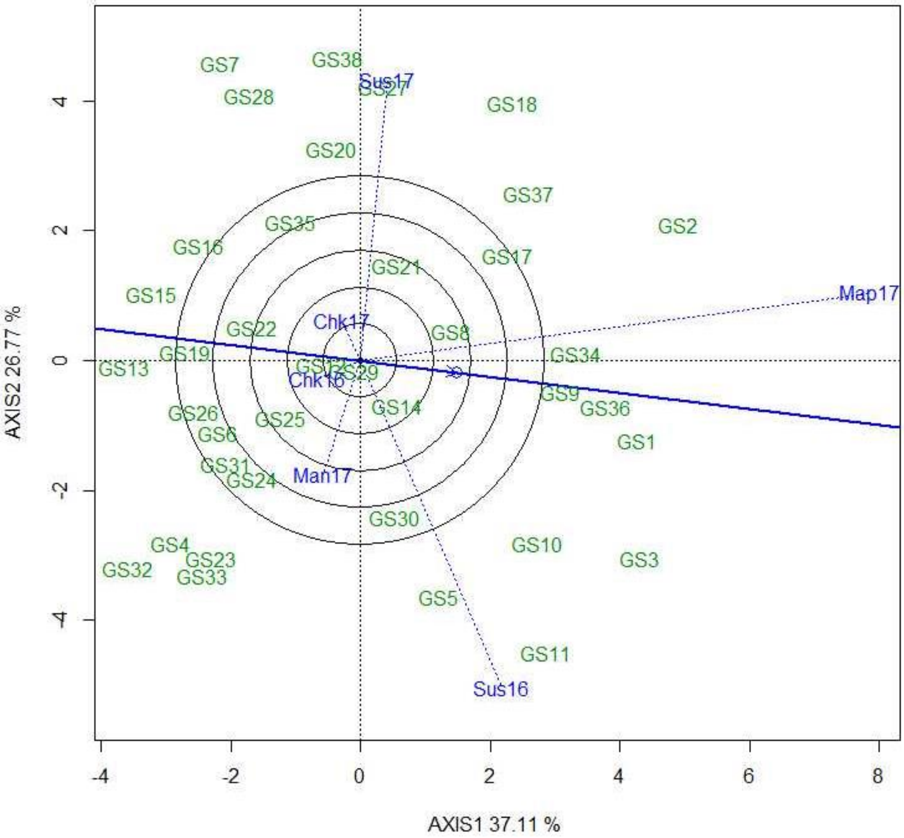

Figure 6-6 The discriminating and representativeness view of the test environments. The environments are described in Figure 6-5

#### 6.3.4.3. Mean performance and stability of the genotypes

High yielding and stable genotypes were found far from the origin and had the shortest vectors from AEC (Figure 6-7). The high yielding hybrids were GS3 and GS2 followed by GS1, GS36, GS11, GS9, GS34 and GS10. The most stable hybrids were GS9 and GS36. The hybrids with high yielding and high stability were GS9, GS36, GS1 and GS34. The hybrids that were unstable although high yielding were GS2, GS3, GS11 and GS10. The low yielding but stable hybrids were GS29, GS12, GS22 and GS19.

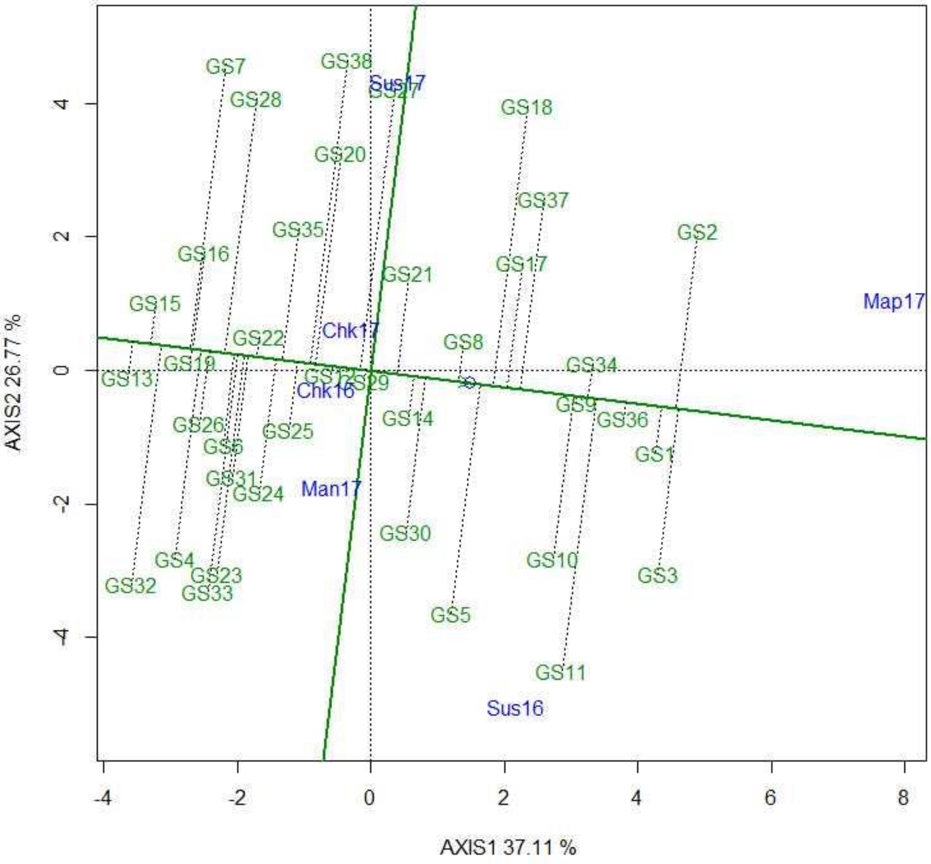

Figure 6-7: GGE biplot based on grain yield (t.ha$^{-1}$) for hybrids performance and stability. The environments are described in Figure 6-5.

### 6.3.4.4. Mega-environment identification and "which-won-where"

Figure 6-8 presents the polygon view biplot of mega-environment classification and the best genotypes based on the rays of the biplot. The rays of the biplot divided the plot into eight sectors. The environments appeared in five sectors. Each environment fell in a different sector except Chk16 and Man17. The winning hybrids for each sector were the ones on the vertex of the environment. The highest yielding hybrid in environment Map17 was GS2 while in Sus16 was GS11. For Sus17, hybrid GS38 was the high yielding and in Chk17 was GS7. The environments Chk16 and Man17 had GS32 as the high yielding genotype. The highest yielding environment was Map17 followed by Sus16 and Sus17. The environments Chk16, Chk17 and Man17 had average yield below the mean.

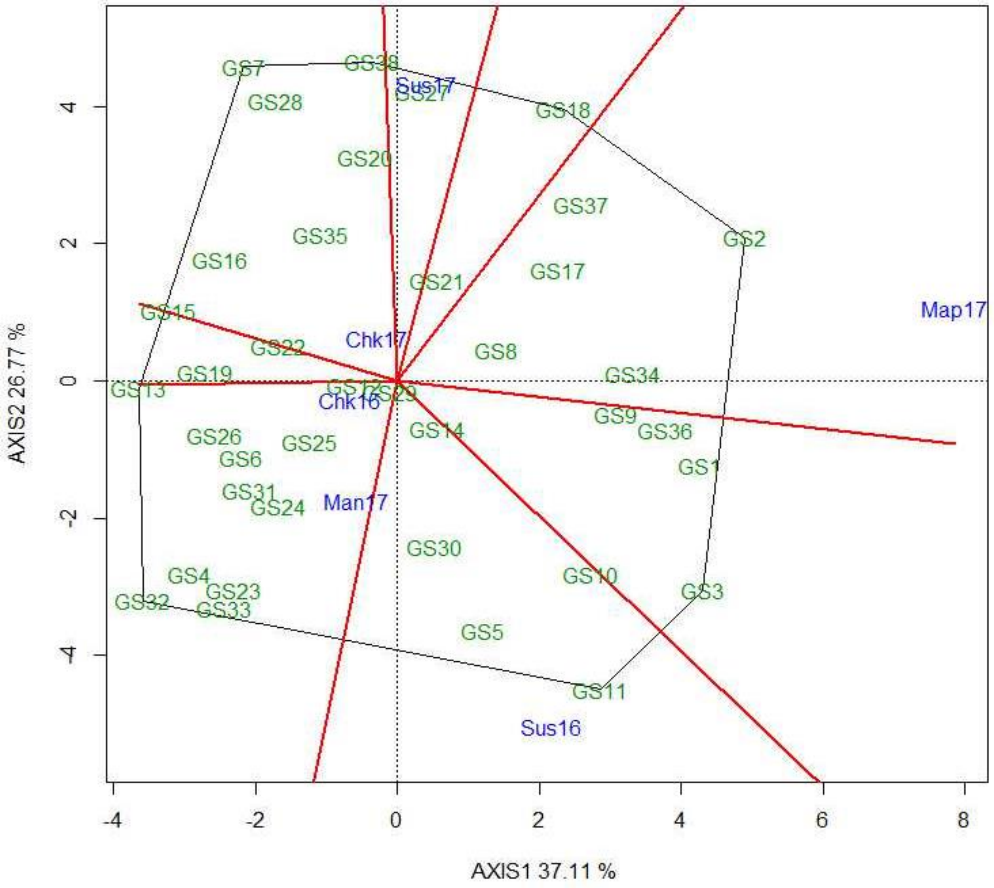

Figure 6-8 Polygon view of the GGE biplot based on grain yield (t.ha$^{-1}$) of 36 hybrids for the mega-environments. The environments are described in Figure 6-5.

## 6.4. Discussion

The hybrids main effects and hybrid x environment interactions for grain yield were significant and showed differences among hybrids and environments. Though checks performed well in some environments, the potential yield was low compared to the hybrids. According to Yan and Rajcan (2002) and Farshadfar *et al.* (2012), the genotype that has high mean yield across test environments and highly stable performance is regarded as the model genotype. This genotype has large PC1 scores (high mean yield) and small PC2 score (high stability) (Akter *et al.*, 2015). Based on the GGE biplot results, the model genotypes for the parents were P12 and P5 followed by P8, P7, P10 and P13. For the hybrids, the model genotypes were GS9 and GS36 followed by GS1 and GS34. These were high yielding and more stable genotypes across the six environments. The other genotypes such as GS29, GS12, GS22 and GS19 were more stable but low yielding across environments. Parent P5 (high yield and stable) was one of the parents for the high yield and stable hybrid GS1. Two of the high yielding parents P7 and P13 were parents of the hybrids that were stable and had high yielding (GS9 and GS34, respectively). None of the tester parents (P1 to P4) was classified as high yielding or stable. However, the high yielding and stable parent P12 and high yielding parents P8 and P10 were not part of any of the high yielding or high yielding and stable hybrids. High yielding parents may appear as poor combiners for hybrid development and this behaviour could be from intra and/or interallelic interaction of genes concerned with the character (Dabholkar, 1999).

The environments Chókwè 16 (Chk16) and Chókwè 17 (Chk17) were positive and strongly correlated, so were environments Sussundenga 16 (Sus16) and Sussundenga 17 (Sus17). This suggested that the seasons were similar in discriminating the parents. It also indicates that in future, evaluation of parents can be done at the two locations in one year/season. The environments Mapupulo 17 (Map17) and Sussundenga 17 (Sus17) and Mapupulo 17 (Map17) and Sussundenga 16 (Sus 16) were positively correlated (acute angle) while Mapupulo 17 (Map17) and Maniquiniqui 17 (Man17), Mapupulo 17 (Map17) and Chókwè 17 (Chk17) were slightly negatively correlated (obtuse angle). The environments Map17 and Chk16 were not correlated (right angle). The slightly negatively correlated environments provide information of presence of crossover genotype by environment. It implies that the genotype by environment was moderately large. GGE biplot analysis was more effective in revealing correlation among treatments in relation to their response to the environment, the correlation among environments, and the crossover genotype by environment interactions (Ma *et al.*, 2004). The presence of strong negative correlations among environments is an indication of a strong crossover genotype by environment (Yan and Tinker, 2006). The presence of close association among test environments suggests that the same information about the genotypes could be obtained from fewer test environments if the two environments are closely correlated consistently across years or seasons. This suggests that additional evaluations are required to confirm the consistency of the environments. Based on the angles of test environment vectors, the six environments were grouped into four groups. In the group including Chókwè 16 (Chk16), Chókwè 17 (Chk17) and Maniquiniqui 17 (Man17), the environments were closely correlated, suggesting that they provided redundant information about genotypes, while Sussundenga 17 (Sus17), Sussundenga 16 (Sus16) and Mapupulo 17 (Map17) were separated by larger angles and could be suitable for evaluation of this set of genotypes using fewer test environments thereby increasing breeding efficiency. The longest vectors were observed for environments Sussundenga 17 (Sus17), Mapupulo 17 (Map17) and Sussundenga 16 (Sus16). The differences in performance of the hybrids in different seasons may be due to the variation in climate, field management, planting date, sowing intensity or depth, or other agronomic practices.

The visualization of the length of the environment vector is proportional to the standard deviation within the respective environments and is a measure of the discriminating ability of the environments. Therefore, all the four environments, were discriminating of the parents. This indicates that the environments provided information about the parents and should be used as test environments. Although the environments were discriminating, they were non-representative environments. Therefore, none of the environments could be considered “ideal environment” for parents’ selection. The ideal environment should be able to differentiate the genotypes and be representative of the target environment. However, this environment might be beneficial to use as a test environment for selecting unstable genotypes. According to Yan and Tinker (2006), in a single mega-environment, the ideal test environment should be most discriminating and also most representative of the target environment. Although Mapupulo 17 (Map17) was slightly representative, indicating that it could be used as a good test environment for selecting generally adapted genotypes. The environment Sussundenga 16 (Sus16) and Sussundenga 17 (Sus17) were discriminating but non-representative, suggesting that they are useful for selecting specifically adapted genotypes. The non-discriminating test environment is less useful because it provides little discriminating information about the genotypes (Yan and Tinker, 2006).

The model environment should be discriminating and representative of important properties of all test environments (Yan, 2001). Presence of GxE interaction confounds the identification of an ideal environment (Yan *et al.*, 2000). According to Akter *et al.* (2015), the test environments should have large PC1 scores to discriminate genotype main effect and absolute small PC2 score in order to represent the overall environments. The model environment for the hybrids was Mapupulo 17 (Map17) because it had a large PC1 score and small PC2 score. Therefore, this environment is more suitable for evaluation of all genotypes because it is stable and high yielding. Besides that, environment, Sussundenga 17 (Sus17) and Sus16 had arge PC2 scores indicating that they contributed most to the GxE interaction and are recommended for studies of stability and adaptability. These two environments were discriminating environments. The most discriminating environment is the one with longest vectors from the biplot origin (Sibiya *et al.*, 2013). Yan *et al.* (2000), also revealed that genotypes showing high PC1 scores (high mean yield) and PC2 scores close to zero (more stable) are considered ideal genotypes. The ideal test environment should have a high PC1 score (genotype discrimination) and PC2 scores close to zero (representative environment) (Yan *et al.*, 2007).

The environments Chókwè 16 (Chk16), Chókwè 17 (Chk17) and Maniquiniqui 17 (Man17) had PC1 and PC2 scores close to zero, indicating good stability although low yielding. This result shows that evaluation in these environments was similar and in future evaluations, it would make sense not to use all of the three environments in order to save resources. Based on the results, the test environments had angles less than 90$^o$ indicating high correlations among them. The environments Chókwè 16 (Chk16), Chókwè 17 (Chk17) and Maniquiniqui 17 (Man17) were more correlated than Sussundenga 17 (Sus17) and Sussundenga 16 (Sus16) and Sussundenga 16 (Sus16) and Mapupulo 17 (Map17). The angles approximately 90$^o$ were found between environment Sus17 and Map17. This indicates that the two environments are less correlated. The angle between the vectors line connecting environments from the biplot origin defines the correlation coefficient between the environments (Kroonenberg, 1995; Akter *et al.*, 2015).

According to Yan et al (2007), genotypes with high yield appeared on the vertices of the polygon. The highest yielding and most stable parents in the mega-environment were P12 and P5. The parents P8, P7, P10 and P13 were also high yielding but less stable than P12 and P5. The parents P1, P3 and P9 were poor in the test environments. Therefore, this suggested that those high yielding parents should be selected and used for the target mega-environment. Yan and Tinker (2006) reported that if the biplot explained a high portion of total variation, the genotypes are truly stable. These estimations were to identify the model/or ideal genotypes across or in a specific environment. According to Yan and Tinker (2006), the pattern of GxE interaction provides a good visualization of multi-environment trials.

The biplot within the polygon view was used for which-won-where and mega environments. Additionally, average environmental coordinate (AEC) was an axis line used to show the ranking of the hybrids and their mean yield and stability. The AEC view in GGE biplot can be referred to as the “the mean vs. stability” view (Yan *et al.*, 2007; Dia *et al.*, 2016). It is the axis with a small circle at the end of the arrow and passes through the average environment and the biplot origin (Yan and Tinker, 2006). The average environment (tester) coordinate (AEC) method in GGE biplot was used to estimate the yield and stability of the genotypes. Genotypes that were located either on the AEC abscissa or had a near zero projection onto the AEC ordinate were more stable (Yan *et al*., 2000). Accordingly, parent P5 and P12 were high yielding and more stable whereas P3 was the unstable parent, revealed by the longest vectors from the AEC and PC1 score below zero. The hybrids GS9, GS36, GS1 and GS34 were the most stable and high yielding genotypes while GS3, GS2, GS11 and GS10 were high yielding. GS9 was the most stable out of four stable hybrids. The biplot indicates the best performing hybrids for each environment and groups of environments (Yan and Hunt, 2001). The highest yielding hybrid in environment Map17 was GS2 while in Sus16 was GS11. For Sus17, hybrid GS38 was the high yielding genotype and in Chk17 it was GS7. The environments Chk16 and Man17 had GS32 as the high yielding hybrid. According to Yan and Hunt (2001), the relation between genotypic traits or environmental factors and PC1 scores varied over years and it could be due to the difference between summer and winter test environments.

## 6.5. Conclusion

The results showed that all test environments for hybrids were discriminating but not representative while for hybrids, environments Mapupulo 17 season (only tested in one season), Sussundenga 16 season and Sussundenga 17 season were the most discriminating environments (Sussundenga was good in both seasons). Mapupulo 17 season was the environment which was slightly representative. Moreover, one mega-environment was found in parent evaluation and five mega-environments for the hybrids. The best parents were P12 (CK 60A) and P5 (LARSVYT46A) but none fell in a specific environment. Additionally, the specific environments for hybrids were: Mapupulo 17 (GS2 = LARSVYT46A x IS 14257R), Sussundenga 16 (GS11 = SPL 38A x SDS 6013R), Sussundenga 17 (GS38 = SIMA), Chókwè 17 (GS7 = 8601A x SDS 6013R) and Chókwè 16 and Maniquenique 17 (GS32 = CK 60A x MZ 37R).

The mean performance and stability showed CK 60A and LARSVYT46A as the high yielding and stable parents. High yielding and stable hybrids were GS9 (SPL 38A x MZ 2R), GS36 (TX 631A x MZ 37R), GS1 (LARSVYT46A x MZ 2R) and GS34 (TX 631A x IS 14257R). The parent LARSVYT46A (high yielding and stable) was one of the parents for high yielding and stable hybrid LARSVYT46 x MZ 2R. Two of the high yielding parents P7 (SPL 38A) and P13 (TX 631A) were parents of the high yielding and stable hybrids GS9 (SPL 38A x MZ 2R) and GS34 (TX 631A x IS 14257R) respectively. These results will help the breeder to recommend the hybrids according to performance and adaption as well as selection of the best environment to test genotypes.

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# 7. Participatory variety selection of sorghum hybrids using farmers' preferences and knowledge in central Mozambique

## Abstract

Understanding farmers' preferences for new varieties is essential for the acceptance and adoption of the improved varieties. Therefore, the objective of this study was to identify and select sorghum hybrids that meet farmers' preferences by using farmers' knowledge and participation. Top six sorghum hybrids pre-selected on-station for grain yield in 2015/16 season at Sussundenga and Chókwè research station trials were evaluated in 10 on-farm trials in Sussundenga district. The trials were conducted using the mother and baby scheme where the mother trial was planted at Sussundenga research station and the baby trials were in farmers' fields around the station. An alpha lattice design with three replications was used for the mother trial and the baby trials were set in a randomized complete block design with two replications. Data collection was based on grain yield, maturity, grain colour, panicle size, plant height and farmers' opinions. The individual and combined data were analysed using PROC GLM procedure in SAS 9.3. The mean squares for grain yield across seasons on-station were highly significant ($P<0.001$) for hybrids, seasons (environment) and their interaction. Days to 50% flowering were highly significant ($P<0.001$) for the environment, hybrids and hybrid x environment interaction. The number of panicles was highly significant only for the hybrid x environment interaction while plant aspect was significant for hybrids and the environment. The results from analysis of variance across the ten farmers' trials were highly significant ($P<0.001$) for all the traits recorded. Hybrid TX 631A x MZ 37R had high yield and shorter plants. The tallest plants on-station were from hybrid SPL 38A x SDS 6013R. In contrast, for on-farm trials, the local variety had the tallest plants and was late in flowering, while for the hybrids SLP 38A x MZ 2R was late in flowering. The mean yield for the local variety was 1.0 $t.ha^{-1}$, while the high yielding hybrid had 3.0 $t.ha^{-1}$. Out of the 25 farmers; the female farmers ranked the hybrid TX 631A x MZ 37R as the best in terms of grain yield, early maturity, less bird damage and white grain colour. These were followed by ICSA 19A x SDS 6013R in terms of plant height and white grain colour. The male farmers chose hybrid ICSA 19A x SDS 6013R based on plant height and sweetness of the stem. In addition to yield, farmers identified additional important traits such as earliness, grain size, and grain colour. The farmers also used drought tolerance and head size as benchmark traits for comparing new varieties to the local variety. Therefore, involving farmers in the evaluation and selection identified hybrids with farmer preferred traits and thus revealed the need for breeders to not only target yield in the development of new varieties. It is also anticipated that the farmers would easily adopt these hybrids.

## 7.1. Introduction

Sorghum grain yield improvement under adverse environments and agronomic management poses many challenges for plant breeders. It is thus important for the breeder to understand the production constraints farmers face in order to select adapted genotypes. The use of participatory plant breeding (PPB) approach could be a solution as it helps breeders to understand farmers' criteria, improve biodiversity by maintain original germplasm, empower farmers, facilitate farmers learning, increases productivity, and speeds the process of releasing and adoption of varieties (Sperling *et al.*, 2001). Involvement of farmers in breeding programmes increases efficiency because breeders orient their breeding strategies to the needs of the farmers. This process is called participatory plant breeding. The other term used and assist breeders on variety selection is participatory variety selection (PVS), known as the selection of released or pre-released varieties by farmers on their own field.

Many studies have outlined the advantages of participatory variety selection (PVS) on adoption of new varieties and increase in productivity (Bänziger and Cooper, 2001; Witcombe *et al.*, 2005; Trouche *et al.*, 2012). Participatory breeding has been proposed as an active approach for developing varieties that combine productivity gains, adaptability to a particular system and quality traits for subsistence agriculture in marginal environments (Trouche *et al.*, 2011). Consequently, it is important to identify germplasm that responds to farmers environments where qualitative and quantitative traits are taken in consideration (Morris and Bellon, 2004; Trouche *et al.*, 2011). Trouche *et al.* (2012) concluded that on-farm selection has many limitations depending on seed generation evaluated but the trials produce more stable genotypes having a combination of earliness, plant height, grain size and yield closer to that expected by farmers. Understanding farmers' preferences and acceptability of a new variety are essential parameters for the adoption and use of the varieties (Horn et al., 2015; Olubunmi, 2015). Therefore, the objective of this study was to identify and select sorghum hybrids that meet farmers' preferences by using farmers' knowledge and participation.

## 7.2. Materials and Methods

### 7.2.1. Plant materials

Top six sorghum hybrids pre-selected on-station for grain yield at Sussundenga and Chókwè research stations in 2015/16 season trials were used in this study (Table 7-1). Farmers were involved in the selection of these hybrids. Each farmer used a local sorghum variety as a check.

Table 7-1 Plant material selected for on-farm trial

| Entry no | Crosses | Group | Origin |
|---|---|---|---|
| 1 | SPL 38A x SDS 6013R | Hybrid | NAR/ICRISAT |
| 2 | TX 631A x MZ 37R | Hybrid | NAR/ICRISAT |
| 3 | LARSVYT 46A x SDS 6013R | Hybrid | NAR/ICRISAT |
| 4 | LARSVYT 46A x MZ 37R | Hybrid | NAR/ICRISAT |
| 5 | SPL 38A x MZ 2R | Hybrid | NAR/ICRISAT |
| 6 | ICSA 19A x SDS 013R | Hybrid | NAR/ICRISAT |
| 7 | Local variety | Local | Farmer seed |

NAR = National Agriculture Research Sorghum Programme;

### 7.2.2. Evaluation sites and experimental design

The trials were conducted during the rainy season of 2016/17 for on-farm trial and seasons 2015/16 and 2016/17 for on-station. Ten participating farmers with knowledge of sorghum management were selected to conduct the on-farm trials around Sussundenga Research Station in Matica locality. The selected farmers included both men and women. The trials were conducted in a Mother and Baby scheme. The mother trial was planted at Sussundenga Research Station while the baby trials were in farmers' fields around the station.

The mother trial included other hybrids and it was layout in a 19 x 2 alpha lattice design with three replications described in chapter 5. Each plot consisted of two rows of 5 m long with 0.75 m inter-row spacing and 0.25 m between plants. Fertilizer was applied at recommended rates of 250 kg ha$^{-1}$ NPK (base application) and 150 kg ha$^{-1}$ urea (top-dressing). Other cultural practices such as land cultivation, hand planting and hand weeding were carried out at each site.

The baby trials were set in a randomized complete block design with two replications in each farmer's field. Each entry had two rows, 5 m long with 0.75 m inter-row spacing and 0.25 m between plants. Fertilizer was applied at a rate of 200 kg ha$^{-1}$ NPK (basal fertilizer) during planting. Farmers took care of all agronomic practices as they would normally do in their own fields. The on-farm trials were monitored by researchers and technical personnel from the research station who also did the data collection. Farmers hosting the trials and other neighbouring farmers were invited to the mother trial during harvesting at Sussundenga Research Station to evaluate and select hybrids based on their criteria of preference. A total of 25 farmers (16 women and 9 men) participated.

### 7.2.3. Data collection and analysis

Farmers' assessed the mother trial twice; during flowering stage and during harvesting. In the baby trial, each farmer did the assessment. Data collection was based on grain yield, maturity, grain colour, panicle size, and plant height. The agronomic scoring criteria were used to capture farmers' preferences of each tested variety where each farmer gave scores according to their preferences. These criteria were ranked according to the following scores; where 1= very good hybrid, 2 = good hybrid, 3 = average, 4 = poor and 5 = very poor hybrid. The score 1 considered hybrids with high grain yield, early to intermediate maturity, white to brown grain colour, large panicle size and medium to tall plant height. The score 5 was for hybrids with low grain yield, late maturity, small panicle size and very short plant height. The individual and combined season data were analysed using PROC GLM procedure in SAS 9.3 (SAS, 2011). ANOVA was done first by season and across season at Sussundenga research station trial and then individual and across farmers' trials. Genotype means were ranked and compared using the t-test (P=0.005).

## 7.3. Results

### 7.3.1. On-station evaluation trial

The mean squares for grain yield across two seasons (2015/16 and 2016/17) on-station showed the main effects of hybrids and seasons (environment) and their interaction to be highly significant ($P<0.001$, Table 7-2). Days to 50% flowering were highly significant ($P<0.001$) for the environments, hybrids and hybrid x environment interaction. The number of panicles was highly significant only for the hybrid x environment interaction, while plant aspect was significant ($P<0.05$) for hybrids and highly significant ($P<0.001$) for the environment. A significant difference was observed for the panicle length and number of plants for the hybrids, plant height was significant for the hybrid x environment interaction. The mean grain yield of the hybrids for the two seasons was 3.4 t.ha$^{-1}$.

Table 7-2 to Table 7-5 show the means for the traits that were significantely significant for the hybrid x environment (season) interaction. Grain yield showed statistical differences among the hybrids in the two seasons (Table 7-2). TX 631A x MZ 37R had the highest grain yield among hybrids across seasons with a mean of 5.7 t.ha$^{-1}$ followed by SPL 38A x SDS 6013R with a mean yield of 4.2 t.ha$^{-1}$. The lowest grain yield was observed for hybrid ICSA 19A x SDS 6013R in the second season with a mean of 1.6 t.ha$^{-1}$.

Table 7-2 Grain yield (t.ha$^{-1}$) comparisons among the sorghum hybrids in the two seasons at Sussundenga Research Station

| Hybrids | Environment | Means |
|---|---|---|
| ICSA 19A x SDS 6013R | 2 | 1.62$^{a}$ |
| SPL 38A x MZ 2R | 2 | 2.08$^{ab}$ |
| LARSVYT 46A x MZ 37R | 2 | 2.38$^{ab}$ |
| LARSVYT 46A x SDS 6013R | 1 | 2.49$^{ab}$ |
| SPL 38A x MZ 2R | 1 | 2.66$^{ab}$ |
| LARSVYT 46A x MZ 37R | 1 | 2.67$^{ab}$ |
| LARSVYT 46A x SDS 6013R | 2 | 3.26$^{bc}$ |
| ICSA 19A x SDS 6013R | 1 | 3.35$^{bc}$ |
| SPL 38A x SDS 6013R | 1 | 3.49$^{bc}$ |
| SPL 38A x SDS 6013R | 2 | 4.84$^{cd}$ |
| TX 631A x MZ 37R | 2 | 5.34$^{d}$ |
| TX 631A x MZ 37R | 1 | 6.0$^{d}$ |
| Mean | | 3.4 |

Environment 1- refers to season 2015/16 and environment 2 – refers to season 2016/17. Means in a column followed by the same letters are not significantly different at P>0.05

The least number of days to 50% flowering was 62 and was obtained by hybrid TX 631A x MZ 37R in the first season, while the most number of days was observed in the second season for hybrid SPL 38A x SDS 6013R (Table 7-3).

Table 7-3 Comparison of days to 50% flowering for the sorghum hybrids evaluated in two seasons at Sussundenga Research Station

| Hybrids | Environment | Mean |
|---|---|---|
| TX 631A x MZ 37R | 1 | $62^{a}$ |
| LARSVYT 46A x SDS 6013R | 1 | $62^{a}$ |
| SPL 38A x SDS 6013R | 1 | $63^{ab}$ |
| ICSA 19A x SDS 6013R | 1 | $64^{bc}$ |
| LARSVYT 46A x SDS 6013R | 2 | $65^{bc}$ |
| TX 631A x MZ 37R | 2 | $67^{cd}$ |
| SPL 38A x MZ 2R | 1 | $68^{cd}$ |
| LARSVYT 46A x MZ 37R | 2 | $68^{de}$ |
| LARSVYT 46A x MZ 37R | 1 | $69^{de}$ |
| ICSA 19A x SDS 6013R | 2 | $70^{de}$ |
| SPL 38A x MZ 2R | 2 | $73^{de}$ |
| SPL 38A x SDS 6013R | 2 | $74^{e}$ |
| Mean | | 67 |

Environment 1- refers to season 2015/16 and environment 2 – refers to season 2016/17. Means in a column followed by the same letters are not significantly different at P>0.05

For the numbers of panicles, it was observed that the four hybrids that had few numbers of panicles in the first season, had many panicles in the second season (Table 7-4). These hybrids were LARVYT 46A x MZ 37R, SPL 38A x SDS 6013R, ICSA 19A x SDS 6013R and LARSVYT 46A x SDS 6013R. Moreover, hybrid TX 631A x MZ 37R did not show significant differences between the two seasons.

Table 7-4 Mean for number of panicles of sorghum hybrids evaluated in two seasons at Sussundenga Research Station

| Hybrids | Environment | Mean |
|---|---|---|
| LARSVYT 46A x MZ 37R | 2 | $5^{a}$ |
| SPL 38A x SDS 6013R | 1 | $8^{ab}$ |
| ICSA 19A x SDS 6013R | 2 | $8^{ab}$ |
| LARSVYT 46A x SDS 6013R | 2 | $10^{bc}$ |
| SPL 38A x MZ 2R | 2 | $12^{bc}$ |
| SPL 38A x SDS 6013R | 2 | $14^{cd}$ |
| TX 631A x MZ 37R | 2 | $14^{cd}$ |
| TX 631A x MZ 37R | 1 | $15^{cd}$ |
| SPL 38A x MZ 2R | 1 | $22^{cd}$ |
| ICSA 19A x SDS 6013R | 1 | $22^{cd}$ |
| LARSVYT 46A x SDS 6013R | 1 | $24^{cd}$ |
| LARSVYT 46A x MZ 37R | 1 | $28^{d}$ |

Environment 1- refers to season 2015/16 and environment 2 – refers to season 2016/17. Means in a column followed by the same letters are not significantly different at P>0.05

Plant height showed statistical differences for the hybrid x environment interaction (Table 7-5). Hybrid TX 631A x MZ 37R had the shortest plants during season two. The same hybrid had an average height of 91.5 cm in the first season. The tallest plants were from hybrid SPL 38A x SDS 6013R with an average of 175.7 cm.

Table 7-5 Mean for plant height of sorghum hybrids evaluated in two seasons at Sussundenga Research Station

| Hybrids | Environment | Mean |
|---|---|---|
| TX 631A x MZ 37R | 2 | 91.5$^{a}$ |
| LARSVYT 46A x SDS 6013R | 2 | 98.7$^{ab}$ |
| SPL 38A x MZ 2R | 2 | 104.7$^{ab}$ |
| LARSVYT 46A x MZ 37R | 1 | 106.2$^{ab}$ |
| SPL 38A x MZ 2R | 1 | 118.8$^{ab}$ |
| LARSVYT 46A x MZ 37R | 2 | 119.0$^{ab}$ |
| SPL 38A x SDS 6013R | 1 | 122.8$^{ab}$ |
| ICSA 19A x SDS 6013R | 2 | 124.3$^{ab}$ |
| TX 631A x MZ 37R | 1 | 126.3$^{ab}$ |
| ICSA 19A x SDS 6013R | 1 | 159.1$^{ab}$ |
| LARSVYT 46A x SDS 6013R | 1 | 170.4$^{ab}$ |
| SPL 38A x SDS 6013R | 2 | 175.7$^{b}$ |
| Mean | | 126.0 |

Environment 1- refers to season 2015/16 and environment 2 – refers to season 2016/17. Means in a column followed by the same letters are not significantly different at P>0.05

The number of plants showed statistical difference for the hybrids with hybrid SPL 38A x SDS 6013R having an average of 20 plants per plot (Table 7-6). Hybrid LARSVYT 46A x MZ 37R had the lowest number of plants per plot (9 plants).

Table 7-6 Mean number of plants of sorghum hybrids evaluated in two seasons at Sussundenga Research Station

| Hybrids | Environment | Mean |
|---|---|---|
| LARSVYT 46A x MZ 37R | 2 | 9.00$^{a}$ |
| LARSVYT 46A x SDS 6013R | 1 | 13.33$^{ab}$ |
| LARSVYT 46A x SDS 6013R | 2 | 13.33$^{ab}$ |
| LARSVYT 46A x MZ 37R | 1 | 13.67$^{ab}$ |
| SPL 38A x MZ 2R | 1 | 15.00$^{ab}$ |
| ICSA 19A x SDS 6013R | 2 | 16.33$^{ab}$ |
| SPL 38A x MZ 2R | 2 | 17.00$^{ab}$ |
| TX 631A x MZ 37R | 1 | 17.33$^{ab}$ |
| TX 631A x MZ 37R | 2 | 17.67$^{ab}$ |
| ICSA 19A x SDS 6013R | 1 | 18.67$^{b}$ |
| SPL 38A x SDS 6013R | 2 | 19.33$^{b}$ |
| SPL 38A x SDS 6013R | 1 | 19.67$^{b}$ |
| Mean | | 16.00 |

### 7.3.2. On-farm evaluation trial

Analysis of variance across the ten farmers' trials showed highly significant main effects of hybrid, environment, and hybrid x environment interaction at ($P<0.001$) for all the traits recorded (Table 7-8). For plant height, there were statistical differences between the hybrids and the local variety. The local variety had the tallest plants with an average mean of 215 cm when compared to the tallest hybrid SPL 38A x SDS 66013R which was 178 cm. However, these two entries were not significantly different, but the local variety was significantly different from the rest of the hybrids ($P<0.001$) for plant height. Most of the farmers preferred tall plants for various purposes including grain yield and stems/stalks for building houses and/or granaries (Figure 7-1). Statistically, days to 50% flowering did not show differences among the hybrids but there were statistical differences between the hybrids and local variety (Figure 7-2). The local variety took longer to 50% days to flowering (78 days), while for the hybrids the days to 50% flowering varied between 62-64 days.

Figure 7-3 shows the number of panicles combined with other traits. The longest panicle size was observed in the local variety with 46 cm, but it was not significantly different from the hybrids LARSVYT 46A x MZ 37R (42 cm), SPL 38A x MZ 2R (39 cm) and TX 631A x MZ 37R (38 cm). The hybrids which were significantly different from the local variety were SPL 38A x SDS 6013R (38 cm), LARSVYT 46A x SDS 6013R (38 cm), ICSA 19A x SDS 6013R (37 cm) and TX 631A x MZ 37R (37 cm).

Figure 7-1 Use of sorghum stems/stalks by farmers to build poultry shelters in Matica locality

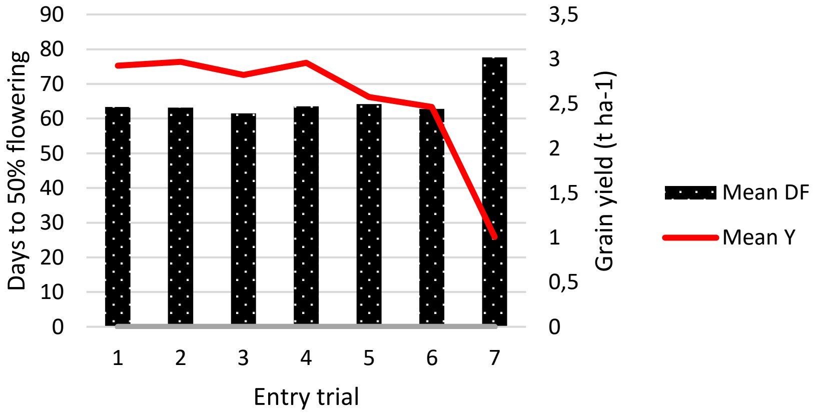

Figure 7-2 Combined grain yield (t.ha$^{-1}$) and days to 50% flowering (DF) across the ten farmers.
Entry numbers were: 1 = SPL 38A X SDS 6013R, 2 = TX 631A X MZ 37R, 3 = LARSVYT 46A X SDS 6013R, 4 = LARSVYT 46A X MZ 37R, 5 = SPL 38A X MZ 2R, 6 = ICSA 19A X SDS 6013R and 7 = $^{\text{Local}}$ variety

Table 7-7 Mean squares for grain yield (t.ha$^{-1)}$ and other components obtained at Sussundenga Research Station

| Source of Variation | DF | Grain yield | Days to flowering | Plant height | Panicle length | Number of plants | Number of panicles | Plant aspect |
|---|---|---|---|---|---|---|---|---|
| Season (Env.) | 1 | 0.32 | 230.03$^{***}$ | 2085.44 | 124.69 | 6.25 | 802.78$^{***}$ | 6.85$^{***}$ |
| Block (Rep x Env.) | 4 | 0.75 | 7.11 | 1838.44 | 101.53$^{*}$ | 0.97 | 32.78 | 0.73 |
| Hybrids | 5 | 10.39$^{***}$ | 40.49$^{***}$ | 1845.18 | 31.29 | 54.63$^{**}$ | 33.78 | 1.33$^{*}$ |
| Env. x Hybrids | 5 | 1.81$^{***}$ | 25.03$^{***}$ | 2804.51$^{*}$ | 12.89 | 8.18 | 163.98$^{***}$ | 0.89 |
| Error | 35 | 0.28 | 4.74 | 777.04 | 29.69 | 11.31 | 26.28 | 0.49 |
| Overall mean | | 3.35 | 66.97 | 126.61 | 35.69 | 15.86 | 15.22 | 2.27 |
| $R^2$ (%) | | 91.97 | 86.07 | 67.78 | 55.87 | 58.91 | 78.53 | 67.87 |

Table 7-8 Mean squares for grain yield (t.ha$^{-1}$) and other components obtained at on-farm trial around Matica

| Source of Variation | DF | Grain yield | Days to flowering | Plant height | Panicle length | Number of plants | Number of panicles |
|---|---|---|---|---|---|---|---|
| Farmers (Env.) | 9 | 41.43$^{***}$ | 1218.28$^{***}$ | 3497.32$^{***}$ | 207.13$^{***}$ | 4148.14$^{***}$ | 1254.59$^{***}$ |
| Block (Rep x Env.) | 10 | 0.43$^{**}$ | 2.24 | 532.21$^{**}$ | 7.11 | 79.90 | 86.70 |
| Hybrids | 6 | 9.81$^{***}$ | 372.56$^{***}$ | 9183.36$^{***}$ | 189.46$^{***}$ | 1457.28$^{***}$ | 3235.46$^{***}$ |
| Env. x Hybrids | 54 | 1.46$^{***}$ | 13.77$^{***}$ | 1446.12$^{***}$ | 60.55$^{***}$ | 153.02$^{***}$ | 196.81$^{***}$ |
| Error | 60 | 0.21 | 1.57 | 211.95 | 14.76 | 60.52 | 51.13 |
| Overall mean | | 2.53 | 65.17 | 169.76 | 39.52 | 54.24 | 59.67 |
| $R^2$ (%) | | 97.66 | 99.36 | 93.04 | 87.75 | 93.98 | 93.22 |

The number of panicles showed significant differences between the hybrids and the local variety. The local variety had the least number of panicles (32 panicles per plot). Among the hybrids, the number of panicles varied between 62-69 with no significant differences amongst them (Figure 7-3). Similarly, the number of plants per plot were significantly different between the hybrids and the local variety. The hybrids' number of plants ranged between 57 and 63 plants per plot compared to 32 plants per plot for the local variety. Among the hybrids, TX 631A x MZ 37R had the least number of plants, while SPL 38A x MZ 2R had the highest number. Grain yield was also significantly different between the hybrids and the local variety where the local variety had the lowest yield compared to the hybrids (Figure 7-2). The mean yield for the local variety was 1.0 t.ha$^{-1}$ and the highest yielding hybrid (TX 631A X MZ 37R) had a mean of 3.0 t.ha$^{-1}$. This hybrid was not significantly different from the other hybrids. The hybrids had a yield advantage ranging from 150% to 200% above the local variety yield.

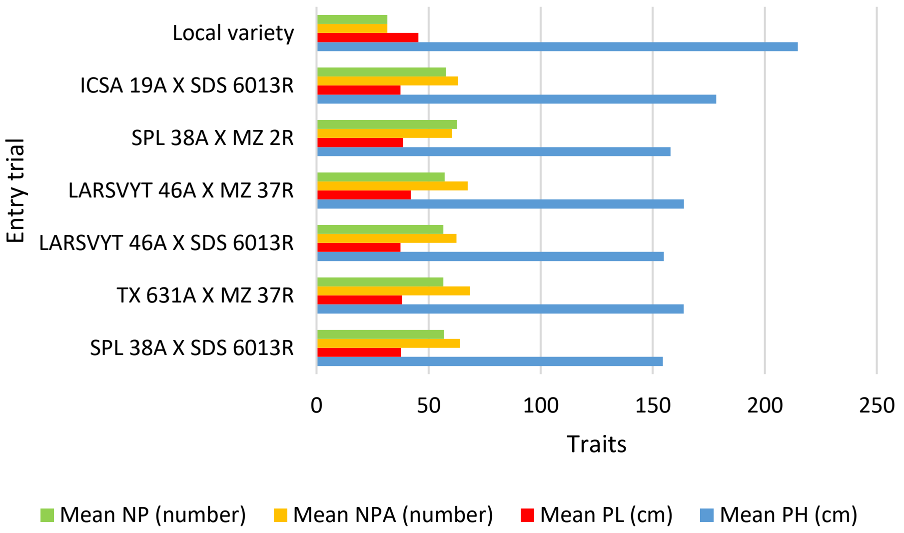

Figure 7-3 Combined plant height (PH), panicle length (PL), number of plants (NP) and number of panicles (NPA) across the ten farmers' fields

### 7.3.3. Other traits selected by farmers

The breeder's target trait during selection was high yield of the hybrids over the local varieties. However, additional traits were selected for by the farmers who participated during harvesting of the mother trial on-station and from individual farmers during harvesting of baby trials. Out of the 25 farmers; the female farmers ranked the hybrid TX 631A x MZ 37R as the best in terms of grain yield, early maturity, less bird damage and white grain colour. These were followed by ICSA 19A x SDS 6013R in terms of plant height and white grain colour. The male farmers chose hybrid ICSA 19A x SDS 6013R based on plant height and sweetness of the stem. In general, the majority of farmers' preferences for sorghum varieties were high yield, early maturity, grain size and colour, and plant height. Farmers mentioned that they also preferred a variety that had stable yield and was adapted to their agro-ecological system. Drought was also mentioned by some farmers, although it was not possible to differentiate the drought tolerant varieties due to the good season which experienced high amounts of rain. Additionally, farmers indicated that one of the characteristics they liked about the hybrids was the compact and big head size when compared to their local variety that has a loose and small head (Figure 7-4). Although this was the preferred characteristic, farmers also mentioned that bird damage was higher in the compacted head than in the loose head.

Figure 7-4 Compact sorghum hybrid head (left) and loose local variety head (right) during evaluation

## 7.4. Discussion

### 7.4.1. On-station evaluation trial

For grain yield across the two seasons (2015/16 and 2016/17), the main effects of hybrids and seasons (environment) and their interaction were highly significant at ($P<0.001$). Hybrid TX 631A x MZ 37R had the highest grain yield among hybrids across seasons with a mean of 5.7 $t.ha^{-1}$ followed by SPL 38A x SDS 6013R with a mean yield of 4.2 $t.ha^{-1}$. The lowest grain yield was obtained for ICSA 19A x SDS 6013R in the second season with a mean of 1.6 $t.ha^{-1}$. It was observed that the grain yield was higher in the second season than the first season. One of the reasons was the limited amount of rain received in the first season during flowering stage. If the drought occurs during post-flowering, it severely affects the translocation of nutrients to the sink and, premature senescence resulting in drastic reduction in grain filling (Crasta et al., 1999). This suggested that hybrids did not express their grain yield potential in the first season. The environmental conditions affect the yield variability of grain crops during the most sensitive stages of crop development (Wheeler et al., 2000). Borrell *et al*. (2000) reported that grain yield declined when a deficit of water in hybrids increases. An important element of yield under stress conditions is the water use efficiency of the crops (Blum, 2009). Therefore, the hybrids in the study exhibited tolerance to drought during the first season and had a higher yield than the commercial/local varieties. This shows that weather conditions were not the limiting factor for the low yields of the adapted varieties like improved varieties and/or local varieties. Similar results were reported in a study that compared exotic genotypes with local adapted genotypes (Calhoun et al., 1994).

The ranking of the hybrids for number of days to 50% flowering changed between the two seasons. The hybrid TX 631A x MZ 37R had the least number of days in the first season and an average number of days in the second season (Table 7-3). A similar trend was observed in the hybrid SPL 38A x SDS 6013R which had the most number of days to 50% flowering. The hybrids were not consistent in the days to 50% flowering in the two seasons, thus contributing to the hybrid x environment interaction observed This variation might have been due to the drought stress experienced during the flowering stage in the first season (2015/16). Drought has been reported as an important stress that affects the genetic and physiological mechanism of the plant (Tuinstra *et al.*, 1996). Both pre-flowering and post-flowering drought stress responses have been identified in sorghum (Harris *et al.*, 2006) and these influence the period of flowering and ultimately the grain yield.

Four hybrids had the least number of panicles in the first season, but the panicles were much larger in size. Similarly, plant height showed significant hybrid x environment interaction across the seasons. This indicated that the number of panicles and plant height are strongly influenced by changes in climatic conditions. Graham and Lessman (1966) reported that high yielding sorghum genotypes may be achieved in a combination of plant height and other components. Plant height was reported to be one of the most important yield components (Fernandez *et al.*, 2009) especially for biofuel production in sweet stem sorghum where it contributed to increased biomass.

### 7.4.2. On-farm evaluation trial

The on-farm trials resulted in highly significant main effects for hybrids, environment and their interaction for all the traits. This indicated that the hybrids responded differently under the different agronomic farmer management practices. This shows that the use of unlike farmers was appropriate to capture their variety preferences. Active involvement of farmers in plant breeding has been shown to increase the efficiency of classical breeding (Witcombe *et al.*, 2005; Gyawali *et al.*, 2007). Morris and Bellon (2004) reported different approaches of participatory plant breeding which include inviting farmers to participate in varietal selection and evaluation activities or teaching them formal selection techniques. Additionally, adoption of new improved varieties by farmers requires an understanding of the important environments and production constraints they face and thus involve them from the initial stages of the breeding process (Bänziger and Cooper, 2001). Moreover, Mekbib (2006) suggested that defining or setting goals and objectives especially for breeding multi-purpose varieties should involve final consumers and industrialists. Many years of participatory approaches to identify genotypes with characters preferred by farmers is an approach that leads to the adoption of the new varieties (Nkongolo *et al.*, 2008). Therefore, understanding farmers' preferences and acceptability of a new variety is essential for the adoption of improved varieties (Horn et al., 2015; Olubunmi, 2015).

Although grain yield was one of the traits that the farmers selected, they had additional characteristics they looked for in a variety. These included adaptability and yield stability. This indicates that farmers were more concerned with their environments which experienced frequent droughts and thus desired a variety that allowed them to harvest something even during the dry seasons. This could be one of the reasons they keep growing the local variety even though it is low yielding. The low adoption rate of high yielding varieties can be explained by the fact that most of the varieties are selected without involving farmers (Asrat *et al.*, 2010).

The best hybrid selected by most farmers was based on good grain yield, early maturity, less bird damage and white grain colour. The majority of men preferred tall plants with sweet stems, while women preferred earliness. This is explained by fact that men are more worried about the use of all the sorghum parts, while women are worried about food for the family. In general, the majority of farmers preferred a sorghum variety with high yield, early maturity, large grain size, white grain colour and tall plants. Moreover, farmers also mentioned that drought tolerance was an important trait for the varieties. These results are in agreement with findings that breeder's on-station selections produce lines with high grain yields, while farmers' selections produce varieties with a combination of earliness, plant height, grain size and grain yield (Trouche *et al.*, 2011; Trouche *et al.*, 2012). Other farmers chose earliness as an important trait and defined it as the ability of the plants to complete the growing stage up to flowering stage before the rainy season stops so that the grain filing period will not be compromised (Vom Brocke *et al.*, 2010). The white grain colour was mentioned as an important trait as most of the farmers mix sorghum flour with maize flour to cook their staple food, a thick porridge. This characteristic might be an important key for future breeding strategies for farmers' preferences where it should be used as one of the traits for selection. Plant height and head size were also important criteria for some of the farmers and it is associated positively with good grain yield. The reasons for selecting plant height were mostly related to the use of the stems for building houses or granaries. The other traits preferred by farmers were post-harvest traits in combination with high yield and variety stability for the short and long rainy season (Lacy *et al.*, 2006). On the other hand, farmers mentioned the importance of having drought tolerant varieties, although the study did not select for drought tolerance among the hybrids due to high amounts of rain during the growing season. Drought resistant crops are essential for food security (Vunyingah and Kaya, 2016).

Farmers, in general, preferred high yielding hybrids combined with other characteristics essential for their environment. Additionally, seed for the improved varieties such as hybrids should be easily accessible and markets for the grain should be available.

### 7.4.3. Implications for breeding

Farmers' selections were based on the production constraints in each environment and this resulted in a variety that combined high grain yield, early maturity, large grain size, tall plant height and drought tolerance. This implies that breeders should pay attention to these traits and other traits that confer drought tolerance such as stay green if the varieties have to be adopted. From this study, two groups of varieties should be deployed; one that responds to high yield and early maturity, and the other to high yield with tall plants. The reason is that normally accumulation of plant biomass takes long, thus varieties will not fit in the short and early maturing group. In addition, farmers usually recycle seed, and this might result in yield reduction in a hybrid. Therefore, farmer education on sorghum hybrids is essential.

## 7.5. Conclusion

The results of on-station and on-farm trials resulted in the identification of hybrid TX 631A x MZ 37R as high yielding, with short plant height. Moreover, the tallest plants on-station were from hybrid SPL 38A x SDS 6013R. In contrast, the local variety had the tallest plants on the on-farm trials and was late in flowering. Within the hybrids, SLP 38A x MZ 2R was late in flowering, followed by LARSVYT 46A x MZ 37R, SPL 38A x SDS 6013R, TX 631A x MZ 37R, ICSA 19A x SDS 6013R and LARSVYT 46A x SDS 6013R. The mean yield for local variety was 1.0 t.ha$^{-1}$ while the highest yielding hybrid had 3.0 t.ha$^{-1}$ (TX 631A x MZ 37R). Out of the 25 farmers; the female farmers ranked the hybrid TX 631A x MZ 37R as the best in terms of grain yield, early maturity, less bird damage and white grain colour. Some morphological traits selected based on farmers' preferences were the same selected based on field performance, such as yield, earliness, grain colour. These were followed by ICSA 19A x SDS 6013R in terms of plant height and white grain colour. The male farmers chose hybrid ICSA 19A x SDS 6013R based on plant height and sweetness of the stem. These results showed the potential of the hybrids over the local variety with a yield advantage ranging from 150% to 200% above the local variety. Thus, the study supports the importance of interactive and involvement of farmers throughout the development of varieties for large scale adoption. Involving farmers in the evaluation and selection of hybrids showed that breeders should not only target yield but other traits important to farmers such as earliness, grain size, grain colour and plant height. Drought tolerance and head size were also mentioned as important traits used to compare new varieties with the local variety.

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# 8. Comparison of selection indices to identify superior sorghum genotypes according to the morphological traits

## Abstract

Different agronomic characters are important to farmers when selecting preferred sorghum genotypes. However, the biggest challenge is to select for these traits at the same time using one score. It is thus crucial to identify selection methods that favour identification of superior genotypes and maximizes genetic gain from selection of the characters of interest simultaneously. A selection index helps to evaluate the total genotypic value of an individual plant regarding the traits of interest. Therefore, the objectives of this study were to develop two selection indices (Smith-Hazel and desired gains) and compare their effectiveness in identifying superior genotypes based on the agronomic traits of importance. Thirty-Six F1 and 36 F2 populations were evaluated in separate trials at the same location and season in a 6 x 6 alpha lattice design with three replications. The genetic and phenotypic variance-covariance matrices were determined to assist in the development of the indices. Four traits; grain yield (GY), plant height (PH), panicle length (PL) and panicle weight (PW) were used to evaluate the selection indices based on the economic values (Smith-Hazel) and desired gains. Scores observed were not associated with the highest yielding genotypes. For Smith-Hazel selection index, the genotype CK 60A x MZ 37R had highest score followed by TX 631A x MZ 37R, CK 60A x MZ 2R, SPL 38A x MZ 37R and TX 628A x MZ 37R. For desired gain index, the top 5 scored genotypes were ICSA 19A x MZ 37R, 8601A x SDS 6013R, SPL 38A x SDS 6013R, CK 60A x MZ2R and TX 628A x IS 14257R. The genotype CK 60A x MZ 2R is the only genotype that appeared in the top five using the two indices. The selection index proposed by Smith-Hazel was the most efficient procedure for simultaneous selection of the hybrids for grain yield and other yield attributes. This method allowed the prediction of genetic gain for the traits evaluated together and a more efficient selection of superior genotypes. Then, this suggests that sorghum breeders should consider the use of different selection strategies and indices to select superior genotypes for grain yield and other traits to improve the crop according to the trait of interest.

## 8.1. Introduction

Sorghum (*Sorghum bicolor* L. Moenchi) is an important annual cereal crop among the cultivated cereals. It is the main crop and a staple food for most of the semi-arid areas in Africa. It is a crop of choice for most African countries due to its wide range of adaptation to stresses, mainly in areas where frequent droughts are experienced (Yohannes *et al.*, 2016). Additionally, sorghum has multi-purpose use ranging from food to beverage. The stems are used to feed animals and for constructing houses. Therefore, farmers have their own preferences and criteria they use for variety selection that is determined by the crop uses. Breeders should, therefore, consider the farmers' trait preferences during variety development. Selection of traits based on the farmers' preferences is an important step for the adoption of a new cultivars. Moreover, farmers give specific weights to traits based on how important they are to them. The most important traits are given high values that make economic sense to the farmers. In sorghum, some of the important characters are grain yield, seed size, plant height, grain quality and resistance to pest or disease.

Cultivar development is based on exploration of interested traits with genetic variability (Ahmad *et al.*, 2011). Variability within segregating populations can be used to exploit new re-combinations to produce superior transgressive segregates through selection (Oliveira *et al.*, 2012). In F2 generation, the maximum variability is obtained allowing effective selection to take place. At early stages, the efficiency of selection can be low due to low heritability of some traits of interest (Backes *et al.*, 2002; Laghari *et al.*, 2010; Oliveira *et al.*, 2012). Furthermore, variability of experimental materials is not the only important component for the success of the selection but also the accuracy of the selection methods used that may allow effective prediction of genetic gain (Resende, 2007; Borges *et al.*, 2010).

The choice of an appropriate selection method for plant breeding may favour identification of superior genotypes during the development of new cultivar and saves time and costs (Kurek *et al.*, 2001). Identification of superior genotypes requires selection methods that can exploit efficiently the available genetic variability, maximizing the genetic gain in relation to the characteristics of interest (Vivas *et al.*, 2012). Therefore, selection index that results from a combination of certain traits that pursue simultaneous selection, allows identifying superior genotypes.

Selection of several traits at the same time is mostly facilitated by the establishment of a selection index that uses the optimal combination of multiple traits (Shook, 2006; Cruz, 2013). The use of the selection index allows identification of superior genotypes established by the optimal linear combination of various traits (Vittorazzi *et al.*, 2017). Selecting of traits simultaneously using an index provides useful information and realistic response to selection for all the traits that are being combined by giving a total genetic value to the individual line (Bänziger and Lafitte, 1997). Initially, Smith (1936) and Hazel (1943) reported the use of a selection index in plants and animals, respectively and then later other indices were proposed by Williams (1962), Pešek and Baker (1969) and Mulamba and Mock (1978).

The Smith-Hazel index has been shown to give maximum genetic advance (Strefeler and Wehner, 1986). However, the index is not as simple as other indices as it requires estimation of genetic variances and covariances and an assignment of economic weights for each trait (Strefeler and Wehner, 1986; Eshghi *et al.*, 2011). On the other hand, the desired gain proposed by Pesek and Baker (1969) specifies the desired gain value rather than economic weights. Hence, it maximizes the expected response in proportion to the gain specified by the breeder. Many breeding programmes use selection indices in different crops to select superior genotypes and predict genetic gain. The limitation to the use of selection indices in some situations is the poor establishment of economic weights for the various traits of interest (Pešek and Baker, 1969; Coimbra *et al.*, 1999; Vittorazzi *et al.*, 2017). For this reason, Cruz (1990) proposed the use of experimental data to estimate the economic weights. The efficiency of the selection indices may be estimated using selection differential as a gain predictable from selection. Selection differential represents a measure of improvement in the given trait due to selection (Nagaraja, 1981). Another important component in selection is heritability of the traits, defined as “the fraction of the selection differential expected to be gained when selection is practised on a defined reference unit” (Hanson, 1963).

The present study developed two indices based on the Smith-Hazel index and the desired gain index and compared these two methods in identification of superior genotypes for many traits simultaneously in order to realize genetic gain.

## 8.2. Materials and Methods

### 8.2.1. Plant materials

F1 crosses were developed from a 9 x 4, line x tester mating scheme. The 36 F1 hybrids were advanced to F2 generation and selected as individual plants in each plot (Table 8-1).

Ten random plants from each plot were selected from F2 for plant height, panicle length, panicle weight and grain yield. In the F1 plot, the number of days to 50% flowering, plant height, panicle length, number of plants, number of panicles, panicle weight and grain yield were recorded.

Table 8-1 Plant material used in the trials using the F1 and F2 generations

| Entry | Genotype | Entry | Genotype |
|---|---|---|---|
| 1 | LARSVYT 46A x MZ 2R | 19 | TX 628A x SDS 6013R |
| 2 | LARSVYT 46A x IS 14257R | 20 | TX 628A x MZ 37R |
| 3 | LARSVYT 46A x SDS 6013R | 21 | ICSA 21A x MZ 2R |
| 4 | LARSVYT 46A x MZ 37R | 22 | ICSA 21A x IS 14257R |
| 5 | 8601A x MZ 2R | 23 | ICSA 21A x SDS 6013R |
| 6 | 8601A x IS 14257R | 24 | ICSA 21A x MZ 37R |
| 7 | 8601A x SDS 6013R | 25 | ICSA 12A x MZ 2R |
| 8 | 8601A x MZ 37R | 26 | ICSA 12A x IS 14257R |
| 9 | SPL 38A x MZ 2R | 27 | ICSA 12A x SDS 6013R |
| 10 | SPL 38A x IS 14257R | 28 | ICSA 12A x MZ 37R |
| 11 | SPL 38A x SDS 6013R | 29 | CK 60A x MZ 2R |
| 12 | SPL 38A x MZ 37R | 30 | CK 60A x IS 14257R |
| 13 | ICSA 19A x MZ 2R | 31 | CK 60A x SDS 6013R |
| 14 | ICSA 19A x IS 14257R | 32 | CK 60A x MZ 37R |
| 15 | ICSA 19A x SDS 6013R | 33 | TX 631A x MZ 2R |
| 16 | ICSA 19A x MZ 37R | 34 | TX 631A x IS 14257R |
| 17 | TX 628A x MZ 2R | 35 | TX 631A x SDS 6013R |
| 18 | TX 628A x IS 14257R | 36 | TX 631A x MZ 37R |

### 8.2.2. Field evaluation sites

The 36 experimental hybrids and families (F1 and F2) were grown for evaluation in two test environments during 2016/17 seasons. The trial sites were Chókwè and Sussundenga research stations (described in chapter 5). The experimental layout in each environment was a 6 x 6 alpha lattice design with three replications. Each plot had two rows that were 5 m long with a spacing of 0.75 m and 0.25 m. A blended NPK (12-24-12) fertilizer was applied at a rate of 250 kg ha$^{-1}$ (basal application). Urea (46% N) was applied as a top dressing at a rate of 150 kg ha$^{-1}$ at four leaf stage and a week before planting. Other cultural practices such as ploughing, disking, hand planting, hand weeding and herbicides application were carried out at each site.

### 8.2.3. Data collection and analysis

Ten plants were randomly selected from each hybrid in each replication to measure the characters such as days to 50% flowering, plant height, panicle length, number of plants, number of panicles, panicle weight and grain yield. Analysis of variance was done using PROC GLM procedure in SAS 9.3 (SAS, 2011). The parent-offspring regression analyses using the F1 and F2 generations was used to obtain the variances and covariances and the .phenotypic and genotypic variance-covariance matrix were estimated using R statistic software (R Team, 2014). R software was also used to estimate the indices coefficients and determine the gains for the genotypes.

### 8.2.4. Construction of selection indices

Both the Smith-Hazel and desired gain indices consider the phenotypic (P) and genotypic (G) variance-covariance matrices. The genetic components of variance and covariance were calculated for grain yield, plant height, panicle length and panicle weight.

For Smith-Hazel index, the index coefficients were estimated from: $\mathbf{b = P^{-1}Ga}$

> Where: **b** = vector of the weights of phenotypic values (**bi** values), $\mathbf{P^{-1}}$ = inverse of the phenotypic (Vp) variance-covariance matrix, **G** = genotypic variance-covariance (Vg) matrix, **a** = vector of the economic weights attributed to genotypic values

The phenotypic variance and covariance matrix were symbolized by $V_p$ and genotypic variance and covariance symbolized by $V_g$. These were estimated and the solution of the matrix obtained according to Dabholkar (1999) equations as follows:

$$V_p = \begin{pmatrix} b_1\delta^2{}_{1} & b_2\delta^2{}_{12} & b_3\delta^2{}_{13} & b_4\delta^2{}_{14} \\ b_1\delta^2{}_{21} & b_2\delta^2{}_{2} & b_3\delta^2{}_{23} & b_4\delta^2{}_{24} \\ b_1\delta^2{}_{31} & b_2\delta^2{}_{32} & b_3\delta^2{}_{3} & b_4\delta^2{}_{34} \\ b_1\delta^2{}_{41} & b_2\delta^2{}_{42} & b_3\delta^2{}_{43} & b_4\delta^2{}_{4} \end{pmatrix}$$

where $\delta^2{}_1$, $\delta^2{}_2$, $\delta^2{}_3$ and $\delta^2{}_4$ are the phenotypic variances of the characters $x_1$, $x_2$, $x_3$ and $x_4$ respectively. The covariances were estimated from $\delta^2{}_{21} = \delta^2{}_{12}$, $\delta^2{}_{31} = \delta^2{}_{13}$, $\delta^2{}_{41} = \delta^2{}_{14}$, $\delta^2{}_{32} = \delta^2{}_{23}$, $\delta^2{}_{42} = \delta^2{}_{24}$, $\delta^2{}_{43} = \delta^2{}_{34}$. The genotypic variance and covariance matrices were estimated as:

$$V_g = \begin{pmatrix} a_1G^2{}_1 & a_2G^2{}_{12} & a_3G^2{}_{13} & a_4G^2{}_{14} \\ a_1G^2{}_{21} & a_2G^2{}_2 & a_3G^2{}_{23} & a_4G^2{}_{24} \\ a_1G^2{}_{31} & a_2G^2{}_{32} & a_3G^2{}_3 & a_4G^2{}_{34} \\ a_1G^2{}_{41} & a_2G^2{}_{42} & a_3G^2{}_{43} & a_4G^2{}_4 \end{pmatrix}$$

Where $a_1$, $a_2$, $a_3$ and $a_4$ are the weights applied and $G^2{}_1$, $G^2{}_2$, $G^2{}_3$ and $G^2{}_4$ are the estimates genotypic variances of the characters $x_1$, $x_2$, $x_3$ and $x_4$ respectively. The genotypic covariances were estimated as $G^2{}_{21} = G^2{}_{12}$, $G^2{}_{31} = G^2{}_{13}$, $G^2{}_{41} = G^2{}_{14}$, $G^2{}_{32} = G^2{}_{23}$, $G^2{}_{42} = G^2{}_{24}$, $G^2{}_{43} = G^2{}_{34}$.

The index coefficients for the Smith-Hazel method were then estimated by solving the matrix below:

$$bs = \begin{pmatrix} b_1\delta^2{}_1 & b_2\delta^2{}_{12} & b_3\delta^2{}_{13} & b_4\delta^2{}_{14} \\ b_1\delta^2{}_{21} & b_2\delta^2{}_2 & b_3\delta^2{}_{23} & b_4\delta^2{}_{24} \\ b_1\delta^2{}_{31} & b_2\delta^2{}_{32} & b_3\delta^2{}_3 & b_4\delta^2{}_{34} \\ b_1\delta^2{}_{41} & b_2\delta^2{}_{42} & b_3\delta^2{}_{43} & b_4\delta^2{}_4 \end{pmatrix}^{-1} * \begin{pmatrix} a_1G^2{}_1 & a_2G^2{}_{12} & a_3G^2{}_{13} & a_4G^2{}_{14} \\ a_1G^2{}_{21} & a_2G^2{}_2 & a_3G^2{}_{23} & a_4G^2{}_{24} \\ a_1G^2{}_{31} & a_2G^2{}_{32} & a_3G^2{}_3 & a_4G^2{}_{34} \\ a_1G^2{}_{41} & a_2G^2{}_{42} & a_3G^2{}_{43} & a_4G^2{}_4 \end{pmatrix} * a$$

$V_p$ $V_g$

For the Desired gain index, the weighting factors (**bi's**) were obtained as: $\mathbf{b = G^{-1}h}$

> Where **b** = vector of bi's, $\mathbf{G^{-1}}$ = inverse of genotypic variance-covariance matrix (Vg), and **h** = vector of desired gains from the trait

The weights for the desired gain index were computed by solving the matrix below:

$$b = \begin{pmatrix} a_1G^2{}_1 & a_2G^2{}_{12} & a_3G^2{}_{13} & a_4G^2{}_{14} \\ a_1G^2{}_{21} & a_2G^2{}_2 & a_3G^2{}_{23} & a_4G^2{}_{24} \\ a_1G^2{}_{31} & a_2G^2{}_{32} & a_3G^2{}_3 & a_4G^2{}_{34} \\ a_1G^2{}_{41} & a_2G^2{}_{42} & a_3G^2{}_{43} & a_4G^2{}_4 \end{pmatrix}^{-1} * h$$

$V_g$

#### 8.2.4.1. Economic and desired gain weights

Plant height was given an economic weight of one and desired gain of zero since not much improvement was needed in this trait for the present study. The desired gain of 10% was given to panicle length and panicle weight and 20% to grain yield (Table 8-2).

Table 8-2 Relative economic values and desired gains used in the study

| Trait | Relative Economic value (a) | Desired gain (h) |
|---|---|---|
| Plant height | 1 | 0 |
| Panicle length | 2 | 0.10 |
| Panicle weight | 2 | 0.10 |
| Grain yield | 4 | 0.20 |

After estimating the genetic components of variance and covariance and evaluating for the **b'**s, the values were substituted in the following index for each F2 family:

$I = b_1X_1 + b_2X_2 + \ldots + b_iX_i + \ldots + b_nX_n$

Following function originated the following:

$$I_y = b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4$$

Where: $I_y$ – selection index for grain yield, plant height, panicle length and panicle weight; $b_i$ – weights for each trait and $X_i$ – phenotypic value of the traits.

The phenotypic and genotypic variances for each trait were used to estimate the broad sense heritability ($h^2_{BS}$) as follows:

$$h^2{}_{(BS)} = \delta^2{}_g/\delta^2{}_p$$

Where: $h^2_{BS}$ – the broad-sense heritability, $\delta^2_g$ – genetic variance and $\delta^2_p$ – phenotypic variance.

The response to selection was calculated based on the indices. The selection intensity used was 5% corresponding to the value of 2.06.

The efficiency of the two indices was compared based on expected gain in the individual trait for yield (GY), plant height (PH), panicle length (PL) and panicle weight (PW).

Expected genetic advance for each trait (ΔG):

$$\Delta G = I * \Sigma\Sigma a_i b_i G_{ij} / (\Sigma\Sigma b_i b_j P_{ij})^{1/2}$$

Expected genetic advance for all studied traits (ΔH):

$$\Delta H = \Sigma a_i * \Delta G$$

For the desired gain index, the desired gain in the traits was considered by the expression: $\Delta g = Gb^{\wedge}_{I} / \delta_i$, where $\Delta g$ – vector of desired gain, G – genetic covariance matrix between traits, $b^{\wedge}$ - vector n and $\delta_i$ square root of the index variance.

## 8.3. Results

The analysis of variance indicated a highly significant difference among the traits for both the F1 hybrids and F2 families (Table 6-3). The observed traits in F2 were used to estimate the selection indices and the traits used were grain yield, plant height, panicle length and panicle weight. The mean for the four traits was higher in F1 than F2 whereby the plant height had a mean of 148 cm in F1 compared to 139 cm in F2. The panicle length was 34 cm and 27 cm for F1 and F2, respectively. The panicle weight and grain yield were 3.2 and 2.9 kg/plot for F1 and 2.6 and 2.3 kg/plot for F2. The heritability for the selected traits in F1 was found to be moderate for plant height ($h^2$=0.50) and low for the other traits such as panicle length ($h^2$=0.29), panicle weight ($h^2$= 0.19) and grain yield ($h^2$= 0.26).

Table 8-3 Mean squares for grain yield of F1 hybrids and F2 families tested across two environments

| Source of variation | DF | GY | PW | PL | PH |
|---|---|---|---|---|---|
| ***F1 hybrids*** | | | | | |
| Site | 1 | 400.52*** | 288.54*** | 908.56*** | 6767.04*** |
| Block(Rep) | 2 | $0.25^{ns}$ | 2.16*** | $37.25^{ns}$ | $484.95^{ns}$ |
| Entry | 35 | 2.71*** | 3.29*** | 41.27*** | 2054.20*** |
| Site*Entry | 35 | 1.71*** | 2.43*** | 66.31*** | 2132.76*** |
| Error | 142 | 0.601849 | 0.419763 | 18.94947 | 565.7284 |
| Total | 215 | | | | |
| ***F2 families*** | | | | | |
| Site | 1 | 64.03*** | 330.65*** | 5642.17*** | $6541.70^{ns}$ |
| Block(Rep) | 2 | $0.10^{ns}$ | 42.26*** | 709.03*** | 13499.45*** |
| Entry | 35 | 1.16*** | 3.22*** | 623.84*** | 21147.59*** |
| Site*Entry | 35 | 0.78*** | 2.10*** | 214.48*** | 3998.44*** |
| Error | 2086 | 0.360671 | 0.667209 | 84.6651 | 2048.532 |
| Total | 2159 | | | | |

$^{***}$ Significant at $p \leq 0.01$, $^{*}$ Significant at $p \leq 0.05$, ns -none significant, PH – plant height, PL - panicle length, PW – panicle weight, GY – grain yield, NPA – number of panicles, NP – number of panicles, DF – days to flowering.

### 8.3.1. Selection indices for four traits

Four traits were used to construct the selection indices based on the combinations of traits and their economic values using two methods of Smith-Hazel and desired gain. Data from the four common traits in the two generations were used to estimate the phenotypic and genotypic variance-covariance matrices. It was observed that the estimates of genotypic variances were smaller than their respective phenotypic variances for all traits. Plant height had higher variance in generations F1 and F2, followed by panicle length. Panicle weight and grain yield had smaller variances (Table 8-4 and Table 8-5).

Table 8-4 Phenotypic variance-covariance matrix for traits in F1 and F2 generation

| | PH | PL | PW | GY |
|---|---|---|---|---|
| F1 hybrids | | | | |
| PH | 244.035 | 12.7183 | 0.86693 | 0.85839 |
| PL | 12.7183 | 6.10678 | 0.39357 | 0.52869 |
| PW | 0.86693 | 0.39357 | 0.37577 | 0.37114 |
| GY | 0.85839 | 0.52869 | 0.37114 | 0.41818 |
| F2 families | | | | |
| PH | 278.97 | 8.03133 | 0.87614 | 0.82549 |
| PL | 8.03133 | 7.0018 | 0.35408 | 0.47834 |
| PW | 0.87614 | 0.35408 | 0.23652 | 0.18927 |
| GY | 0.82549 | 0.47834 | 0.18927 | 0.20521 |

Legend described in Table 8-3

Table 8-5 Genotypic variance-covariance matrix between the F1 and F2 generation

| | F2PH | F2PL | F2PW | F2GY |
|---|---|---|---|---|
| F1PH | 122.745 | 4.81655 | 0.29733 | 0.32288 |
| F1PL | 4.81655 | 1.74868 | 0.23564 | 0.26024 |
| F1PW | 0.29733 | 0.23564 | 0.07205 | 0.0926 |
| F1GY | 0.32288 | 0.26024 | 0.0926 | 0.10717 |

Legend described in Table 8-3

The Smith-Hazel index and desired gain index assumed the economic weights to estimate discriminant coefficients (bi's) by multiplying the weights with genotypic matrix and inverse phenotypic matrix. The calculation was based on the following formula:

$$b_{si} = \underset{\mathrm{V_g}}{\begin{pmatrix} 122.745 & 4.81655 & 0.29733 & 0.32288 \\ 4.81655 & 1.74868 & 0.23564 & 0.26024 \\ 0.29733 & 0.23564 & 0.07205 & 0.0926 \\ 0.32288 & 0.26024 & 0.0926 & 0.10717 \end{pmatrix}} * \underset{\mathrm{a}}{\begin{pmatrix} 1 \\ 2 \\ 2 \\ 4 \end{pmatrix}} * \left(V_p\right)^{-1}$$

Where: $b_{si}$ – estimates for Smith-Hazel discriminant coefficients, $V_g$ – genotypic matrix, a - economic weights and $V_p^{-1}$ – inverse phenotypic matrix.

$$b_i = \underset{V_g^{-1}}{\begin{pmatrix} 0.00407 & 0.09482 & 0.88392 & 1.02538 \\ 0.11484 & 0.28593 & 1.34467 & 1.16866 \\ 16.34928 & 5.02789 & 6.93938 & 5.66769 \\ 3.16198 & 5.39690 & 5.15602 & 4.66548 \end{pmatrix}} * \underset{h}{\begin{pmatrix} 0 \\ 0.1 \\ 0.1 \\ 0.2 \end{pmatrix}}$$

Where: $b_i$ – estimates for desired gain discriminant coefficients, $V_g$ – genotypic matrix, h - desired gain and $V_p^{-1}$ – inverse phenotypic matrix.

The results obtained were $bs_1$= 0.5264, $bs_2$= 0.3299, $bs_3$= -0.8748, $bs_4$= 2.7635 and $b_1$= 0.009, $b_2$=-0.4605, $b_3$=8.5510, $b_4$=-4.4310 corresponding to plant height, panicle length, panicle weight and grain yield, respectively. The mathematical function for selecting index was used to construct the Smith-Hazel index and desired gain index for each trait as presented in Table 8-6 and Table 8-7.

The results from the indices showed that the genotypic scores were not associated with highest grain yielding genotypes. The genotype ICSA 12A x SDS 6013R had the highest grain yield but for Smith-Hazel index was in position 18th. The genotype CK 60A x MZ 37R which had the highest score was the 7th position for grain yield. The genotypes TX 631A x MZ 37R, CK 60A x MZ 2R, SPL 38A x MZ 37R and TX 628A x MZ 37R were the top 5 scored genotypes respectively, in ranking. The selected superior genotypes using the desired gain index were different from those selected using the Smith-Hazel index. For the desired gain index, the top 5 scored genotypes were ICSA 19A x MZ 37R, 8601A x SDS 6013R, SPL 38A x SDS 6013R, CK 60A x MZ2R and TX 628A x IS 14257R. The genotype CK 60A x MZ 2R was the only genotype that appeared in the top five scores for the two indices. The other top five genotypes appeared for the desired gain index were in positions 16th,11th,18th and 7th respectively, in the Smith-Hazel index.

Table 8-6 Superior genotypes selection using Smith-Hazel index

| Rank | Entry | PH | PL | PW | GY | Smith-Hazel index |
|---|---|---|---|---|---|---|
| 1 | CK 60A x MZ 37R | 176.10 | 31.02 | 3.19 | 2.96 | 108.33 |
| 2 | TX 631A x MZ 37R | 166.30 | 35.69 | 3.84 | 3.54 | 105.73 |
| 3 | CK 60A x MZ 2R | 170.05 | 30.25 | 3.32 | 2.91 | 104.63 |
| 4 | SPL 38A x MZ 37R | 167.30 | 32.95 | 3.03 | 2.50 | 103.19 |
| 5 | TX 628A x MZ 37R | 167.35 | 30.04 | 3.07 | 2.54 | 102.34 |
| 6 | LARSVYT 46A x SDS 6013R | 166.10 | 31.91 | 2.64 | 2.29 | 101.97 |
| 7 | TX 631A x SDS 6013R | 157.65 | 34.49 | 2.84 | 2.73 | 99.41 |
| 8 | LARSVYT 46A x MZ 2R | 159.75 | 30.63 | 2.28 | 2.23 | 98.35 |
| 9 | LARSVYT 46A x MZ 37R | 155.65 | 31.53 | 2.52 | 2.30 | 96.49 |
| 10 | LARSVYT 46A x IS 14257R | 151.50 | 32.76 | 3.16 | 2.76 | 95.42 |
| 11 | ICSA 21A x IS 14257R | 149.05 | 31.81 | 3.52 | 3.24 | 94.83 |
| 12 | TX 628A x MZ 2R | 148.55 | 32.62 | 2.85 | 2.46 | 93.27 |
| 13 | ICSA 21A x SDS 6013R | 150.05 | 29.84 | 2.12 | 1.90 | 92.22 |
| 14 | ICSA 12A x MZ 37R | 142.60 | 31.49 | 3.50 | 3.44 | 91.91 |
| 15 | 8601A x IS 14257R | 148.50 | 26.01 | 2.90 | 2.75 | 91.81 |
| 16 | 8601A x MZ 2R | 147.70 | 28.33 | 2.67 | 2.24 | 90.94 |
| 17 | ICSA 19A x SDS 6013R | 142.10 | 32.28 | 2.99 | 2.75 | 90.44 |
| 18 | ICSA 12A x SDS 6013R | 134.40 | 35.21 | 4.12 | 3.99 | 89.78 |
| 19 | TX 631A x IS 14257R | 138.30 | 32.39 | 2.73 | 2.49 | 87.96 |
| 20 | SPL 38A x MZ 2R | 140.20 | 29.54 | 2.61 | 2.23 | 87.43 |
| 21 | ICSA 12A x IS 14257R | 143.40 | 25.39 | 2.55 | 2.05 | 87.31 |
| 22 | TX 631A x MZ 2R | 140.90 | 30.94 | 2.54 | 1.85 | 87.28 |
| 23 | ICSA 19A x IS 14257R | 136.10 | 30.18 | 3.31 | 2.93 | 86.78 |
| 24 | TX 628A x IS 14257R | 133.95 | 31.92 | 3.57 | 3.19 | 86.72 |
| 25 | 8601A x MZ 37R | 133.90 | 30.40 | 3.29 | 3.12 | 86.26 |
| 26 | SPL 38A x IS 14257R | 137.90 | 31.05 | 2.19 | 1.84 | 86.00 |
| 27 | TX 628A x SDS 6013R | 139.70 | 27.21 | 2.54 | 1.99 | 85.80 |
| 28 | ICSA 21A x MZ 2R | 134.35 | 31.68 | 2.90 | 2.48 | 85.49 |
| 29 | ICSA 19A x MZ 37R | 129.20 | 29.58 | 3.61 | 3.35 | 83.85 |
| 30 | SPL 38A x SDS 6013R | 128.90 | 27.85 | 3.20 | 2.82 | 82.03 |
| 31 | CK 60A x IS 14257R | 127.55 | 29.69 | 2.68 | 2.17 | 80.60 |
| 32 | ICSA 21A x MZ 37R | 123.40 | 29.75 | 2.39 | 2.05 | 78.34 |
| 33 | ICSA 19A x MZ 2R | 119.25 | 31.92 | 2.83 | 2.53 | 77.81 |
| 34 | 8601A x SDS 6013R | 120.20 | 28.61 | 3.20 | 2.69 | 77.33 |
| 35 | CK 60A x SDS 6013R | 118.80 | 30.38 | 2.36 | 2.26 | 76.74 |
| 36 | ICSA 12A x MZ 2R | 115.10 | 29.00 | 2.60 | 2.34 | 74.33 |

PH – plant height, PL - panicle length, PW – panicle weight, GY – grain yield

Table 8-7 Superior genotypes selection using Desired gain index

| Rank | Entry | PH | PL | PW | GY | Desired gain index |
|---|---|---|---|---|---|---|
| 1 | ICSA 19A x MZ 37R | 129.20 | 29.58 | 3.61 | 3.35 | 3.58 |
| 2 | 8601A x SDS 6013R | 120.20 | 28.61 | 3.20 | 2.69 | 3.33 |
| 3 | SPL 38A x SDS 6013R | 128.90 | 27.85 | 3.20 | 2.82 | 3.21 |
| 4 | CK 60A x MZ 2R | 170.05 | 30.25 | 3.32 | 2.91 | 3.05 |
| 5 | TX 628A x IS 14257R | 133.95 | 31.92 | 3.57 | 3.19 | 2.93 |
| 6 | ICSA 19A x IS 14257R | 136.10 | 30.18 | 3.31 | 2.93 | 2.70 |
| 7 | TX 628A x MZ 37R | 167.35 | 30.04 | 3.07 | 2.54 | 2.66 |
| 8 | ICSA 12A x SDS 6013R | 134.40 | 35.21 | 4.12 | 3.99 | 2.56 |
| 9 | ICSA 21A x IS 14257R | 149.05 | 31.81 | 3.52 | 3.24 | 2.41 |
| 10 | ICSA 12A x IS 14257R | 143.40 | 25.39 | 2.55 | 2.05 | 2.26 |
| 11 | TX 631A x MZ 37R | 166.30 | 35.69 | 3.84 | 3.54 | 2.23 |
| 12 | 8601A x IS 14257R | 148.50 | 26.01 | 2.90 | 2.75 | 1.94 |
| 13 | TX 628A x SDS 6013R | 139.70 | 27.21 | 2.54 | 1.99 | 1.59 |
| 14 | 8601A x MZ 37R | 133.90 | 30.40 | 3.29 | 3.12 | 1.51 |
| 15 | ICSA 12A x MZ 37R | 142.60 | 31.49 | 3.50 | 3.44 | 1.41 |
| 16 | CK 60A x MZ 37R | 176.10 | 31.02 | 3.19 | 2.96 | 1.41 |
| 17 | 8601A x MZ 2R | 147.70 | 28.33 | 2.67 | 2.24 | 1.16 |
| 18 | SPL 38A x MZ 37R | 167.30 | 32.95 | 3.03 | 2.50 | 1.14 |
| 19 | LARSVYT 46A x IS 14257R | 151.50 | 32.76 | 3.16 | 2.76 | 1.07 |
| 20 | CK 60A x IS 14257R | 127.55 | 29.69 | 2.68 | 2.17 | 0.72 |
| 21 | TX 631A x MZ 2R | 140.90 | 30.94 | 2.54 | 1.85 | 0.49 |
| 22 | ICSA 21A x MZ 2R | 134.35 | 31.68 | 2.90 | 2.48 | 0.38 |
| 23 | SPL 38A x MZ 2R | 140.20 | 29.54 | 2.61 | 2.23 | 0.09 |
| 24 | TX 628A x MZ 2R | 148.55 | 32.62 | 2.85 | 2.46 | -0.23 |
| 25 | ICSA 19A x SDS 6013R | 142.10 | 32.28 | 2.99 | 2.75 | -0.25 |
| 26 | ICSA 12A x MZ 2R | 115.10 | 29.00 | 2.60 | 2.34 | -0.40 |
| 27 | ICSA 19A x MZ 2R | 119.25 | 31.92 | 2.83 | 2.53 | -0.60 |
| 28 | LARSVYT 46A x SDS 6013R | 166.10 | 31.91 | 2.64 | 2.29 | -0.80 |
| 29 | ICSA 21A x MZ 37R | 123.40 | 29.75 | 2.39 | 2.05 | -1.24 |
| 30 | TX 631A x IS 14257R | 138.30 | 32.39 | 2.73 | 2.49 | -1.35 |
| 31 | LARSVYT 46A x MZ 37R | 155.65 | 31.53 | 2.52 | 2.30 | -1.77 |
| 32 | TX 631A x SDS 6013R | 157.65 | 34.49 | 2.84 | 2.73 | -2.26 |
| 33 | SPL 38A x IS 14257R | 137.90 | 31.05 | 2.19 | 1.84 | -2.48 |
| 34 | ICSA 21A x SDS 6013R | 150.05 | 29.84 | 2.12 | 1.90 | -2.71 |
| 35 | CK 60A x SDS 6013R | 118.80 | 30.38 | 2.36 | 2.26 | -2.77 |
| 36 | LARSVYT 46A x MZ 2R | 159.75 | 30.63 | 2.28 | 2.23 | -3.03 |

PH – plant height, PL - panicle length, PW – panicle weight, GY – grain yield

The selection intensity of 5% was used to select the superior genotypes. The Smith-Hazel index showed genetic gain for the traits plant height, panicle length and grain yield with values of 75.47%, 10.14% and 7.21%, respectively. Undesired gain in panicle weight of -2.57% was also observed. In contrast, the desired gain index resulted in the following genetic gain; panicle weight (25.08%) and plant height (1.29%), but undesired gain in grain yield and panicle length with a value of 11.56% and 14.15%, respectively (Table 8-8). The expected genetic gain was 18.06% for Smith-Hazel index and 0.04% for desired gain index.

Table 8-8 Estimates of the percentage gain based on selection differential for the four traits

| Trait | Smith-Hazel index | Desired gain index |
|---|---|---|
| Plant height | 75.47 | 1.29 |
| Panicle length | 10.14 | -14.15 |
| Panicle weight | -2.57 | 25.08 |
| Grain yield | 7.21 | -11.56 |
| Expected genetic advance | 18.06 | 0.04 |

## 8.4. Discussion

The results of this study showed significant differences for all traits evaluated. The estimation of genetic and phenotypic variances showed high variability. These results imply that simple selection methods can be used to identify superior genotypes. High degree of genetic variability allows selection by simple methods that result in significant genetic gain (Coimbra *et al.*, 1999). The higher and mid values for genetic variances are essential for selection of superior genotypes (Laviola *et al.*, 2012).

The heritability estimates of the selected traits were moderate for plant height and low for the other traits (panicle length, panicle weight and grain yield). The low and moderate heritability estimates could imply higher effects of the environment across experimental sites and less additive genetic variance. Presence of different environments may underestimate heritability estimates (Bertoldo *et al.*, 2010). The values of heritability for some traits indicated that there are good prospects for selecting superior individual genotypes within the same population. Hazel (1943) stated that improvement from phenotypic selection is related to the additive genetic variance (narrow sense heritability) of the observed variance and it differs from trait to trait.

The present study aimed at selecting superior genotypes in terms of grain yield and other traits. Two selection indices were used to select superior genotypes. The Smith-Hazel index had higher genetic gain for most of the individual traits of interest. The desired gain index was not important for selection of the progenies in the study population because it resulted in undesired gain of the main trait of interest (grain yield). For expected genetic gain, the Smith-Hazel index was also superior to desired gain index. Similar results of undesired gain for traits in the desired gain index (Pešek and Baker,1969) was reported by Viana *et al.* (2017) for the number of fruits, fruit mass and longitudinal diameter of the fruits. On the other hand, de Paula *et al.* (2002) found that the desired gain index was similar to other selection methods when studying genetic gain for forest breeding in Eucalyptus. Moreover, the same method was found to obtain genetic gain for production traits and fruit quality in papaya (Ide, 2008). Desired positive genetic gain was also obtained by Gonçalves *et al.* (2007) when selecting progenies for recombination in passion fruit. This result is in agreement with findings by Silva and Viana (2012).

The interest of the breeder is to develop sorghum plants that have high grain yield and other positive yield components such as plant height and panicle size. The Smith-Hazel index had higher scores for most of the traits of interest. This indicated that the method was more appropriate for selection of the superior hybrids in the study population. Similar results were found by Viana *et al.* (2017) on the study of passion fruits where Smith (1936) and Hazel (1943) indices delivered higher genetic gain for number of fruits, yield and fruit mass. Smith-Hazel predicted higher gain than other indices when one of the main traits is yield (Cruz *et al.*, 1993; Granate *et al.*, 2002). Contrasting results were reported by Silva and Viana (2012) for Smith-Hazel index when studying alternatives for selection in recurrent intra-population of passion fruits where the genetic gain was negative for the traits of interest. Mock and Bakri (1976) proposed to assign Smith-Hazel index for cold tolerance in maize although it was found difficult to assign weights for cold-tolerance. They concluded that Smith-Hazel index placed too much emphasis on percentage emergence when economic weights were equal for all traits. On the other hand, Laviola *et al.* (2012) reported that most of the elevated genetic gain is expected in the initial stages of the breeding programme because most plants tend to produce very little and groups of plants with high yield will be selected.

The result of different indices efficiencies demonstrates that indices differed in selection strategies and efficiency according to the population and traits used in the study (Crosbie *et al.*, 1980). Williams (1962) stated that the best way of avoiding estimate weights of observable variates using known weights of non-observable linear function is comparing two or more indices for selection. The use of a selection index is to maximize the mean value of traits while retaining a specific fraction of the members of the original population (Cochran, 1951; Singh *et al.*, 2011). Therefore, selection should be based on a set of traits that allows the simultaneous achievement of reasonable genetic gain (Vittorazzi *et al.*, 2017).

The predicted gains with the selection index of Smith (1936) and Hazel (1943) were higher than predictions based on desired gain of Pešek and Baker (1969). Therefore, the selection of superior hybrids was done using Smith-Hazel index according to the experimental conditions. The prediction of the desired gain index (Pešek and Baker, 1969) underestimates the gain for plant height, panicle length and grain yield. This might be because the weights given to the traits were not adequate to express the genetic gain. On the other hand, the selection index of Smith (1936) and Hazel (1943) showed greater values for most of the traits of interest under study. Young (1961) stated that the maximum selection of superior genotypes is achieved when the traits are of equal importance and it increases with increase in number of traits under selection, but decreases with increasing differences in relative importance.

## 8.5. Conclusion

The results showed that the scores from the selection indices were not associated with highest grain yielding genotypes. The genotype CK 60A x MZ 37R had highest score followed by the genotypes TX 631A x MZ 37R, CK 60A x MZ 2R, SPL 38A x MZ 37R and TX 628A x MZ 37R. The selection index proposed by Smith-Hazel was the most efficient for simultaneous selection of hybrids for grain yield and other yield attributes. This method allowed the prediction of genetic gain for the traits evaluated together and a more efficient selection of superior genotypes. This suggested that sorghum breeders should consider the use of different selection strategies and indices to select superior genotypes for grain yield and other traits to improve the crop according to the trait of interest. Moreover, knowledge of the economic weights of the traits demonstrated to be a fundamental key when comparing different indices. Therefore, it is recommended for future studies to compare more selection indices for selecting superior genotypes.

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# 9. General Research Overview

## 9.1. Introduction

The research carried out in the present study explored ICRISAT derived and Mozambican sorghum germplasm for hybrid potential under different environments. This chapter gives an overview on the objectives and major findings from the research. It also, highlights the implications of the findings to breeding strategies. The following specific objectives were used to test the hypothesis under the study:

i. Assess farmers' preferences and needs in sorghum varieties through participatory rural appraisal and participatory plant breeding.

ii. Determine the morphological characteristics that distinguish desirable breeding materials to be exploited in hybrid development.

iii. Study the genotype by environment (G x E) interactions during development of improved varieties.

iv. Determine the combining ability for grain yield among the Mozambican germplasm by using line by tester mating design, and

v. Construct a selection index that can be used to select superior genotypes.

## 9.2. Summary of research findings

### 9.2.1. An appraisal of sorghum farmers' trait preferences, production threats and opportunities for plant breeding in central region of Mozambique

- The study demonstrated that farmers select varieties based on their needs and adaption of the variety to the farming system. The most preferred attributes by farmers included: early maturity, high grain yield, white grain colour, food quality and tall plants for use of the stem as building material.

- Extension service is a key to guide farmers on which technologies they can use to improve sorghum productivity and access to markets.

- The major constraint was drought. The other production challenges were weeding, thinning out plants, threshing, sieving, cutting and transporting grain during and after harvest.

- The important constraints in sorghum commercialization were a combination of low prices, unavailability of seed and limited markets.

- The involvement of more women in sorghum production and marketing could help production improvement in the country. This could also improve quality of seeds used in sorghum production with a market orientation point of view.

### 9.2.2. Identification of important morphological traits in Mozambican sorghum germplasm using multivariate analysis

- The morphological traits such as earliness, grain yield, seed size, drought and bird attack were mentioned as the important traits. Those traits can be used in hybridization programmes.

- Genotypes 150B, IS 14257R, LARSVYT 46B, TX 631B, TX 630B and 8601B could be used for improving earliness, while for late maturity genotypes MA 6B, A 6352R, ICSA 19B and MZ 30R could be selected.

- Grain size and weight were associated with grain yield and genotypes IS 7179R, SPL 9B, A 6353R, SPL 38B, SDS 6013R and MZ 2R were identified.

- Genotypes ICSA 21B, 8610B, MZ 37R, 150B and MZ 2R presented an intense stay green character that can be exploited for drought tolerance variety deployment.

- IS 7179R can be used for hybridization to reduce bird attack due to the presence of awns and for mould resistance, lines 8601B and TX 630B can be used.

- The genotypes grouped in different clusters in the analysis and revealed similarity of some lines used in the breeding programme. This will help reducing the number of lines involved in crosses and better explore the combining ability of those lines.

### 9.2.3. Combining Ability and Heterosis for sorghum grain yield and secondary traits across lowland and midland Mozambique

- The GCA mean squares for testers were significant for the following traits; grain yield, days to 50% flowering, plant height and biomass.

- Testers IS 14257R and MZ 37R showed positive GCA values for grain yield, and negative and significant GCA effects for days to 50% flowering, while tester SDS 6013R had negative and significant GCA effects for plant height. Lines LARSVYT 46A, SPL 38A and TX 631A showed positive GCA effects for grain yield, while 8601A, ICSA 12A, TX 631A and LARSVYT 46A had highly significant negative GCA effects for days to 50% flowering

- For plant height, lines TX 631A, ICSA 12A, ICSA 21A and TX 628A were significant, while for panicle length, lines LARSVYT 46A, SPL 38A and TX 631A had positive significant GCA effects.
- Negative significant GCA values for disease scores were observed for ICSA 12A and TX 631A for rust disease.
- Hybrids resistant to rust were ICSA 12A x MZ 2R, ICSA 12A x SDS 6013R and TX 631A x SDS 6013R, and moderately resistant were LARSVYT 46A x, IS 14257R, LARSVYT 46A x SDS 6013R and 8601A x MZ 37R. Most of the hybrids were resistant to moderately resistant to *Cercospora spp,* and for anthracnose all hybrids were classified as resistant.
- The earliest flowering hybrids were TX 631A x IS 14257R and 8601A x IS 14257R and Macia (check). In addition, Macia had the shortest plants after TX 631A x MZ 2R. The largest panicle was observed in hybrid LARSVYT 46A x MZ 2R.
- None of the checks ranked in the top ten genotypes for grain yield. The hybrid with the highest average grain yield across environments was TX 631A x MZ 37R followed by SPL 38A x SDS 6013R and LARSVYT 46A x IS 14257R.
- Heterosis over the mid-parent and over best check ranged from 52 to 194% and 5 to 76% respectively.
- Lines TX 631A and 8601A combined with tester MZ 37R displayed levels of heterosis of 182% and 148%, respectively. Line LARSVYT 46A with tester IS 14257R displayed level of heterosis of 141%.
- The testers IS 14257R and MZ 37R had desired GCA effect for grain yield and days to 50% flowering while lines LARSVYT 46A, SPL 38A and TX 631A had desired GCA effect for grain yield. MZ 37R and IS 14257R were the testers with better performance and resulted in hybrids with high levels of heterosis for most of the characters that contribute to grain yield.

### 9.2.4. Influence of genotype x environment interaction on grain yield performance of sorghum genotypes across lowlands and midlands of Mozambique

- All the test environments for hybrids were discriminative but not representative. For hybrids: environments Mapupulo 17, Sussundenga 16 and Sussundenga 17 were the most discriminating environments. Mapupulo 17 was the environment slightly representative. One mega-environment was observed for the parents and five mega-environments for the hybrids.

- The best parents in the mega-environments were: P12 (CK 60A) and P5 (LARSVYT46A). Additionally, the specific environments for the hybrids were: Mapupulo 17 (GS2 = LARSVYT46A x IS 14257R), Sussundenga 16 (GS11 = SPL 38A x SDS 6013R), Sussundenga 17 (GS38 = SIMA), Chókwè 17 (GS7 = 8601A x SDS 6013R) and Chókwè 16 and Maniquenique 17 (GS32 = CK 60A x MZ 37R).

- CK 60A and LARSVYT46A were high yielding and stable parents, while high yielding and stable hybrids were; GS9 (SPL 38A x MZ 2R), GS36 (TX 631A x MZ 37R), GS1 (LARSVYT46A x MZ 2R) and GS34 (TX 631A x IS 14257R).

### 9.2.5. Participatory variety selection of sorghum hybrids using Farmers' preferences and knowledge in central area of Mozambique

- Involving farmers in the evaluation of the hybrids and during selection revealed the importance of not only targeting yield in the development of new varieties.

  In addition to yield, farmers identified other important traits such as: earliness, grain size, grain colour and plant height. Drought tolerance and head size were mentioned as important traits used to compare new varieties with local ones.

- The results of on-station and on-farm trials facilitated the identification of hybrid TX 631A x MZ 37R as high yielding with short plants. Moreover, the tallest plants on-station were found in hybrid SPL 38A X SDS 6013R. In contrast, local variety had the tallest plant height during on-farm evaluation.

- Additionally, the local variety had the highest number of days to 50% flowering, while for the hybrids, SLP 38A x MZ 2R had the longest period to 50% flowering followed by

LARSVYT 46A x MZ 37R, SPL 38A x SDS 6013R, TX 631A x MZ 37R, ICSA 19A x SDS 6013R and LARSVYT 46A x SDS 6013R.

- The mean yield for the local variety was 1.0 $t.ha^{-1}$ and the high yielding hybrid had 3.0 $t.ha^{-1}$ (TX 631A x MZ 37R).

### 9.2.6. Identification of superior sorghum genotypes from farmers' preferences traits using selection indices

- Index scores were not associated with highest grain yielding genotypes.
- The Smith-Hazel index was the most efficient procedure for simultaneous selection of hybrids for grain yield and other yield attributes where the genotype CK 60A x MZ 37R had the highest score followed by the genotypes TX 631A x MZ 37R, CK 60A x MZ 2R, SPL 38A x MZ 37R and TX 628A x MZ 37R.
- The use of Smith-Hazel index and desired gains index showed the importance of knowing well the traits to be attributed the economic weights or desired response but it is recommended in future studies, the comparison of more selections indices and more traits when select superior genotypes.

## 9.3. Implication for breeding

The participatory rural appraisal and participatory plant breeding studies showed that breeders and farmers need to work together to develop varieties that will be acceptable to farmers based on their agro-ecological environments and variety preferences. According to the farmers' production environments and selection criteria; a variety can have a combination of high grain yield, early maturity, tall plants and drought tolerance characteristics. This implies that breeders should exploit traits that confer drought tolerance such as stay green combined with large grain size and early flowering. From the results, it was clear that two groups of varieties needed to be deployed; one that responds to high yield and early maturity and the other to high yield with tall plants.

The study also highlighted the need for scientists to take advantage of the available technologies and approaches such as molecular technologies combined with an interactive breeding to improve existing varieties or develop new ones. In addition, the use of some landrace traits in hybrid deployment would have a large positive impact on the households. Besides that, farmers still use recycled seed which results in yield reduction in a hybrid, thus farmer education in sorghum hybrids is important.

A combination of several methods involving farmers from the start where breeding objectives are being defined could increase the crop adoption and dissemination of new improved varieties to other farmers across location. The participation of all stakeholders from formal breeding to farmer breeding, including the consumers and industrialist in development of varieties is a crucial step for variety selection and use.

The results of the Mozambican sorghum germplasm diversity study have provided interesting information that is useful in the improvement of sorghum varieties. The traits that are not strongly related could be exploited in recombination breeding in future. The multivariate analyses clearly showed the grouping of the genotypes according to the characters outlined in the study. Diversity index gave emphasis to the results by evidently showing more diverse traits which can be used in hybridization for grain yield, pest and disease resistance and tolerance to drought. Therefore, these results have implications in the selection of parents for use in sorghum improvement programme.

Morphological characteristics assist breeders in understanding the importance of the germplasm diversity, which will classify important characters that are highly preferred by farmers such as earliness, grain yield, plant height and grain colour. Breeding for new varieties with good storability, resistance to pests and diseases according to farmers criteria could enhance adoption of those varieties.

Selection of superior genotypes using different traits of interest in selection indices should be considered by sorghum breeders for improvement of varieties for multi-traits.