# Heterosis, Combining Ability and Yield Performance of Sorghum Hybrids for the Semi -Arid Lands of Kenya

By

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**DEDICATION**

This thesis is dedicated to my parents, Henry Okoth Okanga and Mama Immaculate Opetu Okoth. Thank you for your prayers.

**DECLARATION**

The thesis is my original work and has not been submitted for award of any degree at any other university.

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**ACRONYMS**

| | |
|---|---|
| AMMI | Additive Main and Multiplicative Interaction |
| ANOVA | Analysis of variance |
| ASALs | Arid and Semi-Arid Lands |
| ASARECA | Association for Strengthening Agricultural Research in Eastern and Central Africa |
| C4 Plants | Plants exhibiting a c4 photosynthetic parthway |
| CGMS | Cytoplasmic genetic male sterility |
| DUS | Distinctiveness, Uniformity and Stability tests |
| EARCAL | East Africa Regional Cereals and Legumes network |
| EARSAM | East Africa Regional Sorghum and Millets network |
| ECARSAM | East and Central Africa Regional Sorghum and Millets |
| $F_1$ | First filial generation |
| FAO | Food and Agriculture Organization |
| FAOSTAT | The Food and Agriculture Organization Corporate Statistical Database |
| G X E/ GEI | Genotype by Environment Interaction |
| GCA | General combining ability |
| IBPGR | International Board of Plant Genetic Resources |
| ICRISAT | International Crops Research Institute for the Semi-Arid Tropics |
| ICSA | ICRISAT Sorghum A- line |
| INTSORMIL | International Sorghum and Millets program |
| IPCA | Interaction Principal Component Analysis |
| KALRO | Kenya Agricultural and Livestock Research Organization |
| KBK | Kiboko |
| KYM | Kampi ya Mawe |
| Mt/ha | Metric tonnes per hectare |
| Subsp. | Sub species |
| USA | United States of America |

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**ABSTRACT**

Sorghum is ranked third in importance in Kenya and forms an integral part in the farmers' livelihoods as a food and nutritional security crop. Despite its critical role, its production and productivity has been low. Drought and use of low yielding unstable varieties are part of the major causes of the low production. A study was conducted at Kenya Agricultural and Livestock Research Organizations (KALRO) Kiboko and Kampi ya Mawe in 2014 and 2014-2015 with an aim of estimating the genetic potential, heterosis and grain yield stability of sorghum hybrids and their parents. A total of 34 male sterile lines from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) India and 12 restorer lines from ICRISAT Kenya were used to generate 34 $F_1$ hybrids following the North Carolina Mating Design I. The hybrids and their parents were evaluated at the two sites in a 9 x 9 square lattice trial design in three replications. Data were collected on grain yield, fresh biomass yield and their related traits. The levels of heterosis, combining ability, correlation, heritability and stability were estimated. Highly significant genotypic differences were recorded for all the traits. Grain and biomass yield of the hybrids was largely determined by the *per se* performance of the parents. Five hybrids were better yielding than the checks ATX 623 x Macia and Seredo. Biomass and grain yield were significantly and positively correlated hence development of dual purpose hybrids is possible. Negative correlation between days to flowering and grain yield greatly demonstrated that early high yielding hybrids would escape drought hence fitting well in the production systems of the Semi-Arid lands (SALs). High phenotypic coefficients of variation (PCV) and genotypic coefficients of variation (GCV) scores for biomass yield, number of tillers and plant height shows that improvement is possible through selection. Selection would be more effective for fresh biomass yield, panicle exertion and plant height in hybrids and their parents due to high heritability. Heterosis was revealed with both positive and negative magnitude for the studied traits. Hybrids ICSA 11037 x Macia, ICSA 11004 x ICSR 24008 and ICSA 29007 x ICSR 24008 had high positive standard, mean and better parent heterosis for grain yield. Hence, these hybrids can be recommended for onfarm testing and possible release in Kenya. Inheritance of the traits was controlled by both additive and non-additive gene action hence genetic gains can be realized through direct selection. The best restorer for biomass yield improvement was ICSV 700 whereas ICSR 160 was a

good general combiner for grain yield. Wahi and Hakika were good combiners for shorter height. Yields of sorghum hybrids were greatly influenced by the genotype and the environment where they were cultivated. Hybrids ATX 623 x Macia, ICSA 11004 x ICSR 24008 and ICSA 11033 x ICSR 160 were high yielding and stable. Selection of hybrids could be done effectively using multiple environments data.

**Key words:** *Heterosis, stability, restorers, mating design, heritability*

# CHAPTER ONE

# INTRODUCTION

## 1.1 Background information

Cultivated sorghum [*Sorghum bicolor* (L.) Moench], is a diploid (2n=20) often self-pollinated crop, with outcrossing rate of 0.6 - 50% (Doggett, 1988 and Rao, 2008) and belongs to the family Poaceae (Deepak, 2014). The Sorghum genus has four species: *Sorghum bicolor* (most common), *Sorghum almum*, *Sorghum halepense* and *Sorghum propinquum* (De wet, 1978). The species bicolor has 3 sub– species: *Verticiflorum (arundinaceum)*, *Bicolor* and *Drummondii* (Anon, 1). Sorghum originated 5000-7000 years ago in Ethiopia and Sudan (Kimber *et al*, 2013) and was first domesticated in the area between western Ethiopia and eastern Chad (Dogget and Prasada, 1995). From its centre of origin, the crop spread to Asia via India then spread to America through the slave trade in the 19$^{th}$ century (Shewale, 2008).

Although ranked 5$^{th}$ globally, sorghum is the second most important cereal crop after maize in Africa. Globally, sorghum is produced on 38m ha and approximately 60% of this land is in Africa (FAOSTAT, 2012). It is an important staple food, animal feed and industrial crop (Bhosale *et al*., 2011). Sorghum is a predominantly drought and heat tolerant crop (Robert and David, 2009) mostly found in the arid and semi-arid parts of the world (Ahamed *at al*., 2015). Climate change effects such as erratic rainfall distribution and higher temperatures affect crop production but sorghum's drought tolerance nature, has made it an important crop in combating such effects.

## 1.2 Sorghum production constraints in Kenya

Sorghum is an integral part of the livelihoods of the farmers where apart from being a food and nutritional security crop it also plays a role in socio-economic aspects of farmers' lives (Kudadjie *et al*., 2004). Most of the sorghum is produced in Eastern, Nyanza, Western and Rift Valley provinces of Kenya, which account for 43%, 41%, 9% and 7% of Kenya's total sorghum production respectively (Kilambya and Witwer, 2013).

Despite playing a critical role as the third most important cereal in Kenya, sorghum production fluctuates from one year to another. The lowest sorghum production was

experienced in the year 2008. The low sorghum productivity is due to abiotic and biotic stress factors (Muturi, 2013). The main abiotic stress factors include drought, high temperatures, low yielding varieties, low soil fertility, poor agronomic practices and lack of markets (Olembo et al., 2010). Sorghum is one of the key crops in the drought stressed semi-arid areas of Kenya (Mamoudou, 2006). These semi-arid areas cover 80% of the Kenyan land mass which are characterized by limited and erratic rainfall and high temperatures. One of the major challenges of sorghum production in these agro ecologies is the use of low yielding and unstable sorghum varieties. The low productivity of sorghum worsens the food security situation of these fragile environments.

### 1.3 Problem statement

Sorghum plays a critical role as food security and income generating crop in the semi-arid areas of Africa (Muii et al, 2013). Sorghum grain demand in East Africa is steadily growing due to shifts of the human population towards healthy foods, emerging new markets like the composite breakfast and weaning flours, malting, ethanol, and livestock feed. Sorghum grain demand in Kenya by the year 2016 was 40,000MT in the brewing industry and 200,000MT in the feed industry (Waikwa, 2016). However, the total annual production in Kenya was 117,000MT the same year. Hence, these production figures are too low to satisfy the demand.

The area under sorghum production in Kenya has been growing steadily however, the production has remained low. The low production is due: to low yields (Okiyo et al., 2008), low levels of technology adoption (Omoro, 2013), little attention given to sorghum subsector by the Kenyan government (Mwadalu and Mwangi, 2013), poor market structures, low product diversity, damage due to biotic stresses such as insect pests, diseases and Striga, drought (Omoro, 2013) and the use of low quality seed. The average grain yields in Kenya between 1990 and 2011 remained low at $0.8 tha^{-1}$. The low grain yields were caused by use of low yielding cultivars and concentration of sorghum production in ASALs (Chepng'etich et al., 2014). These ASALs are characterized by frequent and severe droughts which sometimes spread to a span of two to three years in a row (Mwadalu and Mwangi, 2013). The major drought incidents which occurred in 2001, 2003, 2006, 2009 and 2011 resulted in low

agricultural productivity (Mwadalu and Mwangi, 2013). The low productivity led to perennial food shortages and high poverty levels in the ASALs of Kenya.

### 1.4 Justification of the study

Sorghum improvement should be geared towards producing high yielding cultivars (hybrids and open pollinated varieties) resistant to key abiotic and biotic stresses with farmer and market preferred traits. Sorghum breeding achievements in Africa led to development and release of open pollinated varieties with pest, disease and striga tolerance (Obilana, 2004). Sorghum hybrids research in Kenya is done by the national agricultural research systems (NARS) and ICRISAT and this has led to release of one hybrid with good baking and malting qualities by Egerton University, and three hybrids have been submitted by Kenya Seed Company for DUS testing. The released hybrids have a 30-40% yield advantage over the improved open pollinated varieties (Manyasa, 2016).

The wide variability available in grain yield, pests and disease resistance, striga resistance, stay green, tillering, maturity, height and fertility reaction among the seed parents at Hyderabad (Bantilan et al, 2004) can be used for genetic improvement through exploitation of heterosis. Cytoplasmic male sterility in sorghum identified by Stephens and Holland (1954) has made hybrid development in sorghum possible (Ashok et al., 2008). More than 700 cytoplasmic genetic male sterile (CGMS) lines are available at ICRISAT- India for use in hybrid making (Ashok et al., 2008). Though found adaptable in Kenya, these CGMS lines have not been fully utilized in sorghum hybrid development.

The importance of these CGMS lines depends on their combining ability and heterotic grouping with other sorghum germplasm used as parents in hybridization. Adapted restorer parents with good fertility restoration, early maturity and superior grain qualities are available at ICRISAT- Nairobi for hybrid making. Information on the quantitative genetic studies in sorghum hybrids and their parents have been extensively done in India. However, the results from those studies cannot be adequately applied to the semi-arid conditions of Kenya.

Selection of superior hybrids based on per se performance alone is not effective. Therefore, knowledge on the combining ability helps in understanding the inheritance

of the traits being studied (Bertan et al., 2007) making selection of parental lines easier. Information on the combining ability of CGMS lines from ICRISAT India on the Kenyan restorer lines is limited. Based on the importance of the crop and the facts above, farmers need to adopt indigenous crops such as sorghum which are drought tolerant. The sorghums also ought to be high yielding to help bridge the gap between sorghum supply and demand in Kenya. The yields of sorghum can be improved through development of high yielding hybrids (Oyier et al., 2016). The hybrids should also be adapted to the semi-arid growing conditions. This study was carried out to understand the gene action governing inheritance of yield and its contributory traits, select the superior hybrids and favorable growing conditions for the produced hybrids.

### 1.5 Overall objective of the study

The study aimed at generating high yielding sorghum hybrids adapted to semi-arid environments, identification of potential hybrid parents for yield improvement, and understanding the genetic basis of inheritance for yield and yield related traits among sorghum cultivars, thus increasing sorghum productivity leading to reduced food shortages and poverty levels in the semi-arid areas of Kenya.

#### 1.5.1 Specific objectives of the study were;

1. To assess agronomic performance of sorghum genotypes.
2. To determine the heterosis for grain yield and yield components among sorghum $F_1$ hybrids.
3. To estimate the combining ability for grain and biomass yield and their related traits among sorghum lines.
4. To determine the influence of genotype by environment interaction on yield among sorghum hybrids.

#### 1.5.2 Hypotheses

1. There is no difference in agronomic performance among sorghum $F_1$ hybrids.
2. Sorghum hybrids do not show varied heterosis levels for yield and yield components.

3. Inheritance of grain yield and yield components in sorghum is not conditioned by additive gene action.
4. Some sorghum hybrids are not stable across environments.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Sorghum origin and distribution

Cultivated races of sorghum (*Sorghum bicolor* [L] Moench) originated in Ethiopia between 4000-3000 BC (Olembo *et al*., 2010). Sorghum was first domesticated in the savannah between western Ethiopia and eastern Chad 5000- 7000 years ago (Bantilan *et al.,* 2004). Sorghum spread through the slave trade to America in the 19$^{th}$ century (Shewale, 2008). New biotypes of sorghum arose due to selection, dispersal, genetic adaptation and inter-crossing. The dispersal and biotype development gave rise to five basic races: bicolor, caudatum, guinea, kafir and durra (Moncada, 2000). Today, sorghum cultivation is widely distributed throughout the world (Deb *et al.,* 2004).

## 2.2 Sorghum botany and taxonomy

Sorghum belongs to the grass family *Graminae* and genus *Sorghum* (Reddy *et al*., 2008). The crop has an extensive root system that is twice that of maize and exhibits a $C_4$ photosynthetic pathway (Bantilan *et al*, 2004). Sorghum leaves are flat with stomata on both surfaces. The leaves have motor cells along the midrib that aid in rolling up during moisture stress. The stem is made up of nodes and internodes which most times are covered with a waxy layer. Each node has a bud that can develop into aerial or basal tiller. The inflorescence of sorghum is called a panicle which bears bisexual flowers containing stamens and pistil enclosed in the glumes. Sorghum is a short day plant; its blooming is hastened by short days and long nights. However, its photoperiod sensitivity varies with genotypes (Quinby and Karper, 1947). Sorghum flowers open from the tip of the panicle progressing downwards. The sorghum seed is a caryopsis which occurs in different shades of colour and shape (Jéan du Plessis, 2008).

## 2.3 Importance of sorghum

Sorghum is considered a staple food crop for more than 750 million people in the Semi-arid tropics of Africa, Asia and Latin America (Wambugu, 2011). Africa accounts for more than a third of the global sorghum production (Wambugu, 2011). It has the potential to be the driver of economic development in Africa. The crop has been proven to be the best alternative to barley for lager beer brewing (Anon 1). The main food products prepared from sorghum include thin and thick porridges,

fermented and unfermented breads, alcoholic beers, and beverages, malted flours for brewing, malted porridge mixes and weaning foods (Wambugu, 2011). The grain can also be used as feed for livestock. In Africa, the stalks are used for: fuel, fencing and roofing materials. Sorghum is also grown for forage and sweet stalk sorghum for biofuels (Bantilan *et al*., 2004). In many developing countries, Stover accounts for 50% of the total crop value especially in drought periods (ICRISAT, 2004).

Sorghum has a great advantage over the other cereals due to its ability to yield where other cereals fail. Its eminent characteristics are: extensive root system, leaf waxy bloom which reduces water loss and tillering response to stresses. These traits enable sorghum to thrive in harsh environments making it an important crop to combat climate change and feed the increasing world population.

**2.4 Sorghum production and constraints**

Global sorghum production and utilization is characterized under two broad groups. The first category encompasses Africa and Asia where production is traditional, subsistence, small scale and the sorghum is primarily used for food. The yields are also low and unstable. The second category has most of the developed countries where production is mechanized, high input, large scale and the sorghum is used as an animal feed. Yields under this production system are generally higher (ICRISAT, 2004).

In Kenya, sorghum is often grown in the drought-prone marginal areas of Eastern, Nyanza, and Coast Provinces. It could provide food security and become a suitable alternative to maize in eastern Kenya where frequent crop failures are experienced (Muui *et al*., 2013). The area under sorghum growing in Kenya has been on increase from 97,000ha in 1981 to 235, 000 ha in 2012 (Orr *et al.,* 2016), an increase attributed to new market pull caused by new emerging markets like the brewing sector. However, the national average yield per hectare has been decreasing from 0.941 metric tons (Mt/ha) per hectare in 1991 to 0.700 Mt/ha in 2012 (Orr *et al.,* 2016). The production of the crop has been fluctuating but the trend has been on decline with production figures of 149,656 tons in 2005 and 117, 000 tons in 2016 (faostat3.fao.org).

Sorghum production and utilization has remained low in Kenya despite numerous benefits the crop possess and past research efforts given to it. The low production at

the farm level is due to; highly variable drought stress conditions (Haussmann *et al*., 2000), low yielding varieties, lack of appropriate varieties targeted for specific end uses, poor agronomic management practices, diseases and pests and un-developed seed supply systems (Akuno *et al*., 2011).

### 2.5 Sorghum research in East Africa

Sorghum research in East Africa began in the 1930s and up to 1950 the main research activity was collection and screening of local germplasm in Kenya, Uganda and Tanzania (Obilana, 2004). A breeding program was started in Tanzania in 1948 which led to development of a brown variety called Serena (Obilana, 2004). Another regional program in East Africa focusing on *Striga* and bird resistance led to development of Seredo and Lulu D varieties (Obilana, 2004). ICRISAT began its work in the region in 1978.

The 10 Eastern and Central African countries formed two networks EARCAL and EARSAM facilitated by ICRISAT (1986-1993). These networks led to identification of elite lines by various national programs (Obilana, 2004). Lack of good national seed companies limited use of these promising lines. ICRISATs research on sorghum targeted lowland and highland agro ecologies (Year 1993-2000). From the year 2000 onwards, research targeted 2 production systems- dry lowlands and sub humid regions (Obilana, 2004).

Initially, sorghum hybrid breeding was not part of the East African states strategy. This was due to subsistence farming, informal seed sector and lack of seed companies to venture into sorghum seed production. However, in the early 1990s, research was initiated on screening A/B and R lines from USA and ICRISAT- India for earliness, adaptation, fertility restoration and grain quality traits at ICRISAT- Nairobi (Olembo *et al*., 2010).

The sorghum hybrid development programme in Nairobi gave rise to six hybrids released in Kenya and Tanzania between the years 2013-2016 (Manyasa, 2016). The current priority areas in sorghum breeding vary from region to region and is based on the major sorghum production constraint in that area. Moisture stress is the most important sorghum production constraint in Eastern and Southern Africa. For

enhanced yields in sorghum for the ASALs, research has to focus on drought tolerance and heterosis in adapted sorghum materials.

### 2.5.1 Breeding for drought tolerance in sorghum

Amelework (2012) defined drought as the deficiency of soil moisture over an extended period of time. Drought is a global problem that leads to significant yield losses hence affecting crop production. It commonly occurs in all climatic zones with varied durations and intensity. Drought affects the normal physiological, morphological and biochemical plant processes leading to poor growth and development which culminates to lower yields and sometimes total crop failure (Amelework, 2012). It can occur at seedling, pre- flowering or post flowering stages. Occurrence of drought at seedling stage leads to poor crop establishment whereas drought at flowering or grain filling stage causes lower yield or crop failure.

### 2.5.2 Mechanisms of drought resistance in sorghum

Sorghum is known to withstand drought than most of the cereal crops. Many researchers have studied drought resistance mechanisms in sorghum and concluded that differential drought resistance among sorghum genotypes is due to the variation in morphological structures, biochemical expressions and physiological functions. Crop physiologists have described three drought resistance mechanisms; avoidance, escape and tolerance (Harris, 2007).

Harris (2007) described drought avoidance as the ability of the plant cells to maintain turgor and water content under water stress conditions. This is accomplished through maintaining water uptake through extensive deep root system, minimized water loss through the stomata or cuticle and early plant vigor. Most sorghum genotypes have thick waxy cuticle and extensive root system that confers high water use efficiency. Some plants are able to maintain their metabolic activity under reduced plant water potential by varying their osmotic adjustment and antioxidant activity (Blum 2005 and Rauf *et al*. 2015). This mechanism of resistance is called drought tolerance (Harris, 2007). Drought escape mechanism refers to the completion of the growth cycle before the onset of drought (Rauf *et al*. 2015). Flowering time has been cited as the most critical trait while selecting for drought escape.

Reduced canopy size, tillering, size of upper leaves and number of leaves per stem are reported to reduce pre flowering water demand in sorghum hence increasing water availability at grain filling leading to higher yields (Borrel *et al* 2014). Small and narrow leaves, reduced plant stature were observed to confer drought adaptation to plants. Dwarf cultivars are efficient in balancing translocation of assimilates between the grain and other vegetative organs (Kouressy *et al* 2008).

Short duration varieties have been shown to confer drought escape in most plants however the yields are compromised (Amelework, 2012). Leaf rolling is a good physiological indicator of drought tolerance in sorghum, the rolling reduces the leaf width hence reducing transpiration rate from the leaves (Junhua *et al* 2011). Stay green confers post- anthesis drought resistance by preventing premature leaf senescence. Stay green is indicative of higher chlorophyll content caused by high cytokinin levels (Thomas and Howarth, 2000). Stay green varieties have prolonged root growth which aids in water extraction from deeper soil horizons and over a wide area. Therefore, stay green genotypes would have better grain filling and higher yields under moisture stress (Amelework, 2012). Rauf *et al* (2015) concluded that genotypic variation in different plant species confers adaptation to different drought scenarios.

### 2.5.3 Breeding methods for drought tolerance in sorghum

Several breeding methods have been employed in improving sorghum for drought tolerance and other important traits. The breeding method used depends on the breeding programme and the end product. Some of the breeding methods used are; pure line selection, pedigree, bulk selection, backcrossing and hybrid breeding. Many studies have shown that hybrids have a greater buffering capacity to yield losses caused by drought. Hybrids developed from resistant x susceptible inbred parents which are genetically diverse were found to be more drought resistant (Rauf *et al*., 2015). These hybrids should also be evaluated in multiple environments in drought prone areas and the best hybrids released for cultivation in the ASALs.

## 2.6 Combining ability

Allard (1960) defined combining ability as an estimation of the value of genotypes on the basis of the performance of their offspring in a definite mating design. Initially, the term was generally used in classifying inbred lines in respect to their cross performance then later amended to two concepts; general combining ability (GCA)

and specific combining ability (SCA) (Fasahat *et al*., 2016) which are important in characterizing and describing inbred lines in crosses.

Sprague and Tatum (1942) defined general combining ability as the average performance of a line in a series of hybrid combinations and specific combining ability as those cases in which certain hybrid combinations perform better or poorer than would be expected on the basis of the average performance of the parental inbred lines (Fasahat *et al*., 2016). The GCA of a line is governed by additive gene effect whereas SCA is due to dominance or epistatic gene effect (Sprague and Tatum 1942; Kabir *et al*., 2014). Parental lines showing high combining ability are said to have good GCA. However, if their potential to combine well is confined to a particular cross, they are considered to have good SCA (Fasahat *et al*., 2016). Statistically, the GCA is a main effect and the SCA is an interaction effect (Kulembeka *et al*, 2012).

The choice of the parents for hybrid development should be based on a high SCA and *per se* performance of the hybrid and at least one parent with high GCA (Makanda *et al*., 2010). The significance of SCA and GCA is important in any crop improvement programme hence they are used in early generation testing. High GCA value (positive or negative) shows that the parental mean is superior or inferior to the general mean. This shows desirable gene flow from parents to offspring with high intensity. High GCA value shows high heritability and less environmental influence (Fasahat *et al*., 2016). Elite parents with high GCA values are also known to be highly adaptable. GCA is therefore an important aspect as it makes crop improvement possible through selection.

SCA effect has been used extensively in plant breeding to give inferences on gene action at play (Fasahat *et al*., 2016). SCA effect resulting from crosses where both parents have high GCA effect are caused by additive x additive gene action whereas the one resulting from parents having high and low GCA is due to additive x epistatic gene action (Fasahat *et al*., 2016). High SCA caused by both parents having low GCA is due to dominance x dominance, non-allelic gene interaction producing over dominance which is non- fixable (Fasahat *et al*., 2016).

If both GCA and SCA are non- significant then epistatic gene action is at play in determining the inheritance of the traits (Fasahat *et al*., 2016). Information on GCA and SCA effect makes hybrid development effective, less costly and time efficient. GCA of the parents and the SCA of the crosses have been estimated in many crops such as, sorghum (Makanda *et al*., 2010), wheat (Bao *et al*., 2009 and Khaled *et al*., 2013), rice (Qu *et al*., 2012), maize (Malik *et al*., 2004; Alamerew and Warsi 2015; Asefa *et al*., 2008; Legesse *et al*., 2009; Gichuru *et al*., 2011) and chickpea (Bicer and Sakar, 2008).

### 2.6.1 Combining ability studies in Sorghum

In a study on combining ability for grain yield and component traits in four cytoplasmic male sterile sorghum lines and ten testers, Thakare *et al*. (2014) reported that non- additive gene action (SCA) was responsible for inheritance of plant height, panicle length, number of primary branches per panicle, grains per panicle, days to 50% flowering, brix%, 100 grain weight and grain yield/ plant. Premalatha *et al*., (2006) reported predominant role of non-additive gene action (SCA) for plant height, days to 50% flowering, number of leaves per plant, leaf area index, brix%, panicle length, number of grains per panicle, 100 grain weight and grain yield per plant in a study of 36 sorghum hybrids and their parents.

In a combining ability analysis involving a full diallel set of 10 sorghum parental lines and their 90 crosses including reciprocals, Riyazaddin *et al*, (2015) noted significant additive and non-additive gene action for the inheritance of flowering time, plant height, seed weight, grain yield and panicle attributes. In another study of five traits in sorghum mutants, Kenga *et al*. (2005) reported predominant GCA effects over SCA for days to flowering, panicle length, grain yield and seed mass however, the SCA effect for plant height was of a higher magnitude.

Tadesse *et al*. (2008) reported significant GCA effects in sorghum male and female parents for panicle exertion. However, the GCA for panicle length, grain yield and seed mass was significant for the males and non-significant for the female parents indicating that additive gene action was important in inheritance of these traits. Awadalla *et al*. (2014) reported predominant additive gene effects (GCA) for forage

yields and non-additive gene effect (SCA) for forage quality in 55 $F_1$ hybrids and 11 parents.

### 2.7 Mating Designs

Several mating designs have been developed for estimation of combining ability in plant and animal breeding. They help in providing information on the genetic control of a character, generation of breeding populations, development of potential varieties, estimating genetic gain and providing information on evaluation of the parents used in the breeding program (Acquaah, 2012). The success of any plant breeding program largely depends on selection of good parents and mating designs (Nduwumuremyi *et al*., 2013). Several mating designs among them Bi-parental progenies (BIP), Polycross, Top cross, North Carolina (I, II, III), Diallels (I, II, III, and IV) and Line x tester methods have been used in generating hybrids for genetic studies.

North Carolina Design I (NCD I) mating design was used in developing sorghum hybrids used in studying the combining ability and gene action for yield and its component traits. NCD I is a nested design used in estimation of additive and dominance gene action together with estimation of GCA for the males and the female within male variances (Hallauer *et al*., 2010). A group of male parents is mated to a set of female parents producing half and full sib progeny families (Acquaah, 2012). It is applicable to breeding species with the ability of producing sufficient pollen, species with sufficient seed for replicated trials (Acquaah, 2012) and those with male sterility system all of which are present in sorghum.

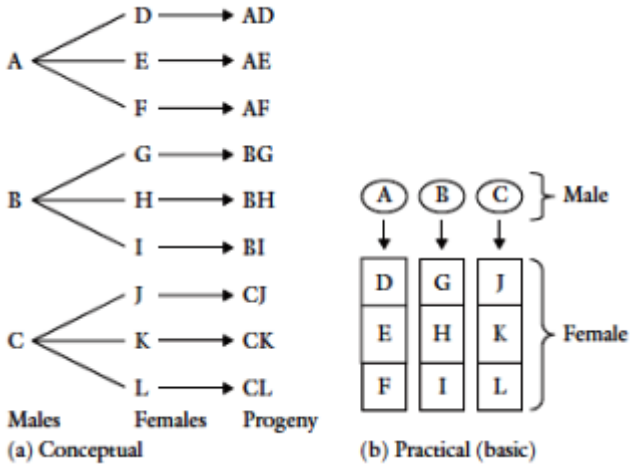



Figure 2. 1 North Carolina Design I Mating scheme (Source: Nduwumuremyi et al., 2013).

**Male sterility**

Male sterility is the inability of the plants to produce or release functional or viable pollen as a result of failure of formation of functional stamens, microspores or male gametes (Lasa and Bosemark, 1993). Cytoplasmic genetic male sterility (CGMS) discovered by Stephens and Holland (1954) has made exploitation of heterosis and recurrent selection in sorghum possible (Ashok *et al*., 2008; Frankel and Galun, 1977). CGMS is a physiological abnormality which is maternally inherited through the mitochondrial genomes. Cytoplasm conferring sterility in sorghum are: $A_1$, $A_2$, $A_3$ and $A_4$ (Schertz and Pring, 1982); $A_5$, $A_6$ and 9E (Webster and Singh, 1964).

The $A_1$ systems are governed by one basic gene and two duplicate complimentary genes acting in dominant manner whereas the $A_2$ and $A_3$ systems are governed by three complementary genes in dominant condition. The inheritance of $A_4$ CMS system is trigenic in nature where any two of the three dominant duplicate-complimentary genes restore fertility (Reddy *et al*. 2010). CMS lines are grouped into two categories based on anther morphology; those with small anthers with non- fertile degenerative pollen (A1, A2, A5 and A6) and those having large non-dehiscent anthers that may contain some viable pollen (A3, A4 and 9E) (Schertz *et al*., 1997). $A_1$ (milo) cytoplasmic genetic male sterility system is the most utilized in development of most of the commercially available hybrids (Reddy *et al*., 2010).

Genetic male sterility is conditioned by a recessive allele in the homozygous state. In sorghum this kind of sterility is conditioned by seven genes; $ms_1$ to $ms_7$. In $ms_1$ the anthers are produced without pollen, $ms_2$, ms3, ms4, ms5 and ms7 confer empty pollen sacs whereas $ms_6$ produce micro-anthers without pollen cells. The genes $ms_3$ and $ms_7$ are the most common due to their stability across environments. Sterility can also be conditioned by antherless gene *al* (Reddy *et al.*, 2004).

The cytoplasmic genetic male sterility system has been utilized extensively in exploiting heterosis in sorghum hybrids since 1960s. Cytoplasmic male sterile lines (A- lines) are maintained by their fertile isolines called B-lines (maintainers). The A and B lines are genetically similar (isolines) however; the A-line has a sterility inducing cytoplasm whereas the B-line possesses a normal fertile cytoplasm (Acquuah, 2012). Lines that produce fertile $F_1$ hybrids when crossed to sterile A- lines are called restorers (R- lines). Restorer lines are genetically different from A- lines and carries dominant fertility restoration alleles (R*f*) needed to restore fertility in the hybrids (Acquuah, 2012). The $F_1$ hybrids resulting from the cross between CGMS A-line and restorer (R- line) may be; sterile, completely fertile, partially fertile or some plants fertile and others sterile. Where the F1 hybrid is fully fertile then the corresponding pollinator parent is a potential R-line. In the instance where the resultant $F_1$ hybrid is sterile then the corresponding pollen parent is a maintainer (B-line) hence a potential source of new CGMS lines.

Plant breeders should ensure that the lines used in development of new hybrid parents (CGMS A-lines and Restorer lines) are genetically diverse, have good *per se* performance and general combining ability (GCA). Seed of the maintainer B- line is made by selfing whereas the A- lines are maintained by crossing them to their maintainer B- lines. Sorghum hybrids are produced by crossing male sterile A- lines to fertile pollinator /restorer parents (Acquuah, 2012).

### 2.8. Heterosis

Shull (1914 and 1952) described heterosis as the superiority or inferiority of the hybrid/ offspring over its parents with respect to vigor, growth, development, and yield. Birchler (2015) defined heterosis as the ability of a progeny of diverse varieties of a species to exhibit greater biomass, growth rate, and fertility than both parents.

According to Flint-Garcia *et al*., (2009), hybrids cannot not be simply classified as heterotic or non-heterotic because the amount of heterosis is trait-dependent.

Heterosis of $F_1$ hybrids can be positive or negative and is expressed over mid parent, better parent or standard check variety or hybrid (Reddy *et al*, 2008 and Deepak, 2014). Mean/ mid- parent heterosis (MPH) is the performance of the $F_1$ compared with average performance of the parents. The performance of the $F_1$ hybrid compared to the best parent in the cross is termed better parent heterosis (BPH) whereas standard heterosis is the performance of the $F_1$ hybrid compared with performance of the commercial variety/hybrid (Reddy *et al*, 2008).

Two main theories were proposed by Bruce (1910) and Hull, (1945) on the causes of heterosis; the dominance and over dominance hypothesis. Dominance hypothesis describes heterosis to be due to the superiority of dominant alleles which mask deleterious effects of recessive alleles in the hybrid (Reddy *et al*, 2008). Therefore, heterosis is in direct proportion with the number of dominant genes contributed by each of the parents (Reddy *et al*., 2008). Over dominance hypothesis explains heterosis as the superiority of the heterozygote over its homozygous parents caused by complementation between divergent alleles. Heterozygosity is considered the cause and heterosis the end effect. According to this theory, the presence of multiple alleles leads to greater performance (Kaeppler, 2012). Hybrid vigor is therefore maximized when we cross individuals that are genetically diverse. Over dominance theory is the cause of better parent heterosis.

### 2.8.1 Heterosis studies in sorghum

Large genetic variability exists in sorghums for improving hybrid parents for grain and fodder yield and quality, resistance to biotic and abiotic stresses. Genes conferring resistance to these stresses need to be deployed in high yielding backgrounds. Heterosis was observed in sorghum as early as 1927 (Conner and Karper, 1927).

Several studies have reported significant heterosis for yield and its related traits. In a study on heterosis for yield and its component traits in sorghum hybrids in Kenya, Okiyo *et al.* (2008) reported better parent and standard heterosis with both positive and negative magnitude. In a heterosis study of 51 $F_1$ forage sorghum hybrids developed from five exotic CMS lines and 11 fertile local inbred lines as testers in

Sudan, Awadalla *et al*., (2014) reported significant heterosis for fresh and dry forage yield.

In a study on heterosis of 121 sorghum $F_1$ hybrids for yield and its components in East Africa, Ringo *et al* (2015) reported significant mid and better parent heterosis for grain yield of up to 81.9% and 77% respectively. Premalatha *et al*, (2006) studied 36 sorghum hybrids and reported that all the hybrids that showed significant heterosis for grain yield were not heterotic for all the traits. They also noted that parents with high *per se* performance produced superior hybrids.

Pfeiffer *et al*, (2010) reported significant positive heterosis for brix content in 6 out of the 20 sorghum genotypes evaluated. In another study involving 139 sorghum hybrids derived from introduced seed parents and locally adapted and introduced R lines in Ethiopia, Taye *et al*. (2016) observed that hybrids from locally adapted materials were superior in plant height and grain yield. In a study of 54 $F_1$ sorghum hybrids made by crossing nine Sudan grass pollinators with six CMS lines in a line x tester mating design, Pandey and Shrotria (2012) observed varied magnitudes of mid parent, better parent and standard heterosis for all the traits.

Significant better parent heterosis was observed in sweet sorghum hybrids for biomass yield, sugar yield and sugar concentration among sorghum hybrids produced by mating sweet grain type females and pure line males (Corn, 2009). In a study on 80 sorghum hybrids produced through mating eight cytoplasmic male sterile lines with ten male lines in a North Carolina Mating Design II, Makanda (2009) observed reasonable amount of standard heterosis of up to 25% and 100% for brix and biomass yield respectively. This is a clear indication that greater gains can be realized through development of hybrids.

A review of literature by Makanda (2009) showed that grain yield heterosis in sorghum was elucidated by; high number of grains per panicle, increased net photosynthetic rate per unit area due to large panicles (larger sink), larger leaf area, greater stomatal conductance and transpiration hence larger carbon dioxide fixation per unit time. Other suggestions on the causes of positive heterosis for yield were; increased plant height, increased biomass with constant harvest index, many vigorous and long roots.

Increased sorghum productivity has been achieved in the developed countries through hybrids which have a yield advantage over OPVs. However, the Kenyan situation is different as the yields are still low due to farmers planting open pollinated varieties. Farmers in the sorghum growing areas of Kenya practice mixed crop livestock farming and due to the increasing human population and reduced land sizes, such farmers need a dual purpose high yielding sorghum cultivar.

Several heterosis studies on sorghum for grain yield, forage yield and sugar content have been done in other parts of Africa however the information is still limited for dual purpose sorghums hybrids developed for the dry lowlands of Kenya. The current study was aimed at estimating the combining ability and heterosis for grain and biomass yield as a criteria for improving the dual purpose sorghum hybrids for the dry lowlands of Kenya.

### 2.9 Genotype by environment interaction

Development of sorghum genotypes with high yield potential, resistance to major pests and diseases, larger grain size and enhanced nutritional content remains an ultimate goal of plant breeders. In addition, the new variety should have stable performance and wide adaptation to a range of environments. However, the phenomenon of yield stability has remained a major challenge to sorghum breeding programs for a long period of time.

Stability analysis is an important tool in developing cultivars for a wide range of environments or for a specific location (Rono *et al*, 2016). According to Lin *et al*. (1986) stability can classified into three classes; Type-1, 2 and 3. Type 1 (biological or static stability) is shown by genotypes which are non-responsive to change in input levels hence are stable across the locations and their environmental variances are small. Agronomic/ dynamic stability is where a genotype has the ability to respond to the environmental changes, that is, a genotype has the ability to perform well relative to the production potential of the environment (Makanda *et al*., 2009). Type-3 stability is realized when the residual mean square value from the regression model on the environmental index is small.

Phenotypes of individuals are determined by the genotype and the environmental effect on that genotype. Therefore, yield performance of any genotype is determined by the genotypic effect (G), Environmental effect (E) and their interaction (G x E)

(Yan *et al.*, 2007). The response of a phenotype to change in environment is not the same for all genotypes hence the advent of genotype by environment interaction (GEI). The success of any plant breeding program related to stability depends on genotype by environment interaction. The phenomenon is also key at post breeding stage during the evaluation of new cultivars before release for commercialization (Sharma, 1998). Genotypes will perform differently across agro-ecologies, within a location, and across seasons (Manyasa, 2013). Stable genotypes have consistent performance across a wide range of environments (Asfaw, 2007).

Sharma *et al*. (1987) highlighted that significant G X E effects reduces the correlation between the genotype and the phenotype of an individual hence making it difficult to measure the genetic potential of a genotype, this in turn complicates the selection process. Therefore, evaluation of genotypes for stability and adaptation is vital during selection of superior genotypes. Development of varieties/hybrids with wide and specific adaptation should be embraced by breeders in order to achieve high genetic gains (Showenimo *et al*, 2007).

Genotype by environment interaction (GEI) occurs as; cross over and non- cross over type. The cross over GEI is exhibited where there is differential genotypic performance in different environments (Ding *et al*., 2007). Non- cross over GEI indicate constant performance of a genotype across different environments. This has necessitated establishment of multi environment trials to help in selection of genotypes for target production agro- ecologies (Yan and Tinker, 2006). The information acquired from stability studies is equally important in distinctiveness, uniformity and stability (DUS) tests (Kannababu and Tonapi, 2008) and national performance trials (NPT) during release of new varieties and hybrids.

A number of statistical techniques have been developed for stability and genotype by environment analysis (Showenimo *et al*, 2007). These includes; Combined ANOVA (Kandus *et al*, 2010), Eberhart and Russells regression and deviation from regression ($s^2d$) analysis proposed in 1966, Ecovalence by Wricke (1962; 1964), coefficient of determination ($r^2$) by Pinthus (1973), the biplot models using Additive Main effects and Multiplicative Interactions (AMMI) (Gauch, 1992) and Genotype and Genotype x Environment interaction (GGE) (Yan and Tinker, 2006).

### 2.9.1 Additive Main and Multiplicative Interaction (AMMI)

AMMI is a multivariate method of studying phenotypic stability (Ferreira, 2006). The model was developed by Gabriel (1971) and Gollob (1968) with an aim of estimating interaction effects through application of Principal Components. It is useful in identification of stable and adapted genotypes (Ferreira, 2006). AMMI is a combination of ANOVA for the main effects of the genotypes and the environment together with principal components analysis (PCA) of the genotype-environment interaction (Kandus *et al*., 2010).

AMMI biplots allow visualization of genotypes (points), environments (vectors) and their interaction (G X E) in the same graph (Gabriel, 1971). According to Filho, (2014), lower scores relative to the number of principal components depict lower contribution of genotypes to the G x E interaction. Stable genotypes are located close to the zero level of the PC1 axis on the AMMI biplot. Ideal genotypes have a high mean and are stable, whereas undesirable genotypes have low stability and mean (Ferreira, 2006). Purchase *et al*. (2000) suggested another index for estimating stability called the AMMI stability value (ASV), which is the distance from zero in a two dimensional scatter diagram of IPCA 1 against IPCA 2 of an AMMI model. In this model, the higher ASV value, either positive or negative, shows specific genotypic adaptation to an environment. Low ASV values show more stable genotypes across environments.

In a study on stability of eleven sweet sorghum hybrids using GGE and AMMI biplot analysis, Rao *et al*. (2011) reported interaction between seasons and years for brix%, sugar yield and grain yield. In a GXE study of eight sweet sorghum varieties in five locations for two seasons, Rono *et al*., (2016) reported significant effects of environment (E), genotype (G) and genotype by environment interaction (GEI) for juice yield. In another study of 25 sorghum hybrids evaluated in 7 locations using 5 stability models, Filho *et al*., (2014) observed that AMMI 1 explained 47.7% of the variation to be due to genotype by environment interaction (GEI). Adugna (2008), in a study of 28 sorghum genotypes for estimation of genotype by environment interaction for grain yield using univariate and multivariate statistical approaches, reported genotypes 2 and 5 as the most stable under AMMI stability rankings.

### 2.9.2 Genotype and Genotype by Environment interaction (GGE)

Genotype and genotype by environment (GGE) interaction model proposed by Yan *et al*., (2000) is an improvement of AMMI model used to study genotype by environment interaction. The GGE groups the genotype effect (the Additive effect in AMMI analysis) together with the genotype by environment interaction (GE), multiplicative effect and analyses them by principal components. The GGE biplot is more accurate and practical than AMMI because it explains an intermediate proportion of the sum of squares of genotypes and genotypes by environments (G + GE), compared to AMMI graphs of mega environments (Marcio *et al*, 2009).

In a study on the agronomic performance and stability of 25 sorghum $F_1$ hybrids and their 10 parents, Ezzat *et al*., (2010) reported significant interactions between genotypes with locations and dates for all the studied traits. However, stability analysis for grain yield showed that $F_1$ hybrids had better grain yields than their parents, but the parents were relatively more stable. In another study on the GxE effect of 25 sorghum genotypes evaluated in nine locations, Figueiredo *et al*., (2015) reported significant GxE interactions for all the traits. Significant genotype by environment interaction was revealed for most of the traits in a study on sweet sorghums (Olweny, 2015). Rono *et al*., (2016) reported significant effects of environment (E) and genotype by environment interaction (GEI) on yield of sweet sorghums.

# CHAPTER THREE

# GENETIC ANALYSIS OF SORGHUM HYBRIDS AND THEIR PARENTS FOR YIELD AND ITS COMPONENT TRAITS


## Abstract

Combining ability and heterosis study for grain and biomass yield with their component traits was done on 34 $F_1$ hybrids and their parents at Kenya Agricultural and Livestock Research Organizations (KALRO) - Kiboko and Kampi ya Mawe in 2014 long rain and 2014-15 short rain seasons. The crosses were developed using North Carolina Mating Design I. The 34 cross combinations together with their 46 parents and a check were evaluated in a 9 x 9 square lattice experimental design with 3 replications. Highly significant differences ($p<0.001$) were recorded between genotypes and locations for all the traits except leaf length. The correlation between grain yield with leaf length, plant height, panicle exertion, panicle length, seed set, waxy bloom, biomass yield was positive and highly significant ($P\leq0.01$). Therefore, improvement of these traits is possible without compromising the grain yield. Highly significant ($P\leq0.01$) negative correlation was recorded between grain yield with days to flowering hence development of early maturing hybrids which can escape drought is possible. Days to 50% flowering and plant height had a very close estimate of phenotypic coefficient of variation (PCV) and genotypic coefficient of variation (GCV) scores. There was minimal influence of environment on the expression of these characters. High heritability scores coupled with high GCV and genetic advance (GA %) for fresh biomass yield, panicle exertion and plant height is an indication that the variation is attributed to additive effect, therefore the traits can be improved through direct phenotypic selection. Sorghum hybrids; ATX 623 x Macia, ICSA 29011 x ICSR 89058, ICSA 11033 x ICSR 160, ICSA 12 x IESV 92172DL and ICSA 11035 x Macia had high magnitudes of the 3 types of heterosis *viz* heterobeltiosis, mean and standard heterosis for grain yield. Restorer parents ICSR 89058, ICSV 700, ICSR 160 and Wahi were good general combiners for earliness, biomass yield, grain yield and short plant height respectively. Maximum SCA effect for grain yield was achieved in ATX 623 x Macia, ICSA11040 x IESV 91104DL and ICSA 29011 x ICSR 89058 hence they can be promoted for on farm testing and possible release for food and fodder.

**Key words:** *Heterosis, combining ability, cytoplasmic male sterility, restorers, mating design, heterobeltiosis*

## 3.1 Introduction

Sorghum is an important crop grown in more than 90 countries in the world. It is utilized as food in Africa and India and as feed in the Americas, Europe and Australia (Ashok *et al*., 2011). Sorghum remains an important crop in the arid and semi-arid (ASALs) areas of the world. The crop is characterized by; a C4 photosynthetic pathway leading to high water use efficiency, tolerance to longer periods of water logging than maize (Muturi, 2013), extensive root system, waxy bloom on the leaves that reduces evapotranspiration and recovery growth after water stress (Muui *et al.,* 2013). As a result, sorghum is able to survive well in the semi-arid areas.

Sorghum plays a critical role as a food and nutritional security crop in the semi-arid Eastern, Nyanza and Coastal parts of Kenya which are prone to maize crop failures. In Kenya, Sorghum grain is used in making fermented and unfermented porridge, beverage, ugali, pilau, chapati, cakes, cookies and biscuits. Grain is also used directly for poultry feeding. The stalks are used for animal feed, thatching and fuel (Muturi, 2013 and Muui *et al.,* 2013). Use of sorghum grain to supplement barley in the brewing industry has increased sorghum demand in Kenya. There is a greater deficit of sorghum grain in Kenya with an annual demand of 40,000MT in the brewing industry and 200,000MT in the feed industry (Waikwa, 2016). However, the total sorghum annual production in Kenya was 117,000MT by the year 2016. The production in the farmers' fields is too low to satisfy this demand.

Africa contributes more than 60 % of land area under sorghum but despite this, the yields have remained low at 0.85 $tha^{-1}$ (Muui *et al.,* 2013). The low yields are due to use of saved seed of open pollinated varieties, drought, high temperatures, poor agronomic practices, *Striga* parasitic weed, fungal diseases, birds and insects (Muii *et al,* 2013 and Muturi, 2013). Drought at grain filling is the most devastating abiotic stress in sorghum production that cause yield losses ranging from 45% to 50% (Wortmann *et al.,* 2009). In order to increase sorghum yields in Africa, the improvement of sorghum for grain quality and resistance to biotic and abiotic stresses has to be done on high yielding backgrounds mainly through hybrid breeding.

The availability of stable cytoplasmic genetic male sterility (CGMS) system has made sorghum hybrid production possible. A total of 758 A/B lines and 922 R-lines with different traits is available at ICRISAT India for use in hybrid making. The CGMS system is of no use if the hybrids produced are not heterotic, and there should be good combining ability between CGMS seed parents and the restorer parents. The seed and pollinator parents should also be well adapted to the environmental conditions in the areas where hybrid production is targeted.

According to Nyadanu and Dikera (2014), the knowledge of genetic variability, heritability and correlation between economically important traits is a pre-requisite for selection and development of high yielding well adapted varieties. Proper selection of hybrid parents depends on their combining ability. Different heterosis levels for grain yield have been reported in sorghum hybrids evaluated in Kenya. However, the information on heterosis and the combining ability of the new A- lines and the adapted restorer lines for biomass yield is scanty. High yielding sorghum varieties are preferred in the semi-arid areas of Kenya. However, the hybrids are not commercially available and the information on their drought tolerance is also scanty.

The current study aimed at establishing the magnitude of heterosis, combining ability of the hybrid parents and genetic parameters in sorghum hybrids developed using ICRISAT- India inbred lines and ICRISAT-Nairobi developed restorer lines for improved grain and forage yield.

## 3.2 Materials and Methods

### 3.2.1 Introduction

The research was carried out at two locations namely; Kenya Agricultural and Livestock Research Stations at Kiboko and Kampi ya Mawe during 2014 long rains and 2014/15 short rains season. The experimental materials were evaluated for grain and biomass yield together with their component traits.

### 3.2.2 Experimental materials

Forty six sorghum lines comprising of 34 A-lines (females) and 12 R-lines (males) were used in this study. The cytoplasmic genetic male sterile female parents were obtained from ICRISAT India. The restorer lines were made up of improved adapted lines from East Africa. The A-lines were crossed to the R-lines in a North Carolina

Mating Design I as proposed by Comstock and Robinson (1952) to generate 34 experimental hybrids (Table 3.1; Appendix 5). During hybrid making, the cytoplasmic genetic male sterile lines were bagged at the onset of flowering to prevent contamination from foreign pollen. Once ¾ of the panicles had produced stigmas, pollen was collected from the restorer lines and dusted on the CGMS female lines during the morning hours. A crossing chart was maintained to ensure that all proposed cross combinations were done. The 34 experimental hybrids, their 46 parents and a commercial check were evaluated as shown in section 3.2.5. During evaluation, the isoline B-line was evaluated in the place of CGMS A- line.

Table 3. 1 Name, pedigree, fertility status and the source of sorghum hybrid parents used in the study

| Entry no. | Name | Pedigree | Role | Fertility status | Source |
|---|---|---|---|---|---|
| 1 | ATX 623 | BTx3197 x SC170-6-4 | Male | CMS | India |
| 2 | ICSA 101 | (Ind.Syn.89-1 x Rs/R 20-682)-5-1-3 | Female | CMS | India |
| 3 | ICSA 11003 | {[(SPV 462 x 296B)-1 x 296B]D-19Xx}-2-1-1-1-1-2-1-1-2-1-1-1-1-1 | Female | CMS | India |
| 4 | ICSA 11004 | (GM 970130 x ICSB 73)-9-1-1-1-1-1-1-1-1-2-1 | Female | CMS | India |
| 5 | ICSA 11007 | ICSP-B-98R Sel-17-2-3-1-1-1-1-1-1-1-1-1 | Female | CMS | India |
| 6 | ICSA 11013 | [{R150-1 x [296Bx(296B x QL3)-6-8-5]-28-3-10-1-2-3-1-1-4-2}x296B]-5-2-1-1-3-1-1-1-1-1-1-2-1-1 | Female | CMS | India |
| 7 | ICSA 11016 | [{R150-1 x [296Bx(296B x QL3)-6-8-5]-28-3-10-1-2-3-1-1-4-2}x296B]-5-2-1-1-3-1-1-1-1-1-1-2-1-1-1-1 | Female | CMS | India |
| 8 | ICSA 11018 | (ICSB 304 x CEM 328-3-3-1-1)-4-1-2-3-3-1-2-1-1-3-1-1-1-1-1 | Female | CMS | India |
| 9 | ICSA 11019 | [IS 152 x S 35]-2-2-1-1-1-1-1 | Female | CMS | India |
| 10 | ICSA 11033 | (ICSB 52 x ICSB 101)-4-1-1-1-1-2-1-1-1 | Female | CMS | India |
| 11 | ICSA 11034 | (ICSB 52 x ICSB 101)-4-1-1-1-1-2-1-1-1-1 | Female | CMS | India |
| 12 | ICSA 11035 | (Giddi Maldandi x 296B)- 8-8-1-2-1-1-1 | Female | CMS | India |
| 13 | ICSA 11036 | (Giddi Maldandi x 296B)- 8-8-1-2-1-3-1 | Female | CMS | India |
| 14 | ICSA 11037 | (ICSB 52 x ICSB 83)-1-4-1-1-1-1-1-1-2-2 | Female | CMS | India |
| 15 | ICSA 11038 | (ICSB 52 x ICSB 101)-1-5-1-1-1-1-1-1-1-1 | Female | CMS | India |
| 16 | ICSA 11039 | (ICSB 52 x ICSB 101)-1-5-1-1-1-1-1-1-1-2 | Female | CMS | India |
| 17 | ICSA 11040 | ([{(SPV 462 x [(ICSB 101 x PM17467B)-4-2-6 x (ICSB 6 x PM17467B)-6-1-1]]-9-1-3-1-2-1-7-5 x 296B} D-8xSP46505?]-1-2-1-1-1 x ICSB 52)-11-2-3-1-1-1-2-1-2-1 | Female | CMS | India |
| 18 | ICSA 12 | | Female | CMS | India |
| 19 | ICSA 206 | (ICSB 37 x SP 36257)-5-3-3-2-1-1 | Female | CMS | India |
| 20 | ICSA 228 | [296 B x(296 B x QL 3)]27-2-1-2-9-5 | Female | CMS | India |
| 21 | ICSA 232 | [296 B x(296 B x QL 3)]27-2-1-7-1-2-3-1 | Female | CMS | India |
| 22 | ICSA 25002 | ([{{SPV 462 x(ICSB 101 x PM17467B)-1-3-4} x ICSB 6}-3-2 x PM17467B)-9-1-3-1-2-1-7-2 x 296B}D-9-2-1-1-1-3-1-1-1 | Female | CMS | India |
| 23 | ICSA 29001 | ICSP-SFB 53-2-1-1 | Female | CMS | India |

Table 3. 1 Name, pedigree, fertility status and the source of sorghum hybrid parents used in the study

| Entry no. | Name | Pedigree | Role | Fertility status | Source |
|---|---|---|---|---|---|
| 24 | ICSA 29002 | ICSP-SFB 53-3-1-1 | Female | CMS | India |
| 25 | ICSA 29003 | ICSP-SFB 56-3-1-1 | Female | CMS | India |
| 26 | ICSA 29004 | [{[SPV 462 x(ICSB 51 x ICSV 705)-3-4-1] x PS 19349B}-8-2-1-1-2-3-1 x 296B]-1-1-1-3-1-1-1--2-3-1-1 | Female | CMS | India |
| 27 | ICSA 29005 | [{[SPV 462 x(ICSB 51 x ICSV 705)-3-4-1] x PS 19349B}-8-2-2-2-4-4-7x296B]-5-1-2-1-1-1-1-1-1-1-1 | Female | CMS | India |
| 28 | ICSA 29007 | (ICSB 403 x ICSB 11)-1-1-3-1-4-1-1-1-1-1-1-1-1-1 | Female | CMS | India |
| 29 | ICSA 29011 | (ICSB 403 x ICSB 11)-1-1-3-1-4-1-1-6-1-1-1-2-1-1-3 | Female | CMS | India |
| 30 | ICSA 29015 | [NRCS GMR 4 x SRT 26B]-1-2-1-1-2-2-1-1-2 | Female | CMS | India |
| 31 | ICSA 29016 | (ICSB 333 x ((ICSB 403 x ICSB 11)-1-1-3-1-4-1)-4-1-1-1-1-1-1 | Female | CMS | India |
| 32 | ICSA 29017 | [{[SPV 462 x(ICSB 51 x ICSV 705)-3-4-1] x PS 19349B}-8-2-1-1-2-3-1 x 296B]-1-1-1-3-1-1-1-2-1-2-2-2-1B | Female | CMS | India |
| 33 | ICSA 74 | [(296 B x SPV 105 ) x (2077B x M 35-1)]-22 | Female | CMS | India |
| 34 | ICSA 75 | [(2077B x 4-54) x (2077B x 2219 B)]-3 | Female | CMS | India |
| 35 | Hakika | P9405 | Male | CMF | Nairobi |
| 36 | ICSR 160 | | Male | CMF | Nairobi |
| 37 | ICSR 24008 | | Male | CMF | Nairobi |
| 38 | ICSR 24010 | | Male | CMF | Nairobi |
| 39 | ICSR 89058 | | Male | CMF | Nairobi |
| 40 | ICSV 700 | (IS 1082 x 12 ICSV 700 SC 108-3)-1-1-1-1-1 | Male | CMF | Nairobi |
| 41 | Macia | F3A-115-2 (Syn M91057) | Male | CMF | Nairobi |
| 42 | Wahi | P9406 | Male | CMF | Nairobi |
| 43 | KARI Mtama 1 | KAT 83/369 | Male | CMF | Nairobi |
| 44 | ICSR 38 | | Male | CMF | Nairobi |
| 45 | IESV 91104 DL | | Male | CMF | Nairobi |
| 46 | IESV 92172 DL | | Male | CMF | Nairobi |

CMF= cytoplasmic male fertile, CMS = cytoplasmic genetic male sterile

### 3.2.3 Experimental sites

KALRO Kiboko is situated at latitude 2.15$^{o}$ S and longitude 37.75$^{o}$E with an altitude of 975m above sea level. The area receives an annual rainfall of 530mm which is bimodal in distribution. The main season occurs between October and February and the minor season from April to July. The mean minimum and mean maximum annual temperature is 14.3$^{o}$C and 35.1$^{o}$C respectively with an annual mean temperature of 24.7$^{o}$C. The soils in Kiboko are predominantly sandy clay. The trials at Kiboko field station were evaluated under supplementary irrigation.

KALRO- Kampi ya Mawe field station is situated in Makueni County at latitude 1°57' S and longitude 37°40'E with an altitude of 1125m above sea level. The area receives a mean annual rainfall of 643mm which is bimodal in distribution. The main season occurs between October and February and the minor season spreading from March to July. The mean minimum and mean maximum annual temperature is 14.0°C and 31.0°C respectively with an annual mean temperature of 23.0°C. The soils in Kampi ya Mawe are predominantly chromic luvisols (Siderius and Muchena, 1977; Njiru *et al*., 2006; Manyasa *et al*., 2009). The trials at Kampi ya Mawe field station were evaluated under rain fed conditions.

### 3.2.4 Weather conditions

Data on the total rainfall amount in mm, temperature in degrees Celsius and the percent relative humidity for the two stations, Kiboko and Kampi ya Mawe for the season 2014 long rains and 2014-15 short rains season is shown in appendix 4.

### 3.2.5 Evaluation of the $F_1$ hybrids and their parents

The experiment was sown at KALRO- Kiboko and Kampi ya Mawe field stations in 2014 long rain and 2014-15 short rain seasons. Experimental materials comprised 34-$F_1$ hybrids, 46 parental lines and 1 commercial check. The experiment was laid out in a square lattice block design with three replications at both locations. Seed of each entry were sown by hand in 2 row plots of 4m length with inter-row and intra- row spacing of 0.75m and 0.2m respectively. Seed was drilled in furrows (2.5-3.0 cm deep) and covered with a light layer of soil. The trial was given supplementary irrigation at Kiboko up to when 50% of the plots had flowered.

At planting 87kgha-1 of Di- Ammonium Phosphate fertilizer (18:46:0) was applied to supply 16 kg N and 40 kg $P_2O_5$ per hectare. Top dressing was done using Urea (46%N) at the rate of 52kgha$^{-1}$ 30 days after crop emergence to supply 24kgN. Thinning was done at 21 days after emergence to give a plant density of 67,134 plants ha$^{-1}$. Hand weeding was done twice to keep the plots weed free. Confidor (Imidacloprid 200SL 17.8%w/w) systemic pesticide was applied to prevent damage from chaffer grubs and shootfly. Bulldock granules (Cyfluthrin 5g/Kg) were placed in the funnels of the plants during active vegetative growth to control stalk borers.

Four panicles were bagged in each plot to access fertility restoration. Standard agronomic practices were followed to raise the crop to physiological maturity based on the recommendations of the crop at each location. Fresh biomass weight was taken at hard dough stage by cutting the stalks at approximately 2cm above the ground and weighed. Harvesting was done manually at all the locations by cutting mature panicles using a knife.

### 3.2.6 Data Collection

Data were collected from five randomly sampled plants for plant height, waxy bloom, leaf length, leaf width, panicle exertion, panicle length, panicle width and stem girth whereas data on plant stand, days to flowering, productive tillers, % seed set, grain yield, lodging and seed mass were collected from the net plot. Observations were recorded at the appropriate stage as described in the sorghum descriptor by IBPGR and ICRISAT (1993) as shown in Table 3.2.

Table 3. 2 Description of the traits and how they were measured

| Trait | Description and scoring of the trait |
|---|---|
| Stand at thinning (Count) | Total number of main culms of the plants in the net plot after thinning |
| Days to 50% flowering | Days from sowing to when at least 50% of plants in the net plot had shed pollen |
| Plant height (cm) | Measured from the ground level to the tip of panicle at dough stage |
| Waxy bloom (Score) | Waxy bloom cover on the stems and leaves. 3=Slightly, 5=Intermediate, 9=Completely bloomy |
| Leaf length (cm) | Distance from the ligule to the tip of 4$^{th}$ leaf from the top on the main tiller at flowering |
| Leaf width (cm) | Breadth of 4$^{th}$ leaf from the top on the main tiller at the widest point during flowering |
| Tiller number (Counts) | Count the number of basal tillers in the net plot at maturity |
| Panicle exertion | Length between the ligule of flag leaf and base of the panicle measured at dough stage |
| Panicle length (cm) | The distance between the base and the tip of the panicle at physiological maturity |
| Panicle width (cm) | The diameter of the panicle measured at widest point at physiological maturity |
| Seed set (%) | The fraction of the selfed panicles with seed visually scored at physiological maturity |
| Stem girth (cm) | The circumference of the stem at the 4$^{th}$ internode from the top of the plant at maturity |
| Plant aspect (Score) | Overall agronomic performance of a genotype taken on a scale of 1-5, 1 = Very good, 5 = Poor |

Table 3. 2 Description of the traits and how they were measured

| Trait | Description and scoring of the trait |
|---|---|
| Harvested panicles | Count the panicles with mature grain including those on tillers in the net plot at harvesting |
| Fresh biomass yield ($tha^{-1}$) | Net plot weight of the harvested stalks converted to $tha^{-1}$ |
| Grain weight (g) | Weight of the grain harvested from the 5 sampled plants |
| Grain yield ($tha^{-1}$) | Net plot weight of the threshed sorghum grain at 12.5% moisture content converted to $tha^{-1}$ |
| Dry panicle weight (g) | Sorghum panicles harvested from the net plot weighed at 12.5% moisture content |
| Threshing % | Grain weight expressed as a percentage of the panicle weight |
| Lodging (Count) | Number of main culms with stem and root lodging in the net plot at maturity |
| Number of Leaves | Count the total number of leaves from the base to the top including the flag leaf at flowering |
| Seed mass (g) | A sample of 100 grains from each plot was counted then weighed at 12.5% moisture content |

Where; %=percent, cm=centimeter, g=gram, $tha^{-1}$= metric ton per hectare

Threshing % (Panicle harvest index) was computed as the ratio between the grain weight and the dry panicle weight using the formula described by Bickel (1983).

Equation 3. 1: Formula for computing threshing percent

$$TH = \frac{GWt}{PWt} \times 100\%$$

Where: TH = threshing percent; GWt = grain weight (gm); PWt = dry panicle weight before threshing.

Grain yield ($tha^{-1}$) was computed as follows

Equation 3. 2: Formula for computing grain yield

$$GY = \frac{GW}{100A}$$

Where: GW = grain weight per plot in grams; A = net plot area harvested in square meters.

Equation 3. 3: Formula for calculating net plot area harvested

$$A = (R * I * L)$$

Where: R = number of rows in the net plot; I = inter row spacing in centimeters and L = row length in centimeters.

Biomass yield ($tha^{-1}$) was computed as follows

Equation 3. 4: Formula for computing biomass yield

$$BYLD = \frac{10BW}{A}$$

Where: BW = fresh biomass weight per plot in kilograms and A = net plot area harvested in $m^2$.

### 3.2.7 Data analysis

#### 3.2.7.1 Analysis of variance

The data were subjected to analysis of variance using GenStat v18.1 statistical software for individual locations and combined analysis over locations. The combined analysis over locations was done considering environment and block effects as random and the genotypes as fixed effects (Piepho, 1994). Mean squares due to replication, location, genotype and interaction for grain yield and other traits were calculated for individual and multi locations to explain the observed variations using the model adopted from Bondari, (2013) as shown in equation 3.5 and Table 3.3.

Equation 3. 5: Model Analysis of Variance (ANOVA) equation for a multi environment lattice design

$$Y_{ijk} = \mu + G_i + E_j + GE_{ij} + B_{jk} + g_{ijk}$$

Where: $Y_{ijk}$= Observed genotypic performance; μ= Overall trial mean; $G_i$ = effect of the $i^{th}$ genotype; $E_j$ = effect of the $j^{th}$ environment; $GE_{ij}$ = interaction effect of the $i^{th}$ genotype with the $j^{th}$ Environment; $B_{jk}$ = effect of the $k^{th}$ replication in the $j^{th}$ environment; $g_{ijk}$ = random experimental error.

Table 3. 3 Outline of Analysis of variance for traits replicated over environments

| **Source of variation** | **DF** | **SS** | **MS** | **(VR)** |
|---|---|---|---|---|
| Environment (E) | e-1 | $SS_E$ | $MS_E$ | $MS_E/ MS_e$ |
| Replication (R) | r-1 | $SS_R$ | $MS_R$ | $MS_R/ MS_e$ |
| Genotype (G) | a-1 | $SS_G$ | $MS_G$ | $M_{SG}/ MS_e$ |
| GxE | (e-1)(a-1) | $SS_{GE}$ | $MS_{GE}$ | $MS_{GE}/ MS_e$ |
| Error (e) | By subtraction | $SS_e$ | $MS_e$ | |
| Total | (aer-1) | | | |

DF-degrees of freedom, SS-sum of squares, MS-Mean sum of squares, VR-Variance ratio, GxE-Genotype by environment interaction.

### 3.2.7.2 Pearson correlation analyses

Correlations between all traits were done at 5% confidence interval using a two way test correlation against zero and the correlation matrix generated in Genstat v18.1. The Pearson's correlation was calculated using equation 3.6 (Zou et al., 2003).

Equation 3. 6: Pearson's correlation equation

$$r = \frac{SS_{XY}}{\sqrt{(SS_{XX})\,(SS_{YY})}}$$

Where: $SS_{xy}$ is the sum of the cross products calculated as

$$SS_{XY} = \sum (X_i - \bar{X})(Y_i - \bar{Y})$$

$SS_{XX}$ is the sum of squares for variable X is

$$SS_{XX=} \sum (X_i - \bar{X})^2$$

The sum of squares for variable Y is

$$SS_{YY=} \sum (Y_i - \bar{Y})^2$$

Where; r= Pearson correlation coefficient, $X_i$-individual values of X variable, $Y_i$-individual values of Y variables, $\bar{X}$- mean of X variables, $\bar{Y}$- mean of the Y variables.

### 3.2.7.3 Multiple linear regression

A multiple linear regression model was used for determining the relative contribution of yield related components to yield using the following equation (Saed-Moucheshi *et al*., 2013).

$$y = a + b_1x_1 + b_2x_2 + b_3x_3 + \cdots + b_ix_i$$

Where; *y* is the dependent variable (yield), *x*'s are independent variables (measured traits) affecting dependent variable, *a* is the intercept coefficient, and *b*'s are the related coefficients of independent variables in predicting the dependent variable.

### 3.2.7.4 Percent heterosis

The data collected from the $F_1$ populations and their parents was used in calculating the heterosis. The heterotic effects were estimated using the formulae highlighted by Hallauer and Miranda, (1981).

Mid parent, better parent and standard heterosis were estimated using the formulae shown in equations 3.7, 3.8 and 3.9.

Equation 3. 7: Formula for calculating mid- parent heterosis

$$MPH = \left[F1 - \frac{(P1+P2)}{2}\right] X100\%$$ (Hallauer et al., 2010).

Where: F1= Means of the progenies; P1= Mean of parent 1; P2= Mean of parent 2; MPH= mid- parent heterosis.

Equation 3. 8: Formula for calculating better parent heterosis

$$BPH = \left[\frac{(F1-BP)}{BP}\right] X\ 100\%$$ (Hallauer et al., 2010).

Where: BPH= Better parent heterosis; F1= Mean of progenies; BP= Better parent.

Equation 3. 9: Formula for computing standard heterosis

$$SH = \left[\frac{(F1-Check)}{Check}\right] X\ 100\%$$ (Fehr, 1987)

Where: SH= Standard heterosis; F1= Mean of progenies; Check = Commercial variety

**3.2.7.5 Estimation of variance components and heritability**

Phenotypic and genotypic coefficients of variation were estimated using the methods proposed by Burton (1952) whereas the broad sense heritability ($h^2$) was expressed as the percentage of the ratio of the genotypic variance to the phenotypic variance. It was estimated on genotype mean basis as described by Allard (1960).

Equation 3. 10: Environmental variance formula (Singh and Chaudhary, 1985).

$$\delta_e^2 = MS_e$$

Where: MSe = error mean square, $\delta^2$e = environmental variance.

Equation 3. 11: Genotypic variance formula (Singh and Chaudhary, 1985)

$$\delta_g^2 = \frac{(MSg - MSe)}{r}$$

Where: MSg = Mean square for the genotype, MSe= Error Mean square and *r*= replications.

Equation 3. 12: Phenotypic variance formula (Singh and Chaudhary, 1985)

$$\delta_p^2 = \delta_g^2 + \delta_e^2$$

Where: $\delta^2$e= environmental variance and $\delta^2$g= genotypic variance

Phenotypic coefficient of variation and genotypic coefficient of variation were calculated using the formulae described by Singh and Chaudhary, 1985 as follows:

Equation 3. 13: Phenotypic coefficient of variation formula

$$PCV = \frac{\delta_p}{\bar{x}} x \quad 100\%$$

Equation 3. 14: Genotypic coefficient of variation formula

$$GCV = \frac{\delta p}{\bar{x}} \quad X \quad 100\%$$

Where: PCV is the phenotypic coefficient of variation, GCV is the genotypic coefficient of variation, $\delta p$ is the phenotypic standard deviation, $\delta g$ is the genotypic standard deviation and $\bar{X}$ is the phenotypic trait population mean.

Environmental coefficient of variation was computed following a method described by Kwon and Torrie (1964).

Equation 3. 15: Environmental coefficient of variation formula

$$ECV = \frac{\delta_e}{\bar{x}} \quad X \quad 100\%$$

Where: ECV is the environmental coefficient of variation, $\delta e$ is the random error standard deviation and $\bar{X}$ is the phenotypic trait population mean.

Siva Subramanian and Menon (1973) categorized PCV and GCV scores into the following classes; 0-10% = low, 10-20% = moderate and >20% = high (Manyasa, 2013).

Broad sense heritability for single location and combined analysis across locations was computed according to the method of Singh and Chaudhary (1985).

Equation 3. 16: Broad sense heritability formula

$$h^2 = \frac{\delta^2 g}{\delta^2 p} \quad X \quad 100\%$$

Analysis of broad sense heritability across locations was computed using the formula,

$$H^2 = \frac{\delta_g^2}{\left(\delta_g^2 + \delta_g^2 l + \delta_e^2 / rl\right)}$$

Where: $\delta^2 gl$ is the variance due to genotype x environment interaction, $r$ is the number of replications and $l$ the number of environments.

Robinson *et al.*, (1949) classified heritability into the following classes; 0-30%= low, 31-60%= medium and >61% = high (Manyasa, 2013).

The Genetic advance was calculated according to the method described in Shukla *et al.*, (2006) whereas Genetic advance as the percentage of the mean was computed in accordance with Johnson *et al*., (1955) using broad sense heritability as follows:

Equation 3. 17: Genetic advance formula

$$\text{Genetic advance GA} = \frac{\delta^2 g}{\delta p} \text{ X } k$$

Equation 3. 18: Genetic advance as a percentage of the mean formula

$$\text{GA \%} = \frac{K\delta^2 g}{\delta p} \text{ x } \frac{100}{\bar{x}}$$

Where: GA= Genetic advance, GA %= Genetic advance as a percentage of the mean, $\delta p$ is the phenotypic standard deviation, k= selection differential which takes the value 2.06 at 5% selection intensity. The GA% scale proposed by Johnson *et al*, (1955) is given as follows; 0-10% = low, 10-20% = moderate and >20% = high.

**3.2.7.6 Combining ability**

Data were analyzed using Restricted Maximum Likelihood (REML) procedure in NCD I of AGD-R *V*.3.0 (Analysis of Genetic Designs in R) described by Rodriguez *et al*., (2015). The model for analysis of NCD I extracted from Singh and Chaudhary (1985) is as follows;

$$Y_{ijk} = \mu + s_i + d_{i(j)} + e_{ijk}$$

Where; $s_i$, $d_{i(j)}$, and $e_{ijk}$ are assumed to be independently and normally distributed random variables with means zero and variances δ, μ is the mean.

## 3. 3 RESULTS

### 3.3.1 Analysis of variance

#### 3.3.1.1 Single site analysis of variance for yield and its component traits

The analysis of variance revealed that, variances due to genotypes were highly significant ($p<0.001$) for the studied characters *viz*, days to 50% flowering, stem girth, biomass yield, plant height, leaf length, leaf width, panicle length, panicle width, panicle exertion, number of lodged plants, 100 seed mass, grain yield and seed set percent at individual environments. However, number of tillers was significant ($p<0.05$) at Kampi ya Mawe (Table 3.6).

Table 3. 4 Mean squares for yield and its component traits at Kiboko in 2014 long rains season.

| SOV | df | DFL | SG | NTIL | BYLD | PHT | LL | LW | PL | PW | PE | LO | SD | GY | SS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| REP | 2 | 4.4 | 2 | 18.4 | 19 | 175.3 | 68.2 | 8.3 | 27.6 | 19.3 | 19 | 24 | 0.1 | 5.3 | 11.3 |
| Genotype | 78 | 80.3*** | 0.7*** | 25.8*** | 31.5*** | 2856.8*** | 79.1*** | 1.9*** | 37.5*** | 12.3*** | 180.4*** | 17.3*** | 0.6*** | 3.3*** | 2350.5*** |
| Error | 141 | 4.9 | 0.2 | 7.4 | 3.7 | 79.39 | 20.4 | 0.5 | 5.6 | 2.8 | 9.3 | 7.4 | 0.1 | 0.6 | 68.2 |

SOV=Source of Variation, DFL=days to flowering, SG=stem girth (cm), NTIL=number of tillers, BYLD=biomass yield (tha-$^{1}$), PHT=plant height (cm), LL=leaf length (cm), LW=leaf width (cm), PL=panicle length (cm), PW=panicle width (cm), PE=panicle exertion (cm), LO=number of plants lodged, SD=100 seed mass (g), GW=grain weight per 5 plants, GY=grain yield (tha$^{-1}$), SS- seed set%, ns= not significant at P≤0.05, *, **, *** significant at P≤0.05, P≤0.01 and P≤0.001 probability levels respectively.

Table 3. 5 Mean squares for yield and its component traits at Kiboko in 2014-15 short rains season.

| SOV | df | DFL | SG | NTIL | BYLD | PHT | LL | LW | PL | PW | PE | LO | SD | GY | SS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| REP | 2 | 8.7 | 2.6 | 1.6 | 89.5 | 2814.6 | 469.8 | 26 | 105.9 | 11.3 | 64.3 | 244.1 | 1.4 | 5.9 | 225 |
| Genotype | 77 | 64.4*** | 1.2*** | 3.3*** | 35.9*** | 3973.1*** | 108.2*** | 1.9*** | 43.2*** | 3.7*** | 51*** | 23.4*** | 0.6*** | 3.2*** | 1771.5*** |
| Error | 108 | 3.9 | 0.4 | 2.2 | 5.5 | 95.5 | 23.5 | 0.6 | 4.5 | 0.9 | 10.2 | 18.5 | 0.2 | 0.6 | 248.6 |

SOV=Source of Variation, DFL=days to flowering, SG=stem girth (cm), NTIL=number of tillers, BYLD=biomass yield (tha-$^{1}$), PHT=plant height (cm), LL=leaf length (cm), LW=leaf width (cm), PL=panicle length (cm), PW=panicle width (cm), PE=panicle exertion (cm), LO=number of plants lodged, SD=100 seed mass (g), GW=grain weight per 5 plants, GY=grain yield (tha$^{-1}$), SS- seed set%, ns= not significant at P≤0.05, *, **, *** significant at P≤0.05, P≤0.01 and P≤0.001 probability levels respectively.

Table 3. 6 Mean squares for yield and its component traits at Kiboko in 2014-15 short rains season.

| SOV | d.f. | DFL | SG | NTIL | BYLD | PHT | LL | LW | PL | PW | PE | LO | SD | GYLD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rep | 2 | 38.2 | 2.3 | 0.1 | 12.4 | 3223.3 | 315.1 | 8.8 | 151.1 | 29.4 | 44.8 | 55.5 | 0.2 | 5.1 |
| Genotype | 79 | 66.9*** | 0.6*** | 0.1* | 18.1*** | 3724.6*** | 72.8*** | 1.7*** | 28.3*** | 1.7*** | 43.7*** | 252.5*** | 0.6*** | 1.3*** |
| Error | 316 | 6.7 | 0.3 | 0.0 | 3.7 | 244.7 | 19.9 | 0.6 | 6.1 | 0.8 | 16.6 | 26.4 | 0.3 | 0.4 |

SOV=Source of Variation, DFL=days to flowering, SG=stem girth (cm), NTIL=number of tillers, BYLD=biomass yield (tha-$^{1}$), PHT=plant height (cm), LL=leaf length (cm), LW=leaf width (cm), PL=panicle length (cm), PW=panicle width (cm), PE=panicle exertion (cm), LO=number of plants lodged, SD=100 seed mass (g), GW=grain weight per 5 plants, GY=grain yield (tha$^{-1}$), SS- seed set%, ns= not significant at P≤0.05, *, **, *** significant at P≤0.05, P≤0.01 and P≤0.001 probability levels respectively.

### 3.3.1.2 Pooled analysis of variance for yield and its component traits in sorghum hybrids and their parents

Pooled analysis of variance for different characters in the study are shown in Table 3.7. Variances due to genotypes, environments, and genotypes x environment interaction were highly significant ($p<0.001$) for all traits except for seed set percent which recorded non-significant environmental effect.

Table 3. 7 Mean squares for yield and yield components evaluated across environments over 2014 long rains and 2014-15 short rain seasons.

| SOV | REP | Environment | Genotype | G X E | Error |
|---|---|---|---|---|---|
| df | 2 | 2 | 79 | 158 | 458 |
| DFL | 4.6 | 1040.8*** | 183.6*** | 12.7*** | 5.192 |
| SG | 0.4 | 48.1*** | 1.5*** | 0.7*** | 0.3295 |
| WB | 0.2788 | 157.7*** | 0.9*** | 1.3*** | 0.3334 |
| PAS | 3.8 | 15.9*** | 2.2*** | 0.6*** | 0.3706 |
| NTIL | 1.8 | 1787.5*** | 9.7*** | 8.9*** | 3.162 |
| BY | 21.4 | 1079.6*** | 58.3*** | 14.6*** | 4.7 |
| PHT | 2647.7 | 8947.4*** | 9848.9*** | 527.3*** | 150.9 |
| LL | 288.2 | 163.3** | 179.4*** | 39.7*** | 24 |
| LW | 7.4 | 144.4*** | 3.7*** | 1.3*** | 0.7 |
| PL | 127.1 | 3166.4*** | 87.9*** | 18.0*** | 6.5 |
| PW | 12.5 | 1209.0*** | 10.7*** | 4.3*** | 1.721 |
| PE | 50.4 | 2684.3*** | 185.0*** | 37.7*** | 11.79 |
| LO | 75.4 | 2555.2*** | 121.3*** | 83.6*** | 16.35 |
| SD | 1 | 25.2*** | 1.1*** | 0.3*** | 0.1866 |
| GY | 10 | 282.9*** | 3.5*** | 2.0*** | 0.6 |
| SS | 541.8 | 225.7ns | 4781.7*** | 701.5*** | 161.8 |

SOV= Source of variation, DFL=days to flowering, SG=stem girth (cm), NTIL=number of tillers, BYLD=biomass yield ($tha^{-1}$), PHT=plant height (cm), LL=leaf length (cm), LW=leaf width (cm), PL=panicle length (cm), PW=panicle width (cm), PE=panicle exertion (cm), LO=number of plants lodged, SD=100 seed mass (g), GW=grain weight per 5 plants, GY=grain yield ($tha^{-1}$), SS- seed set%, ns= not significant at $P\leq0.05$, *, **, *** significant at $P\leq0.05$, $P\leq0.01$ and $P\leq0.001$ probability levels respectively.

### 3.3.2 Mean agronomic performance of sorghum hybrids and their parents at individual and across locations

### 3.3.2.1 Mean agronomic performance of sorghum hybrid parents at KALRO-Kiboko in 2014 long rains and 2014-15 short rains

Significant ($p<0.001$) variation was reported among the evaluated hybrid parents for days to 50% flowering, biomass yield, plant height, leaf length, leaf width, panicle width, panicle exertion, number of lodged plants, 100 seed mass and grain yield (Table 3.8). The earliest flowering male and female hybrid parents at Kiboko were

KARI Mtama 1 (68 days) and BTX 623 (71 days) with a mean of 76 days. The average biomass yield of the parents was 7.9 t $ha^{-1}$ with a range of 1.2 to 14.6 t $ha^{-1}$. The highest biomass yielder was ICSB 74 (14.6$tha^{-1}$) and ICSV 700 (13.1$tha^{-1}$) among the females and males respectively (Appendix 1). The mean plant height was 123.8cm with a range of 64 cm to 193.8 cm in ICSB 206 and ICSR 24010.

The longest and shortest leaves were recorded in; ICSB 29007 (79.3cm) and ICSB 206 (50.4cm) respectively. The average leaf width at Kiboko was 8.1cm with the widest leaves recorded in ICSB 29017 (11.2cm). The longest and widest panicles were recorded in ICSB 29017 whereas ICSB 206 recorded the shortest and thinnest panicles. The average panicle exertion was 3.8cm with the longest exertions recorded in ICSB 29017 (10.7cm) (Appendix 1). The mean grain yield was 2.9$tha^{-1}$ with ICSR 24008 (4.1$tha^{-1}$) recording the highest and ICSB 206 (1.1$tha^{-1}$) recording the lowest grain yield (Table 3.8). IESV 91104DL and KARI Mtama 1 recorded the highest 100 seed mass at 3.2g (Appendix 1).

### 3.3.2.2 Mean agronomic performance of sorghum hybrid parents at KALRO-Kampi ya Mawe in 2014-15 short rains

Highly significant differences ($p<0.001$) were revealed for days to flowering, biomass yield, plant height, leaf length, leaf width, stem girth, panicle length and grain yield. The results for the yield superiority among the hybrid parents are represented in table 3.9. The highest yielding sorghum hybrid parents were; ICSB 29003 (1.8$tha^{-1}$), ICSB 75 (1.6$tha^{-1}$) and ICSR 24010 (1.6$tha^{-1}$) whereas the lowest yielding was ICSB 228 (0.3$tha^{-1}$) with a mean grain yield of 1.0$tha^{-1}$ (Table 3.9). Earliest flowering male and female hybrid parents were ICSR 89058 (70days) and ICSB 11003 (71 days) with a mean of 76 days after sowing. ICSB 29007 took the longest number of days to flower (Appendix 2). The mean biomass yield of the trial was 5.8$tha^{-1}$ with the highest yielding parents ICSB 74 (13.7$ha^{-1}$), ICSV 700 (11.8$tha^{-1}$) and ICSB 11036 (11.1$tha^{-1}$).

The tallest and shortest hybrid parents were ICSV 700 (202.5cm) and ICSB 206 (71cm) with mean of 111cm. The longest and shortest leaves were revealed in IESV 91104DL (84cm) and ICSB 206 (51.5cm) respectively. The widest leaves were recorded in ICSB 11016 (8.3cm). The longest panicles were recorded in ICSB 75 (26.3cm) whereas ICSV 700 (14cm) recorded the shortest panicles (Appendix 2).

Table 3. 8 Mean agronomic performance of best 20 yielding sorghum hybrid parents evaluated at KALRO- Kiboko in 2014LR and 2014/15 SR.

| Genotype | Status | DFL | SG | NTIL | BYLD | PHT | LL | LW | PL | PW | PE | LO | SD | GW | GY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ICSR 24008 | Male | 77.0 | 5.6 | 2.0 | 7.6 | 137.6 | 62.8 | 7.9 | 27.0 | 8.1 | 1.5 | 7.0 | 2.2 | 393.5 | 4.1 |
| ICSB 29004 | Female | 75.0 | 6.1 | 4.0 | 8.0 | 127.4 | 66.5 | 8.1 | 26.1 | 8.6 | 3.7 | 2.0 | 2.2 | 398.4 | 4.0 |
| ICSR 24010 | Male | 73.0 | 5.1 | 2.0 | 12.2 | 193.8 | 63.8 | 8.1 | 22.9 | 9.1 | 3.3 | 2.0 | 1.7 | 328.3 | 3.8 |
| ICSB 11040 | Female | 77.0 | 6.0 | 4.0 | 9.4 | 111.4 | 70.3 | 7.3 | 29.8 | 7.5 | 2.8 | 1.0 | 2.4 | 300.6 | 3.7 |
| ICSR 160 | Male | 75.0 | 5.5 | 2.0 | 7.4 | 136.3 | 71.7 | 7.9 | 28.9 | 8.1 | 4.2 | 3.0 | 1.9 | 373.2 | 3.6 |
| IESV 92172 DL | Male | 73.0 | 6.3 | 1.0 | 9.2 | 116.3 | 67.0 | 7.9 | 30.6 | 7.7 | 4.6 | 2.0 | 2.6 | 327.7 | 3.5 |
| ICSB 11038 | Female | 74.0 | 5.9 | 2.0 | 7.7 | 112.8 | 70.0 | 7.8 | 27.4 | 8.5 | 4.5 | 1.0 | 2.5 | 365.3 | 3.5 |
| ICSB 11018 | Female | 80.0 | 6.4 | 7.0 | 10.3 | 124.6 | 63.9 | 8.4 | 26.2 | 7.2 | 2.6 | 1.0 | 2.2 | 378.4 | 3.5 |
| ICSB 29016 | Female | 76.0 | 6.2 | 4.0 | 8.6 | 132.2 | 68.6 | 9.6 | 28.3 | 8.3 | 3.3 | 0.0 | 2.3 | 419.0 | 3.4 |
| ICSR 89058 | Male | 71.0 | 5.7 | 1.0 | 7.1 | 143.0 | 68.2 | 7.3 | 30.4 | 7.1 | 6.0 | 7.0 | 2.1 | 331.9 | 3.4 |
| ICSB 11037 | Female | 81.0 | 6.0 | 3.0 | 8.3 | 121.8 | 75.7 | 8.8 | 29.2 | 11.4 | 1.7 | 1.0 | 2.3 | 424.3 | 3.4 |
| ICSV 700 | Male | 81.0 | 5.0 | 2.0 | 13.1 | 189.3 | 55.5 | 7.6 | 23.9 | 7.4 | 0.3 | 3.0 | 2.3 | 344.9 | 3.4 |
| ICSB 11019 | Female | 76.0 | 6.4 | 3.0 | 9.6 | 117.4 | 70.4 | 8.0 | 25.8 | 6.2 | 0.8 | 1.0 | 2.7 | 393.0 | 3.2 |
| IESV 91104 DL | Male | 72.0 | 5.5 | 1.0 | 9.6 | 164.8 | 74.2 | 8.9 | 21.3 | 8.0 | 7.1 | 2.0 | 3.2 | 452.1 | 3.2 |
| ICSR 38 | Male | 72.0 | 5.1 | 1.0 | 5.4 | 127.5 | 67.7 | 7.3 | 28.0 | 7.9 | 5.1 | 8.0 | 1.7 | 287.9 | 3.2 |
| ICSB 11033 | Female | 73.0 | 6.1 | 4.0 | 3.7 | 136.5 | 71.0 | 8.2 | 30.1 | 11.0 | 0.0 | 4.0 | 2.3 | 405.6 | 3.2 |
| ICSB 11036 | Female | 81.0 | 6.4 | 3.0 | 9.7 | 117.3 | 67.4 | 8.0 | 22.1 | 9.8 | 1.3 | 0.0 | 2.3 | 320.8 | 3.1 |
| ICSB 11039 | Female | 73.0 | 5.5 | 1.0 | 5.6 | 112.2 | 70.8 | 7.8 | 26.5 | 8.1 | 5.8 | 4.0 | 2.2 | 304.1 | 3.1 |
| BTX 623 | Female | 71.0 | 5.6 | 3.0 | 7.2 | 110.7 | 70.6 | 8.0 | 28.4 | 6.5 | 6.2 | 2.0 | 2.3 | 362.8 | 3.1 |
| ICSB 29011 | Female | 80.0 | 5.5 | 4.0 | 9.0 | 145.2 | 67.9 | 8.9 | 26.3 | 9.2 | 11.7 | 2.0 | 2.0 | 328.4 | 3.1 |
| **G.Means** | | **76** | **5.9** | **3** | **7.9** | **123.8** | **67.7** | **8.1** | **27.6** | **8** | **3.8** | **2** | **2.3** | **336** | **2.9** |
| Fpr | | <.001 | 0.002 | 0.21 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 |
| $LSD_{0.001}$ | | 8.46 | 2.25 | 9.34 | 7.52 | 37.19 | 15.59 | 3.16 | 12.33 | 5.07 | 9.7 | 8.26 | 1.07 | 234.3 | 2.39 |
| CV% | | 4.3 | 14.7 | 118.2 | 36.4 | 11.5 | 8.8 | 14.8 | 17.1 | 24.1 | 95.4 | 159 | 17.3 | 26.5 | 30.9 |

DFL=days to flowering, SG=stem girth (cm), NTIL= Number of tillers BYLD=biomass yield ($tha^{-1}$), PHT=plant height (cm), LL=leaf length (cm), LW=leaf width (cm), PL=panicle length (cm), PW=panicle width (cm), PE=panicle exertion (cm), LO=number of plants lodged, SD=100 seed mass (g), GW=grain weight per 5 plants, GY=grain yield ($tha^{-1}$), LSD=least significant difference, SE=standard error of differences, CV%=Coefficient of variation.

Table 3. 9 Mean agronomic performance of best 20 yielding sorghum hybrid parents evaluated at KALRO- Kampi ya Mawe in 2014/15 short rains.

| Genotype | Status | DFL | SG | BYLD | PHT | LL | LW | PL | PW | PE | LO | SD | GW | GY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Seredo | Check | 66 | 5.3 | 6.0 | 143.0 | 71.7 | 6.7 | 23.0 | 5.3 | 3.7 | 4.0 | 2.0 | 146.7 | 2.6 |
| ICSB 29003 | Female | 74 | 6.0 | 4.3 | 97.7 | 62.7 | 6.7 | 21.3 | 6.0 | 4.7 | 0.0 | 2.0 | 95.0 | 1.8 |
| ICSB 75 | Female | 74 | 6.3 | 8.1 | 131.3 | 75.7 | 7.3 | 26.3 | 5.0 | 4.3 | 1.0 | 2.7 | 113.3 | 1.6 |
| ICSR 24010 | Male | 77 | 5.3 | 8.3 | 172.3 | 66.0 | 7.3 | 18.0 | 5.7 | 2.7 | 11.0 | 2.0 | 88.3 | 1.6 |
| ICSB 29002 | Female | 74 | 6.0 | 4.9 | 118.3 | 71.3 | 6.7 | 24.0 | 5.7 | 2.0 | 2.0 | 1.7 | 86.7 | 1.5 |
| IESV 91104 DL | Male | 74 | 5.7 | 9.6 | 182.0 | 84.0 | 8.0 | 19.0 | 6.5 | 2.5 | 10.0 | 2.0 | 121.7 | 1.5 |
| ICSR 24008 | Male | 77 | 5.7 | 6.1 | 121.7 | 65.7 | 7.0 | 18.7 | 5.3 | 0.0 | 0.0 | 2.0 | 103.3 | 1.4 |
| ICSB 11040 | Female | 76 | 5.7 | 5.3 | 106.3 | 69.3 | 6.3 | 23.7 | 5.0 | 3.0 | 0.0 | 1.3 | 71.7 | 1.4 |
| ICSB 29004 | Female | 72 | 6.3 | 5.9 | 98.7 | 67.0 | 7.3 | 18.7 | 4.3 | 1.0 | 4.0 | 2.0 | 96.7 | 1.3 |
| Macia | Male | 74 | 6.0 | 5.1 | 95.7 | 65.0 | 6.3 | 17.7 | 4.3 | 0.0 | 1.0 | 2.0 | 81.7 | 1.2 |
| ICSB 11003 | Female | 71 | 6.0 | 3.5 | 101.7 | 61.0 | 5.0 | 21.3 | 4.7 | 1.3 | 2.0 | 2.0 | 71.7 | 1.2 |
| ICSB 11036 | Female | 82 | 6.3 | 11.1 | 100.0 | 69.0 | 7.0 | 20.0 | 4.7 | 2.3 | 0.0 | 2.3 | 118.3 | 1.1 |
| ICSB 29016 | Female | 76 | 6.3 | 6.7 | 117.0 | 67.0 | 7.0 | 20.0 | 4.3 | 1.3 | 1.0 | 2.0 | 81.7 | 1.1 |
| ICSB 11037 | Female | 78 | 6.3 | 6.7 | 121.5 | 74.5 | 6.5 | 25.5 | 6.0 | 5.0 | 0.0 | 1.7 | 71.7 | 1.1 |
| ICSR 160 | Male | 72 | 5.3 | 2.3 | 110.0 | 70.0 | 6.3 | 19.0 | 4.7 | 0.0 | 18.0 | 2.3 | 86.7 | 1.1 |
| ICSB 11038 | Female | 74 | 5.7 | 4.3 | 110.3 | 70.3 | 6.3 | 22.7 | 5.0 | 0.0 | 4.0 | 2.0 | 70.0 | 1.1 |
| ICSB 11034 | Female | 73 | 6.0 | 3.7 | 94.7 | 66.0 | 7.0 | 25.7 | 4.7 | 2.3 | 1.0 | 1.7 | 70.0 | 1.1 |
| ICSB 74 | Female | 83 | 6.3 | 13.7 | 139.0 | 73.7 | 6.7 | 23.0 | 5.0 | 2.3 | 0.0 | 2.7 | 90.0 | 1.0 |
| BTX 623 | Female | 71 | 6.7 | 4.2 | 95.0 | 68.3 | 6.0 | 20.0 | 3.7 | 1.3 | 3.0 | 1.7 | 68.3 | 1.0 |
| Hakika | Male | 71 | 5.3 | 5.9 | 115.0 | 64.3 | 6.3 | 20.7 | 4.0 | 0.0 | 1.0 | 2.0 | 70.0 | 1.0 |
| **G. Means** | | **76** | **5.9** | **5.8** | **111.0** | **67.9** | **6.7** | **20.7** | **4.7** | **1.7** | **3.0** | **2.0** | **74.8** | **1.0** |
| Fpr | | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | 0.013 | 0.017 | <.001 | 0.042 | 0.1 | 0.001 |
| $LSD_{0.001}$ | | 10.8 | 2.1 | 5.3 | 45.0 | 17.7 | 2.6 | 9.8 | 3.1 | 11.0 | 14.7 | 1.9 | 127.8 | 1.9 |
| SE | | 2.8 | 0.6 | 1.4 | 11.7 | 4.6 | 0.7 | 2.6 | 0.8 | 2.9 | 3.8 | 0.5 | 33.2 | 0.5 |
| CV% | | 3.7 | 9.3 | 24 | 10.6 | 6.8 | 10.2 | 12.4 | 17.2 | 190.8 | 133.1 | 26.2 | 43.9 | 50.2 |

DFL=days to flowering, SG=stem girth (cm), BYLD=biomass yield ($tha^{-1}$), PHT=plant height (cm), LL=leaf length (cm), LW=leaf width (cm), PL=panicle length (cm), PW=panicle width (cm), PE=panicle exertion (cm), LO=number of plants lodged, SD=100 seed mass (g), GW=grain weight per 5 plants, GY=grain yield ($tha^{-1}$), LSD=least significant difference, SE=standard error of differences, CV%=Coefficient of variation, ns=not significant.

### 3.3.2.3 Mean agronomic performance of sorghum hybrid parents across locations

Significant differences ($p<0.01$) were recorded between the performance of sorghum hybrid parental lines for all studied agronomic traits except for waxy bloom (Table 3.10). Days to 50% flowering ranged from 65 to 87 days with a mean of 76 days. The earliest flowering female and male parent was BTX 623 (70.6 days) and KARI Mtama 1 (68 days) respectively (Appendix 3).

There was a wide variation ($p<0.01$) in grain yield among the evaluated hybrid parents with a range of 0.9 $tha^{-1}$ to 3.2 $tha^{-1}$. The highest and lowest yielding females were ICSB 29004 (3.1 $tha^{-1}$) and ICSB 206 (0.9 $tha^{-1}$) respectively. The highest yielding males were ICSR 24008 (3.2 $tha^{-1}$) and ICSR 24010 (3.0 $tha^{-1}$). The lowest yielding male was Wahi (2.1 $tha^{-1}$) (Table 3.9). The mean biomass yield of the parents was 7.2 $tha^{-1}$ with a range of 1.0 to 14.3 $tha^{-1}$. The highest fresh biomass yielders were ICSB 74 (14.3 $tha^{-1}$), ICSV 700 (12.7 $tha^{-1}$) and ICSR 24010 (10.9 $tha^{-1}$) whereas the lowest biomass yield was recorded in ICSB 206 (1 $tha^{-1}$) (Appendix 3). The plant height ranged from 66 cm (ICSB 206) to 192.6 cm (ICSV 700) with a mean of 119.6cm.

The longest leaves were recorded in ICSB 29007 (77.4cm) and IESV 91104DL (76.7cm) whereas ICSB 206 (50.7cm) recorded the shortest leaves. The longest and shortest panicle exertions were recorded in ICSB 29011 (10cm) and ICSB 228 (0cm) respectively. BTX 623 (13.5 leaves) and ICSB 206 (8.6 leaves) had the highest and lowest number of leaves per plant respectively. Hybrid parents KARI Mtama 1 (2.9g) and ICSB 75 (2.9g) recorded the highest 100 seed mass (Appendix 3).

Table 3. 10 Mean performance of best 20 grain yielding sorghum hybrid parents evaluated across locations.

| Rank | Genotype | Status | DFL | SG | BYLD | PHT | LL | LW | PL | PW | LN | PE | LO | SD | GY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | ICSR 24008 | Male | 76.9 | 5.6 | 7.1 | 132.3 | 63.8 | 7.6 | 24.2 | 7.2 | 11.8 | 1.0 | 4.9 | 2.1 | 3.2 |
| 2 | ICSB 29004 | Female | 73.9 | 6.2 | 7.3 | 117.8 | 66.7 | 7.9 | 23.6 | 7.2 | 11.8 | 2.8 | 2.9 | 2.1 | 3.1 |
| 3 | ICSR 24010 | Male | 74.6 | 5.2 | 10.9 | 186.6 | 64.6 | 7.8 | 21.3 | 7.9 | 11.0 | 3.1 | 5.0 | 1.8 | 3.0 |
| 4 | ICSB 11040 | Female | 76.7 | 5.9 | 8.0 | 109.7 | 70.0 | 7.0 | 27.7 | 6.7 | 12.0 | 2.8 | 0.9 | 2.0 | 3.0 |
| 5 | ICSR 160 | Male | 73.7 | 5.4 | 5.7 | 127.5 | 71.1 | 7.4 | 25.6 | 6.9 | 10.7 | 2.8 | 8.3 | 2.1 | 2.7 |
| 6 | ICSB 11038 | Female | 73.7 | 5.8 | 6.6 | 112.0 | 70.1 | 7.3 | 25.8 | 7.3 | 9.9 | 3.0 | 1.9 | 2.4 | 2.7 |
| 7 | ICSB 11018 | Female | 79.8 | 6.4 | 9.0 | 117.8 | 64.3 | 7.9 | 23.7 | 6.4 | 12.1 | 1.8 | 0.6 | 2.0 | 2.6 |
| 8 | ICSB 29016 | Female | 76.1 | 6.2 | 8.0 | 127.2 | 68.0 | 8.8 | 25.5 | 7.0 | 11.8 | 2.7 | 0.7 | 2.2 | 2.6 |
| 9 | IESV 91104 DL | Male | 72.4 | 5.5 | 9.6 | 169.1 | 76.7 | 8.7 | 20.7 | 7.6 | 10.6 | 6.0 | 4.3 | 2.8 | 2.6 |
| 10 | IESV 92172 DL | Male | 73.6 | 6.3 | 7.5 | 107.4 | 68.1 | 7.4 | 27.4 | 6.8 | 10.7 | 3.1 | 2.8 | 2.4 | 2.6 |
| 11 | ICSB 11037 | Female | 79.9 | 6.1 | 7.8 | 121.7 | 75.4 | 8.2 | 28.3 | 10.1 | 11.4 | 2.6 | 0.7 | 2.1 | 2.6 |
| 12 | ICSR 89058 | Male | 71.0 | 5.8 | 6.2 | 135.4 | 66.7 | 6.9 | 28.2 | 6.1 | 9.7 | 4.0 | 7.7 | 1.9 | 2.6 |
| 13 | Seredo | Check | 65.8 | 5.2 | 7.3 | 145.3 | 63.5 | 6.7 | 28.0 | 7.0 | 9.8 | 5.5 | 3.1 | 2.3 | 2.6 |
| 14 | ICSV 700 | Male | 81.0 | 5.0 | 12.7 | 192.6 | 58.7 | 7.5 | 21.4 | 6.8 | 12.2 | 0.2 | 2.7 | 2.1 | 2.5 |
| 15 | ICSB 75 | Female | 75.6 | 6.4 | 10.3 | 142.9 | 74.9 | 8.5 | 30.5 | 6.5 | 12.3 | 6.7 | 3.6 | 2.9 | 2.5 |
| 16 | ICSB 11036 | Female | 81.3 | 6.3 | 10.1 | 111.6 | 67.9 | 7.7 | 21.4 | 8.1 | 11.9 | 1.6 | 0.3 | 2.3 | 2.5 |
| 17 | Macia | Male | 73.7 | 5.8 | 8.1 | 109.4 | 62.8 | 7.4 | 21.2 | 6.7 | 10.9 | 4.5 | 2.5 | 2.2 | 2.4 |
| 18 | ICSR 38 | Male | 72.8 | 5.1 | 5.0 | 120.2 | 66.8 | 7.0 | 25.3 | 6.7 | 9.6 | 4.6 | 6.9 | 1.8 | 2.4 |
| 19 | BTX 623 | Female | 70.6 | 6.0 | 6.2 | 105.5 | 69.8 | 7.3 | 25.6 | 5.6 | 13.5 | 4.6 | 2.1 | 2.1 | 2.4 |
| 20 | ICSB 11019 | Female | 76.1 | 6.3 | 8.4 | 112.1 | 71.4 | 7.7 | 23.6 | 5.5 | 11.2 | 1.0 | 0.8 | 2.3 | 2.4 |
| | **G.means** | | **75.9** | **5.9** | **7.2** | **119.6** | **67.7** | **7.7** | **25.4** | **7.0** | **11.0** | **3.1** | **2.2** | **2.2** | **2.3** |
| | F pr. | | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 |
| | LSD0.01 | | 4.01 | 0.96 | 3.50 | 17.53 | 7.35 | 1.01 | 5.82 | 2.38 | 2.21 | 4.55 | 3.90 | 0.50 | 1.12 |
| | SE± | | 3.27 | 0.78 | 2.86 | 14.31 | 6.00 | 0.82 | 4.75 | 1.95 | 1.81 | 3.71 | 3.19 | 0.41 | 0.91 |
| | CV% | | 4.3 | 13.4 | 36.3 | 11.5 | 8.9 | 10.2 | 17.1 | 24 | 16.5 | 94.4 | 160 | 17.4 | 30.7 |

DFL=days to flowering, SG=stem girth (cm), BYLD=biomass yield (tha-$^{1}$), PHT=plant height (cm), LL=leaf length (cm), LW=leaf width (cm), PL=panicle length (cm), PW=panicle width (cm), PE=panicle exertion (cm), LO=number of plants lodged, SD=100 seed mass (g), GW=grain weight per 5 plants, GY=grain yield (tha$^{-1}$), LSD=least significant difference, SE=standard error of differences, CV%=Coefficient of variation, ns=not significant.

### 3.3.2.4 Mean agronomic performance of sorghum hybrids evaluated at KALRO Kiboko

Highly significant differences ($p \leq 0.001$) were revealed among sorghum hybrids for all traits measured except leaf length and leaf number (Table 3.11). The mean days to flowering was 71.4 days with a range of 65 to 81 days in ICSA 11038 x KARI Mtama 1 and ICSA 29002 x ICSV 700 respectively (Table 3.11). All hybrids had wider stem girths than the check Seredo. Biomass yield ranged from 4.6 $tha^{-1}$ in ICSA 29015 x ICSR 89058 to 15.3 $tha^{-1}$ in ICSA 29017 x ICSR 24010 (Table 3.11).

Three hybrids were significantly ($p < 0.001$) shorter than the check hybrid, ICSA 12 x IESV 92172DL (154.9cm). The shortest and tallest hybrids were ICSA 11016 x Wahi (88.2cm), and ICSA 29017 x ICSR 24010 (219.7cm) respectively (Table 3.11). All hybrids developed from restorer parent ICSR 24010 were tall. The shortest and longest panicles were recorded in ICSA 29001 x ICSV 700 (23.4cm) and ICSA 11004 x ICSR 24008 (42.6cm) respectively. All hybrids developed from restorer ICSV 700 were late with shorter panicles. Leaf number ranged from 8.2 to 13.7 leaves in ICSA 11016 x Wahi and ICSA 29004 x ICSR 24010 respectively.

Panicle exertion ranged from 0.2 to 19.2cm in ICSA 11016 x Wahi and ICSA 29011 x ICSR 89058. Seed set % ranged from 0% to 99.3% with an average of 72.7%. Six hybrids had better seed set than the check hybrid ICSA 12 x IESV 92172 DL (95.9%) (Table 3.11). Seed mass ranged from 2.1g to 3.6g with a mean of 2.7g. The highest 100 seed mass was recorded in a short duration hybrid ICSA 11038 x KARI Mtama 1. Grain yield ranged from 1.6 $tha^{-1}$ in ICSA 11036 x KARI Mtama 1 to 4.8 $tha^{-1}$ in ICSA 29005 x ICSR 24010 with a mean of 3.2 $tha^{-1}$. Nine hybrids recorded superior grain yields than the check ICSA 12 x IESV 92172DL (3.9 $tha^{-1}$) however the differences were non-significant (Table 3.11).

Table 3. 11 Mean agronomic performance of sorghum hybrids evaluated at KALRO Kiboko in 2014 long rains and 2014-15 short rains

| Rank | Hybrids | DFL | SG | BYLD | PHT | LL | LW | PL | PW | LN | PE | SS | SD | GY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | ICSA 29005 x ICSR 24010 | 70.0 | 5.2 | 13.5 | 210.0 | 69.2 | 8.8 | 28.2 | 10.7 | 10.5 | 17.2 | 88.4 | 2.6 | 4.8 |
| 2 | ATX 623 x Macia | 69.2 | 5.6 | 12.9 | 172.9 | 75.4 | 8.4 | 30.8 | 7.9 | 10.5 | 17.9 | 99.3 | 2.6 | 4.6 |
| 3 | ICSA 29011 x ICSR 89058 | 67.5 | 5.8 | 9.8 | 163.5 | 72.5 | 8.0 | 31.8 | 10.1 | 10.0 | 19.2 | 96.1 | 2.6 | 4.4 |
| 4 | ICSA 11040 x IESV 91104 DL | 70.3 | 5.7 | 13.8 | 202.7 | 78.2 | 8.9 | 26.4 | 9.0 | 10.4 | 12.2 | 91.4 | 2.9 | 4.3 |
| 5 | ICSA 11004 x ICSR 24008 | 69.7 | 6.2 | 7.4 | 158.5 | 73.3 | 8.4 | 42.6 | 11.6 | 11.0 | 7.0 | 92.4 | 2.7 | 4.3 |
| 6 | ICSA 11037 x Macia | 71.2 | 6.0 | 8.1 | 158.4 | 78.6 | 9.2 | 30.5 | 11.0 | 10.6 | 11.2 | 85.8 | 2.6 | 4.3 |
| 7 | ICSA 11033 x ICSR 160 | 69.7 | 5.9 | 7.5 | 159.9 | 75.4 | 8.3 | 32.6 | 12.9 | 10.4 | 6.8 | 88.2 | 2.1 | 4.2 |
| 8 | ICSA 232 x ICSR 24008 | 71.7 | 5.6 | 9.2 | 151.3 | 66.7 | 9.0 | 34.1 | 10.7 | 11.2 | 7.9 | 97.8 | 2.3 | 4.0 |
| 9 | ICSA 29017 x ICSR 24010 | 69.7 | 5.5 | 15.3 | 219.7 | 70.3 | 8.4 | 28.6 | 9.9 | 10.6 | 17.3 | 85.9 | 2.4 | 3.9 |
| 10 | ICSA 12 X IESV 92172 DL | 68.3 | 5.7 | 10.0 | 154.9 | 73.1 | 7.6 | 29.4 | 8.0 | 9.7 | 15.7 | 95.5 | 2.6 | 3.9 |
| 11 | ICSA 11003 x ICSR 160 | 69.3 | 5.6 | 7.7 | 162.9 | 72.0 | 8.5 | 31.8 | 10.3 | 10.0 | 12.7 | 92.1 | 2.6 | 3.6 |
| 12 | ICSA 29007 x ICSR 24008 | 74.2 | 6.0 | 7.2 | 158.4 | 67.6 | 9.0 | 32.4 | 9.3 | 10.5 | 8.8 | 92.1 | 2.3 | 3.5 |
| 13 | ICSA 29015 x ICSR 89058 | 65.5 | 5.4 | 4.6 | 162.6 | 69.2 | 7.9 | 31.4 | 8.5 | 9.4 | 17.2 | 99.2 | 2.3 | 3.3 |
| 14 | ICSA 11035 x Macia | 70.2 | 6.5 | 11.8 | 150.0 | 70.1 | 9.2 | 27.2 | 8.9 | 10.6 | 6.5 | 73.5 | 2.6 | 3.3 |
| 15 | ICSA 29002 x ICSV 700 | 81.3 | 5.4 | 11.8 | 182.3 | 63.4 | 8.3 | 24.0 | 7.4 | 11.1 | 1.1 | 48.4 | 2.5 | 3.3 |
| 16 | ICSA 11034 x Macia | 71.0 | 5.9 | 9.3 | 140.9 | 75.3 | 8.5 | 30.0 | 9.4 | 10.2 | 10.9 | 80.5 | 2.8 | 3.3 |
| 17 | ICSA 29004 x ICSR 24010 | 70.3 | 5.6 | 12.5 | 216.1 | 71.2 | 8.4 | 28.0 | 9.2 | 13.7 | 14.3 | 93.6 | 2.4 | 3.3 |
| 18 | ICSA 11016 x Wahi | 73.0 | 5.6 | 9.1 | 88.2 | 54.8 | 7.2 | 24.6 | 6.0 | 8.2 | 0.2 | 31.0 | 2.9 | 3.1 |
| 19 | ICSA 101 x ICSR 38 | 71.0 | 5.7 | 8.9 | 147.2 | 73.1 | 8.0 | 32.9 | 10.2 | 9.4 | 11.5 | 64.8 | 2.4 | 3.1 |
| 20 | ICSA 228 x Hakika | 71.3 | 6.0 | 11.2 | 135.7 | 74.8 | 9.6 | 33.1 | 8.5 | 10.5 | 3.2 | 23.9 | 3.1 | 3.0 |
| 21 | ICSA 29001 x ICSV 700 | 79.7 | 5.5 | 12.0 | 195.8 | 63.0 | 8.3 | 23.4 | 7.7 | 12.1 | 2.9 | 97.3 | 2.6 | 3.0 |
| 22 | ICSA 11038 x KARI Mtama 1 | 65.0 | 5.2 | 12.3 | 184.2 | 70.2 | 7.9 | 25.3 | 8.6 | 9.4 | 16.9 | 0.0 | 3.6 | 2.9 |
| 23 | ICSA 29016 x ICSR 38 | 68.0 | 5.4 | 7.9 | 156.4 | 70.2 | 7.8 | 29.3 | 8.8 | 9.5 | 14.9 | 97.8 | 2.3 | 2.9 |
| 24 | ICSA 75 x ICSR 38 | 68.3 | 5.6 | 6.7 | 172.7 | 69.7 | 8.0 | 36.0 | 8.5 | 10.2 | 16.6 | 93.4 | 2.5 | 2.9 |
| 25 | ICSA 11019 x Hakika | 73.2 | 6.2 | 12.6 | 138.9 | 75.6 | 8.5 | 29.9 | 7.8 | 10.9 | 1.4 | 85.0 | 2.9 | 2.7 |
| 26 | Seredo (Check) | 65.5 | 5.1 | 8.0 | 146.4 | 59.4 | 6.7 | 30.4 | 7.9 | 9.8 | 6.5 | 97.6 | 2.4 | 2.6 |

DFL=days to flowering, NTIL=number of productive tillers, BYLD=biomass yield ($tha^{-1}$), PHT= plant height (cm), LL=Leaf length (cm), LW=Leaf width (cm), PL= panicle length (cm), PW= panicle width (cm), PE= panicle exertion (cm), SS= seed set (%), LO= number of plants lodged, SD= 100 seed mass (g), GW= grain weight per 5 sampled plants, GY= grain yield ($tha^{-1}$)

Table 3. 11 Cont'd: Mean agronomic performance of sorghum hybrids evaluated at KALRO Kiboko in 2014 long rains and 2014-15 short rains

| Rank | Hybrids | DFL | SG | BYLD | PHT | LL | LW | PL | PW | LN | PE | SS | SD | GY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 27 | ICSA 74 x Macia | 73.3 | 6.2 | 11.3 | 164.4 | 74.5 | 9.5 | 32.3 | 8.4 | 10.8 | 8.0 | 39.4 | 2.9 | 2.5 |
| 28 | ICSA 11007 x Wahi | 74.7 | 5.5 | 7.8 | 132.3 | 59.7 | 7.2 | 31.5 | 6.3 | 9.2 | 5.9 | 76.8 | 2.8 | 2.4 |
| 29 | ICSA 29003 x ICSV 700 | 80.0 | 5.9 | 13.1 | 173.2 | 67.5 | 8.0 | 24.0 | 7.5 | 12.6 | 4.2 | 59.8 | 2.8 | 2.4 |
| 30 | ICSA 206 x IESV 91104 DL | 67.5 | 5.3 | 7.8 | 161.9 | 66.9 | 7.8 | 31.5 | 8.8 | 9.3 | 12.7 | 77.5 | 3.2 | 2.3 |
| 31 | ICSA 11039 x KARI Mtama 1 | 66.0 | 5.5 | 8.0 | 172.1 | 73.3 | 8.5 | 24.4 | 8.5 | 8.9 | 13.3 | 3.3 | 3.5 | 2.0 |
| 32 | ICSA 11013 x Hakika | 72.8 | 6.5 | 7.9 | 124.7 | 70.4 | 9.5 | 32.8 | 10.9 | 10.3 | 1.6 | 33.8 | 2.9 | 1.9 |
| 33 | ICSA 11018 x Wahi | 73.5 | 6.7 | 8.7 | 132.0 | 73.2 | 9.5 | 32.4 | 8.6 | 10.7 | 3.3 | 88.2 | 3.2 | 1.9 |
| 34 | ICSA 25002 x IESV 91104 DL | 78.7 | 6.3 | 13.7 | 145.8 | 77.5 | 8.9 | 27.6 | 7.9 | 10.9 | 2.3 | 45.8 | 3.0 | 1.7 |
| 35 | ICSA 11036 x KARI Mtama 1 | 79.5 | 6.8 | 14.8 | 123.7 | 90.2 | 8.1 | 25.6 | 7.1 | 11.2 | 2.6 | 30.6 | 2.9 | 1.6 |
| | **Means** | **71.4** | **5.8** | **10.1** | **160.6** | **71.0** | **8.4** | **29.9** | **8.9** | **10.4** | **9.5** | **72.7** | **2.7** | **3.2** |
| | Fpr | <.001 | <.001 | <.001 | <.001 | 0.031 | <.001 | 0.001 | <.001 | 0.001 | <.001 | <.001 | <.001 | <.001 |
| | LSD | 7.393 | 1.4 | 7.558 | 35.88 | 12.85 | 1.8402 | 12.87 | 4.392 | 2.372 | 13 | 37.27 | 0.9 | 2.75 |
| | SE | 3.817 | 0.7 | 3.902 | 18.53 | 11.27 | 0.9502 | 6.643 | 2.268 | 2.08 | 6.73 | 19.24 | 0.5 | 1.42 |
| | CV% | 5.3 | 12 | 38.6 | 11.4 | 15.7 | 11.2 | 21.9 | 24.8 | 19.8 | 67 | 26.3 | 17 | 45.1 |
| | Prob | 0.1 | 0.1 | 0.1 | 0.1 | 5 | 0.1 | 0.1 | 0.1 | 5 | 0.1 | 0.1 | 0.1 | 0.1 |

DFL=days to flowering, NTIL=number of productive tillers, BYLD=biomass yield ($tha^{-1}$), PHT= plant height (cm), LL=Leaf length (cm), LW=Leaf width (cm), PL= panicle length (cm), PW= panicle width (cm), PE= panicle exertion (cm), SS= seed set (%), LO= number of plants lodged, SD= 100 seed mass (g), GW= grain weight per 5 sampled plants, GY= grain yield ($tha^{-1}$)

### 3.3.2.5 Mean agronomic performance of sorghum hybrids evaluated at KALRO Kampi ya Mawe over the 2014-15 Short rains

Highly significant differences ($p \leq 0.001$) were revealed between sorghum hybrids for days to 50% flowering, stem girth, biomass yield, plant height, leaf width, panicle length, panicle exertion and grain yield (Table 3.12).

Days to 50% flowering ranged from 66 to 81.3 days in ICSA 29015 x ICSR 89058 and ICSA 11036 x KARI Mtama 1 respectively. The stem girth ranged from 5cm to 7cm with a mean of 5.8cm. The largest girth was recorded in ICSA 11039 x KARI Mtama 1. There was a wide variation in biomass produced with a range of 3.3 to 12 $tha^{-1}$ and a mean of 6.9$tha^{-1}$. The highest biomass yielders were ICSA 11035 x Macia (12$tha^{-1}$), ICSA 228 x Hakika and ICSA 29002 x ICSV 700 (11$tha^{-1}$). ICSA 12 X IESV 92172 DL released hybrid check recorded the lowest biomass yield.

Plant height ranged from 110cm to 220.7cm with a mean of 157.4cm. The shortest hybrid was ICSA 11036 x KARI Mtama 1 whereas the tallest was ICSA 29002 x ICSV 700. All hybrids developed from Wahi and Hakika restorer parents were short. ICSA 75 x ICSR 38 recorded the longest panicles at 30cm. Panicle exertion ranged from 0 to 12cm with ICSA 29011 x ICSR 89058 recording the longest exertion. Grain yield ranged from 0.7$tha^{-1}$ to 2.8$tha^{-1}$ with a mean of 1.8 $tha^{-1}$. The highest grain yielders were ICSA 206 x IESV 91104 DL (2.8$tha^{-1}$), ICSA 11004 x ICSR 24008 (2.7$tha^{-1}$) and ICSA 11003 x ICSR 160 (2.6$tha^{-1}$). However, the yields were not significantly different from the check ICSA 12 x IESV 92172DL.

Table 3. 12 Mean agronomic performance of sorghum hybrids evaluated at KALRO Kampi ya Mawe in 2014-15 short rains

| Hybrids | DFL | SG | WB | BYLD | PHT | LL | LW | PL | PW | PE | LOD | SD | GW | GY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ICSA 206 x IESV 91104 DL | 66.7 | 6.3 | 3.0 | 6.9 | 191.0 | 67.3 | 6.7 | 23.7 | 5.3 | 7.0 | 24.3 | 2.0 | 158.3 | 2.8 |
| ICSA 11004 x ICSR 24008 | 68.7 | 6.0 | 2.8 | 6.0 | 140.7 | 69.3 | 7.3 | 25.3 | 5.7 | 6.0 | 24.0 | 1.3 | 168.3 | 2.7 |
| ICSA 11003 x ICSR 160 | 67.3 | 5.7 | 2.5 | 5.3 | 163.7 | 76.7 | 7.3 | 26.3 | 6.0 | 8.0 | 20.0 | 2.3 | 148.3 | 2.6 |
| Seredo (Check) | 66.3 | 5.3 | 2.5 | 6.0 | 143.0 | 71.7 | 6.7 | 23.0 | 5.3 | 3.7 | 4.0 | 2.0 | 146.7 | 2.6 |
| ICSA 11033 x ICSR 160 | 68.0 | 6.0 | 3.5 | 3.8 | 159.7 | 70.7 | 7.0 | 26.3 | 7.7 | 2.0 | 23.0 | 1.7 | 145.0 | 2.5 |
| ICSA 11038 x KARI Mtama 1 | 67.7 | 6.0 | 2.5 | 7.9 | 185.7 | 70.7 | 7.3 | 22.7 | 6.0 | 7.7 | 13.7 | 3.0 | 141.7 | 2.5 |
| ICSA 11039 x KARI Mtama 1 | 67.7 | 5.0 | 3.0 | 7.4 | 207.7 | 69.0 | 6.7 | 23.7 | 6.3 | 8.7 | 8.7 | 3.0 | 168.3 | 2.5 |
| ICSA 11035 x Macia | 71.7 | 6.3 | 4.0 | 12.0 | 151.7 | 69.3 | 9.0 | 26.7 | 6.3 | 5.3 | 5.7 | 2.3 | 175.0 | 2.3 |
| ATX 623 x Macia | 69.3 | 6.0 | 2.5 | 4.9 | 152.7 | 72.3 | 8.0 | 25.3 | 4.3 | 7.0 | 25.3 | 2.0 | 116.7 | 2.3 |
| ICSA 29004 x ICSR 24010 | 70.3 | 5.3 | 2.8 | 7.4 | 196.7 | 66.3 | 6.7 | 22.3 | 6.0 | 10.0 | 21.0 | 2.0 | 145.0 | 2.2 |
| ICSA 29017 x ICSR 24010 | 70.0 | 5.3 | 3.0 | 6.1 | 206.0 | 67.0 | 7.3 | 19.7 | 4.7 | 4.0 | 16.3 | 1.7 | 143.3 | 2.0 |
| ICSA 11034 x Macia | 68.3 | 6.0 | 3.5 | 5.7 | 134.7 | 76.3 | 7.3 | 23.7 | 5.0 | 3.7 | 15.3 | 2.3 | 143.3 | 2.0 |
| ICSA 29011 x ICSR 89058 | 68.7 | 5.7 | 3.8 | 5.9 | 168.0 | 67.3 | 7.0 | 27.7 | 6.7 | 12.0 | 12.7 | 2.0 | 128.3 | 2.0 |
| ICSA 11040 x IESV 91104 DL | 72.7 | 5.7 | 3.7 | 7.0 | 175.0 | 80.7 | 7.7 | 21.7 | 5.3 | 2.0 | 22.3 | 2.7 | 111.7 | 1.8 |
| ICSA 12 X IESV 92172 DL | 68.7 | 6.0 | 4.0 | 3.3 | 147.7 | 70.7 | 6.3 | 27.0 | 4.7 | 9.0 | 26.0 | 1.7 | 113.3 | 1.8 |
| ICSA 29001 x ICSV 700 | 76.0 | 6.0 | 3.0 | 9.6 | 175.0 | 71.3 | 7.0 | 20.0 | 4.7 | 0.0 | 17.3 | 2.0 | 146.7 | 1.8 |
| ICSA 75 x ICSR 38 | 66.7 | 6.3 | 3.0 | 3.8 | 162.7 | 74.7 | 6.7 | 30.0 | 4.7 | 11.0 | 28.0 | 1.7 | 98.3 | 1.8 |
| ICSA 74 x Macia | 72.3 | 6.0 | 3.5 | 10.4 | 160.7 | 67.3 | 7.0 | 24.0 | 4.7 | 4.0 | 2.7 | 2.3 | 133.3 | 1.8 |
| ICSA 11018 x Wahi | 70.7 | 7.0 | 3.5 | 5.6 | 114.3 | 71.3 | 8.0 | 24.0 | 5.0 | 3.7 | 1.0 | 2.7 | 143.3 | 1.6 |
| ICSA 232 x ICSR 24008 | 74.0 | 6.0 | 3.2 | 7.3 | 147.0 | 68.7 | 8.0 | 24.0 | 5.7 | 5.7 | 2.7 | 1.3 | 113.3 | 1.6 |
| ICSA 29007 x ICSR 24008 | 73.0 | 6.3 | 3.7 | 6.4 | 162.7 | 68.3 | 7.3 | 25.0 | 5.0 | 8.3 | 18.3 | 2.0 | 93.3 | 1.6 |

Table 3.12 Cont'd: Mean agronomic performance of sorghum hybrids evaluated at KALRO Kampi ya Mawe in 2014-15 short rains

| Hybrids | DFL | SG | WB | BYLD | PHT | LL | LW | PL | PW | PE | LOD | SD | GW | GY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ICSA 101 x ICSR 38 | 70.3 | 5.7 | 3.5 | 4.7 | 128.0 | 69.7 | 6.0 | 25.7 | 5.0 | 4.3 | 14.3 | 2.3 | 98.3 | 1.5 |
| ICSA 11037 x Macia | 72.0 | 6.0 | 3.3 | 4.3 | 133.0 | 76.7 | 7.0 | 21.7 | 4.7 | 1.7 | 22.7 | 1.7 | 101.7 | 1.5 |
| ICSA 11007 x Wahi | 73.7 | 6.3 | 3.2 | 7.3 | 138.3 | 71.7 | 7.3 | 27.3 | 5.0 | 2.0 | 6.0 | 2.3 | 110.0 | 1.4 |
| ICSA 29005 x ICSR 24010 | 71.7 | 5.3 | 2.7 | 5.4 | 181.0 | 71.0 | 7.0 | 22.3 | 5.7 | 5.0 | 28.3 | 1.7 | 65.0 | 1.4 |
| ICSA 228 x Hakika | 73.0 | 6.0 | 3.3 | 11.0 | 134.0 | 68.0 | 8.3 | 25.3 | 5.0 | 4.7 | 0.3 | 2.3 | 100.0 | 1.3 |
| ICSA 29002 x ICSV 700 | 79.7 | 5.3 | 2.5 | 11.0 | 220.7 | 72.0 | 7.0 | 19.3 | 6.0 | 11.7 | 5.0 | 2.0 | 91.7 | 1.3 |
| ICSA 29016 x ICSR 38 | 67.3 | 5.7 | 3.0 | 3.5 | 131.0 | 69.7 | 7.3 | 21.3 | 4.0 | 4.3 | 28.7 | 1.7 | 73.3 | 1.3 |
| ICSA 29015 x ICSR 89058 | 66.0 | 5.3 | 3.5 | 3.6 | 149.0 | 67.0 | 7.0 | 22.7 | 4.7 | 4.7 | 27.3 | 2.3 | 83.3 | 1.2 |
| ICSA 11016 x Wahi | 75.7 | 6.3 | 3.5 | 8.7 | 118.3 | 71.3 | 8.0 | 25.7 | 5.0 | 0.0 | 0.3 | 2.7 | 80.0 | 1.1 |
| ICSA 11013 x Hakika | 76.0 | 6.3 | 3.3 | 8.3 | 114.3 | 71.7 | 8.3 | 26.7 | 5.0 | 0.0 | 0.7 | 2.7 | 85.0 | 1.1 |
| ICSA 11019 x Hakika | 74.7 | 6.3 | 3.0 | 9.5 | 138.7 | 72.3 | 7.7 | 22.0 | 4.7 | 4.0 | 0.0 | 2.5 | 100.0 | 1.0 |
| ICSA 25002 x IESV 91104 DL | 76.5 | 6.7 | 2.3 | 7.4 | 175.5 | 85.5 | 9.0 | 23.5 | 5.5 | 0.0 | 2.0 | 2.3 | 106.7 | 0.9 |
| ICSA 29003 x ICSV 700 | 76.0 | 5.7 | 3.0 | 9.0 | 189.5 | 75.5 | 7.5 | 18.5 | 5.0 | 4.0 | 20.7 | 2.7 | 41.7 | 0.9 |
| ICSA 11036 x KARI Mtama 1 | 81.3 | 6.3 | 4.0 | 8.5 | 110.0 | 66.0 | 7.0 | 17.0 | 4.7 | 0.0 | 0.3 | 2.7 | 66.7 | 0.7 |
| **Means** | **71.4** | **5.9** | **3.2** | **6.9** | **157.4** | **71.3** | **7.3** | **23.7** | **5.3** | **5.0** | **14.0** | **2.2** | **116.7** | **1.8** |
| Fpr | <.001 | 0.001 | 0.868 | 0.005 | <.001 | 0.034 | <.001 | <.001 | 0.045 | <.001 | 0.001 | 0.023 | 0.686 | 0.001 |
| LSD | 5.20 | 1.30 | 1.75 | 8.36 | 35.64 | 17.06 | 1.97 | 10.54 | 4.30 | 10.68 | 13.75 | 1.62 | 312.40 | 2.25 |
| SE | 3.31 | 0.83 | 1.12 | 5.33 | 22.73 | 10.88 | 1.25 | 6.72 | 2.74 | 6.81 | 8.77 | 0.58 | 199.30 | 1.43 |
| CV% | 4.6 | 14.2 | 34.4 | 57.8 | 14.3 | 15.3 | 15.6 | 24.1 | 35.5 | 85.3 | 146.9 | 26.5 | 64.2 | 53.4 |
| Prob | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |

DFL=days to flowering, NTIL=number of productive tillers, BYLD=biomass yield ($tha^{-1}$), PHT= plant height (cm), LL=Leaf length (cm), LW=Leaf width (cm), PL= panicle length (cm), PW= panicle width (cm), PE= panicle exertion (cm), SS= seed set (%), LO= number of plants lodged, SD= 100 seed mass (g), GW= grain weight per 5 sampled plants, GY=grain yield ($tha^{-1}$).

### 3.3.2.6 Mean agronomic performance of sorghum hybrids evaluated across locations

Highly significant differences ($p<0.001$) were noted among sorghum hybrids for stem girth, days to 50% flowering, biomass yield, plant height, panicle length and width, 100 seed mass and grain yield (Table 3.13). Days to 50% ranged from 65.7 to 80.8 days. The earliest flowering hybrid was ICSA 29015 x ICSR 89058. Stem girth ranged from 5.2 to 6.8cm. Biomass yield ranged from 4.2 to 12.7 $tha^{-1}$ with a mean of 9.0 $tha^{-1}$. The highest biomass yielders were ICSA 11036 x KARI Mtama 1 (12.7 $tha^{-1}$), ICSA 29017 x ICSR 24010 (12.2 $tha^{-1}$) and ICSA 11035 x Macia (11.9 $tha^{-1}$). However, the yields were not significantly different from the check, ICSA 12 X IESV 92172 DL.

The tallest and shortest hybrids were ICSA 29017 x ICSR 24010 (215.1cm) and ICSA 11016 x Wahi (99.5cm). Panicle length ranged from 22.3cm to 36.9cm with a mean of 27.9cm. All hybrids developed from male lines ICSV 700 and KARI Mtama 1 had shorter panicles. Panicle exertion ranged from 0.1cm to 16.8cm with 30 out of 34 hybrids being well exerted. 100 Seed mass ranged from 2.0 to 3.4g with hybrids ICSA 11038 x KARI Mtama 1 (3.4g) and ICSA 11039 x KARI Mtama 1 (3.3g) recording the highest score. The mean grain yield was 2.7$tha^{-1}$ with a range of 1.3 to 3.8 $tha^{-1}$. The highest grain yielders were ATX 623 x Macia (3.8$tha^{-1}$) and ICSA 11004 x ICSR 24008 (3.8$tha^{-1}$) however the yields were not significantly different from the check hybrid ICSA 12 X IESV 92172 DL (3.2$tha^{-1}$)

Table 3. 13 Mean performance of sorghum hybrids evaluated across locations in 2014 long and 2014-15 short rains

| Hybrids | DFL | SG | WB | BYLD | PHT | LL | LW | PL | PW | PE | LO | SD | GW | GYLD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ATX 623 x Macia | 69.2 | 5.8 | 3.2 | 10.3 | 166.2 | 74.4 | 8.2 | 29.0 | 6.7 | 14.2 | 9.7 | 2.4 | 345.0 | 3.8 |
| ICSA 11004 x ICSR 24008 | 69.3 | 6.1 | 2.8 | 6.9 | 152.5 | 72.0 | 8.0 | 36.9 | 9.6 | 6.7 | 10.7 | 2.3 | 423.6 | 3.8 |
| ICSA 11033 x ICSR 160 | 69.1 | 5.9 | 2.9 | 6.3 | 159.8 | 73.8 | 7.9 | 30.5 | 11.1 | 5.2 | 11.6 | 2.0 | 343.4 | 3.7 |
| ICSA 29005 x ICSR 24010 | 70.6 | 5.3 | 3.3 | 10.8 | 200.3 | 69.8 | 8.2 | 26.2 | 9.0 | 13.1 | 10.4 | 2.3 | 290.8 | 3.7 |
| ICSA 29011 x ICSR 89058 | 67.9 | 5.8 | 3.3 | 8.5 | 165.0 | 70.8 | 7.7 | 30.4 | 9.0 | 16.8 | 5.4 | 2.4 | 396.8 | 3.6 |
| ICSA 11040 x IESV 91104 DL | 71.1 | 5.7 | 3.3 | 11.5 | 193.5 | 79.0 | 8.5 | 24.8 | 7.8 | 8.8 | 8.9 | 2.8 | 327.1 | 3.5 |
| ICSA 11037 x Macia | 71.4 | 6.0 | 3.4 | 6.9 | 150.0 | 78.0 | 8.5 | 27.6 | 8.9 | 8.0 | 10.9 | 2.3 | 437.7 | 3.3 |
| ICSA 29017 x ICSR 24010 | 69.8 | 5.5 | 3.1 | 12.2 | 215.1 | 69.2 | 8.0 | 25.6 | 8.1 | 12.8 | 7.3 | 2.1 | 339.0 | 3.3 |
| ICSA 11003 x ICSR 160 | 68.7 | 5.6 | 3.0 | 6.9 | 163.2 | 73.5 | 8.1 | 30.0 | 8.9 | 11.1 | 8.1 | 2.5 | 380.7 | 3.3 |
| ICSA 12 X IESV 92172 DL | 68.4 | 5.8 | 3.6 | 7.8 | 152.5 | 72.3 | 7.2 | 28.6 | 6.9 | 13.4 | 9.1 | 2.3 | 313.1 | 3.2 |
| ICSA 232 x ICSR 24008 | 72.4 | 5.7 | 3.4 | 8.5 | 149.8 | 67.4 | 8.7 | 30.8 | 9.0 | 7.1 | 3.9 | 2.0 | 326.7 | 3.2 |
| ICSA 11035 x Macia | 70.7 | 6.5 | 3.7 | 11.9 | 150.5 | 69.8 | 9.1 | 27.0 | 8.1 | 6.1 | 2.4 | 2.5 | 312.9 | 3.0 |
| ICSA 29004 x ICSR 24010 | 70.3 | 5.5 | 3.1 | 10.8 | 209.6 | 69.6 | 7.8 | 26.1 | 8.1 | 12.9 | 8.0 | 2.3 | 352.4 | 2.9 |
| ICSA 11034 x Macia | 70.1 | 6.0 | 2.9 | 8.1 | 138.8 | 75.6 | 8.1 | 27.9 | 8.0 | 8.5 | 6.1 | 2.6 | 321.4 | 2.9 |
| ICSA 29007 x ICSR 24008 | 73.8 | 6.1 | 3.1 | 7.0 | 159.8 | 67.8 | 8.5 | 30.0 | 7.8 | 8.6 | 8.2 | 2.2 | 431.2 | 2.8 |
| ICSA 11038 x KARI Mtama 1 | 65.9 | 5.5 | 3.3 | 10.8 | 184.7 | 70.4 | 7.7 | 24.4 | 7.7 | 13.8 | 6.0 | 3.4 | 295.8 | 2.8 |
| ICSA 29015 x ICSR 89058 | 65.7 | 5.4 | 2.8 | 4.2 | 158.0 | 68.4 | 7.6 | 28.5 | 7.2 | 13.0 | 11.0 | 2.3 | 358.7 | 2.6 |
| Seredo (Check) | 65.8 | 5.2 | 3.4 | 7.3 | 145.3 | 63.5 | 6.7 | 28.0 | 7.0 | 5.5 | 3.1 | 2.3 | 221.9 | 2.6 |
| ICSA 29001 x ICSV 700 | 78.4 | 5.6 | 4.0 | 11.2 | 188.9 | 65.8 | 7.9 | 22.3 | 6.7 | 1.9 | 5.9 | 2.4 | 330.9 | 2.6 |
| ICSA 29002 x ICSV 700 | 80.8 | 5.4 | 2.8 | 11.6 | 195.1 | 66.3 | 7.9 | 22.4 | 6.9 | 4.6 | 1.7 | 2.3 | 330.2 | 2.6 |
| ICSA 101 x ICSR 38 | 70.8 | 5.7 | 2.9 | 7.5 | 140.8 | 71.9 | 7.3 | 30.5 | 8.5 | 9.1 | 6.3 | 2.4 | 288.9 | 2.6 |
| ICSA 75 x ICSR 38 | 67.8 | 5.8 | 3.4 | 5.7 | 169.4 | 71.4 | 7.5 | 34.0 | 7.2 | 14.7 | 11.9 | 2.2 | 341.9 | 2.5 |
| ICSA 206 x IESV 91104 DL | 67.2 | 5.6 | 3.5 | 7.4 | 171.6 | 67.1 | 7.4 | 28.9 | 7.6 | 10.8 | 9.0 | 2.8 | 311.9 | 2.5 |
| ICSA 228 x Hakika | 71.9 | 6.0 | 3.2 | 11.1 | 135.1 | 72.5 | 9.2 | 30.5 | 7.3 | 3.7 | 0.1 | 2.9 | 252.1 | 2.5 |
| ICSA 29016 x ICSR 38 | 67.8 | 5.5 | 3.9 | 6.4 | 148.0 | 70.0 | 7.6 | 26.6 | 7.2 | 11.4 | 14.7 | 2.1 | 245.0 | 2.4 |

DFL=days to flowering, NTIL=number of productive tillers, BYLD=biomass yield ($tha^{-1}$), PHT= plant height (cm), LL=Leaf length (cm), LW=Leaf width (cm), PL= panicle length (cm), PW= panicle width (cm), PE= panicle exertion (cm), SS= seed set (%), LO= number of plants lodged, SD= 100 seed mass (g), GW= grain weight per 5 sampled plants, GY=grain yield ($tha^{-1}$)

Table 3. 13 Cont'd: Mean performance of sorghum hybrids evaluated across locations in 2014 long and 2014-15 short rains

| Hybrids | DFL | SG | WB | BYLD | PHT | LL | LW | PL | PW | PE | LO | SD | GW | GYLD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ICSA 74 x Macia | 73.0 | 6.1 | 3.3 | 11.0 | 163.1 | 72.1 | 8.6 | 29.5 | 7.1 | 6.6 | 1.9 | 2.7 | 324.2 | 2.2 |
| ICSA 11039 x KARI Mtama 1 | 66.6 | 5.3 | 3.1 | 7.8 | 184.0 | 71.9 | 7.9 | 24.2 | 7.8 | 11.7 | 3.1 | 3.3 | 278.2 | 2.2 |
| ICSA 11019 x Hakika | 73.7 | 6.3 | 3.6 | 11.5 | 138.8 | 74.5 | 8.2 | 27.2 | 6.8 | 2.3 | 0.2 | 2.8 | 244.8 | 2.1 |
| ICSA 11016 x Wahi | 74.0 | 5.9 | 3.6 | 9.0 | 99.5 | 61.0 | 7.5 | 25.0 | 5.7 | 0.1 | 0.1 | 2.8 | 199.2 | 2.1 |
| ICSA 11007 x Wahi | 74.3 | 5.8 | 3.1 | 7.6 | 134.3 | 63.7 | 7.3 | 30.1 | 5.9 | 4.6 | 2.6 | 2.6 | 259.0 | 2.0 |
| ICSA 29003 x ICSV 700 | 79.0 | 5.8 | 2.8 | 11.7 | 177.3 | 69.5 | 7.9 | 22.6 | 6.9 | 4.2 | 7.3 | 2.7 | 248.2 | 1.9 |
| ICSA 11018 x Wahi | 72.6 | 6.8 | 3.6 | 7.7 | 126.1 | 72.6 | 9.0 | 29.6 | 7.4 | 3.4 | 0.6 | 3.0 | 290.1 | 1.8 |
| ICSA 11013 x Hakika | 73.6 | 6.4 | 3.2 | 8.1 | 121.2 | 70.8 | 9.1 | 30.7 | 8.9 | 1.0 | 0.4 | 2.8 | 244.1 | 1.6 |
| ICSA 25002 x IESV 91104 DL | 78.1 | 6.4 | 2.6 | 11.6 | 153.2 | 79.5 | 8.9 | 26.6 | 7.3 | 1.7 | 0.8 | 2.8 | 287.4 | 1.5 |
| ICSA 11036 x KARI Mtama 1 | 80.1 | 6.6 | 3.4 | 12.7 | 119.1 | 82.1 | 7.7 | 22.8 | 6.3 | 1.7 | 1.4 | 2.8 | 177.0 | 1.3 |
| **Means** | 71.4 | 5.8 | 3.3 | 9.0 | 159.4 | 71.1 | 8.0 | 27.9 | 7.7 | 8.0 | 6.0 | 2.5 | 310.6 | 2.7 |
| Fpr | <.001 | <.001 | 0.628 | <.001 | <.001 | 0.034 | <.001 | <.001 | 0.118 | <.001 | 0.008 | <.001 | 0.856 | 0.001 |
| LSD | 5.2 | 1.1 | 1.7 | 6.3 | 30.5 | 15.1 | 1.7 | 10.1 | 4.2 | 10.8 | 13.7 | 0.9 | 311.6 | 1.8 |
| SE | 3.3 | 0.7 | 1.1 | 4.0 | 19.4 | 9.6 | 1.1 | 6.4 | 2.7 | 6.9 | 8.7 | 0.6 | 198.6 | 1.4 |
| CV% | 4.6 | 11.4 | 33.8 | 43.1 | 12.1 | 13.4 | 13.5 | 22.7 | 34.5 | 85.3 | 150.8 | 22.2 | 61.9 | 53.4 |

DFL=days to flowering, NTIL=number of productive tillers, BYLD=biomass yield ($tha^{-1}$), PHT= plant height (cm), LL=Leaf length (cm), LW=Leaf width (cm), PL= panicle length (cm), PW= panicle width (cm), PE= panicle exertion (cm), SS= seed set (%), LO= number of plants lodged, SD= 100 seed mass (g), GW= grain weight per 5 sampled plants, GY=grain yield ($tha^{-1}$)

### 3.3.3 Correlation and regression analysis among sorghum agro-morphological traits

#### 3.3.3.1 Correlation analysis among agro-morphological traits at Kiboko

Highly significant (P≤0.001), negative correlations were recorded between days to flowering and grain yield (r=-0.4). Plant height recorded highly significant (P≤0.001) positive correlation with biomass yield (r=0.5) and panicle exertion (r=0.5). Grain yield recorded moderately positive (r=0.4) highly significant (P≤0.001) correlation with plant height (Table 3.14). Number of tillers recorded highly significant (P≤0.001) positive correlation with panicle width (r=0.5), however its correlation with waxy bloom was highly negative (r=-0.6). Moderate positive correlation (r=0.4) was recorded between number of tillers and 100 seed mass, however its correlation with stem girth was moderately negative (r=-0.4). Stem girth recorded highly significant (P≤0.001) positive correlation (r=0.5) with waxy bloom however its correlation with panicle exertion was highly negative (r=-0.5). Leaf length recorded moderately positive, highly significant (P≤0.001) correlation with panicle length and leaf width (r=0.4).

#### 3.3.3.2 Correlation analysis among agro-morphological traits at Kampi ya Mawe

Days to 50% flowering recorded highly significant (P≤0.001) negative correlation with number of lodged plants (r=-0.6), and panicle length (r=-0.5). However, its correlation with biomass yield was moderately positive (r=0.4) (Table 3.15). Biomass yield recorded significant strong positive correlation with leaf width (r=0.5) and plant height (r=0.5). Grain yield depicted highly significant (P≤0.001) positive correlation with number of lodged plants (r=0.6), plant height (r=0.7), panicle exertion (r=0.6), panicle length (r=0.5) and width (r=0.6). However, its correlation with days to 50% flowering was highly negative (r=-0.7) (Table 3.15). Plant height was significantly positively correlated with number of lodged plants (r=0.6), panicle exertion and width (r=0.6 and 0.5 respectively). However, its correlation with waxy bloom was highly negative (r=-0.5).

#### 3.3.3.3 Correlation analysis among different traits across locations

Days to flowering recorded highly significant (P≤0.001) negative correlation with grain yield (r=-0.4), plant height (r=-0.3), panicle exertion (r=-0.3) and waxy bloom (r=-0.3), however, the values were moderate. Biomass yield was highly positively

correlated with plant height (r=0.5) however its correlation with grain yield was moderately positive (r=0.3). There was moderate positive correlation between grain yield and number of plants lodged (r=0.4), plant height (r=0.4) and seed set% (r=0.3) as shown in table 3.16. Tiller number and panicle width recorded highly significant (P≤0.001) positive correlation (r=0.5). The correlation between tiller number with panicle exertion and 100 seed mass was significant and positive (r=0.4). However, its correlation with waxy bloom was highly negative (r=-0.6) and significant (P≤0.001).

Plant height and panicle exertion recorded a significantly strong positive correlation (r=0.5). Strong negative correlation was recorded between stem girth and panicle exertion (r=-0.5) (Table 3.16). The correlations between waxy bloom with panicle width (r=-0.5) and 100 seed mass (r=-0.4) were negative and highly significant (P≤0.001). However, its association with stem girth was significantly positive (r=0.5).

Table 3. 14 Correlation coefficients (r) among 15 sorghum agro-morphological traits at Kiboko in 2014LR and 2014-15SR seasons

| | DFL | BY | GY | LL | LW | NTIL | LO | PH | PE | PL | PW | SD | SS | SG | WB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **DFL** | - | | | | | | | | | | | | | | |
| **BY** | 0.0ns | - | | | | | | | | | | | | | |
| **GY** | -0.4*** | 0.3*** | - | | | | | | | | | | | | |
| **LL** | -0.2** | 0.2** | 0.2** | - | | | | | | | | | | | |
| **LW** | 0.2* | 0.2** | -0.1ns | 0.4*** | - | | | | | | | | | | |
| **NTIL** | 0.2** | -0.2** | -0.1ns | -0.1ns | 0.1 ns | - | | | | | | | | | |
| **LO** | -0.2** | -0.2* | 0.4*** | 0.0 ns | -0.2 ns | -0.1ns | - | | | | | | | | |
| **PH** | -0.3*** | 0.5*** | 0.4*** | 0.3*** | 0.2** | 0.0ns | 0.1ns | - | | | | | | | |
| **PE** | -0.3*** | 0.0ns | 0.1ns | 0.1 ns | 0.0 ns | 0.4*** | 0.1ns | 0.5*** | - | | | | | | |
| **PL** | -0.2* | -0.2* | 0.1ns | 0.4*** | 0.3*** | 0.2ns | 0.2* | 0.0ns | 0.2ns | - | | | | | |
| **PW** | 0.0ns | -0.2* | 0.0ns | 0.1 ns | 0.3*** | 0.5*** | 0.1ns | 0.3*** | 0.4*** | 0.4*** | - | | | | |
| **SD** | -0.1ns | 0.1ns | -0.3*** | 0.1 ns | 0.2 ns | 0.4*** | -0.2** | 0.2** | 0.3*** | 0.1ns | 0.3*** | - | | | |
| **SS** | 0.1ns | -0.2** | 0.3*** | -0.2** | -0.3*** | 0.0ns | 0.2** | -0.1ns | 0.0ns | 0.0ns | 0.0ns | -0.4*** | - | | |
| **SG** | 0.0ns | 0.2* | -0.1ns | 0.2* | 0.3*** | -0.4*** | -0.2ns | -0.3*** | -0.5*** | 0.2* | -0.3*** | -0.1ns | -0.2** | - | |
| **WB** | -0.3*** | 0.2** | 0.2ns | 0.0 ns | -0.1ns | -0.6*** | 0.0ns | -0.1ns | -0.4*** | -0.2* | -0.5*** | -0.4*** | 0.0ns | 0.5*** | - |

DFL=days to flowering, NTIL=number of productive tillers, BY=biomass yield ($tha^{-1}$), PH= plant height (cm), LL=Leaf length (cm), LW=Leaf width (cm), PL= panicle length (cm), PW= panicle width (cm), PE= panicle exertion (cm), SS= seed set (%), LO= number of plants lodged, SD= 100 seed mass (g), GY=grain yield ($tha^{-1}$), ns= not significant at $P \leq 0.05$, *, **, *** significant at $P \leq 0.05$, $P \leq 0.01$ and $P \leq 0.001$ probability levels respectively.

Table 3. 15 Correlation coefficients (r) among 14 sorghum agro-morphological traits at Kampi ya Mawe in 2014-15SR

| | DFL | BY | GY | LL | LW | NTIL | LO | PHT | PE | PL | PW | SD | SG | WB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DFL | - | | | | | | | | | | | | | |
| BY | 0.4** | - | | | | | | | | | | | | |
| GY | -0.7*** | 0.2ns | - | | | | | | | | | | | |
| LL | 0.0ns | 0.3** | 0.3* | - | | | | | | | | | | |
| LW | 0.0ns | 0.5*** | 0.3** | 0.4** | - | | | | | | | | | |
| NTI | -0.3* | -0.1ns | 0.4*** | 0.0ns | -0.1ns | - | | | | | | | | |
| LO | -0.6*** | -0.2ns | 0.6*** | 0.3* | 0.1ns | 0.3** | - | | | | | | | |
| PHT | -0.3* | 0.5*** | 0.7*** | 0.4*** | 0.3** | 0.2ns | 0.6*** | - | | | | | | |
| PE | -0.4** | 0.2ns | 0.6*** | 0.1ns | 0.1ns | 0.2ns | 0.4*** | 0.6*** | - | | | | | |
| PL | -0.5** | -0.1ns | 0.5*** | 0.2ns | 0.2ns | 0.2* | 0.3** | 0.2ns | 0.4*** | - | | | | |
| PW | -0.3* | 0.2ns | 0.6*** | 0.2ns | 0.4** | 0.2ns | 0.2* | 0.5*** | 0.4*** | 0.4** | - | | | |
| SD | 0.0ns | 0.4** | 0.1ns | 0.2ns | 0.3* | -0.1ns | -0.1ns | 0.2ns | 0.1ns | 0.1ns | 0.2ns | - | | |
| SG | 0.1ns | 0.0ns | -0.1ns | 0.0ns | 0.3* | 0.2ns | -0.2* | -0.4*** | -0.2* | 0.2* | -0.1ns | 0.0ns | - | |
| WB | 0.2ns | -0.1ns | -0.3ns | -0.2ns | -0.1ns | 0.0ns | -0.2* | -0.5*** | -0.2ns | 0.1ns | -0.3** | -0.1ns | 0.4ns | - |

DFL=days to flowering, NTIL=number of productive tillers, BY=biomass yield ($tha^{-1}$), PH= plant height (cm), LL=Leaf length (cm), LW=Leaf width (cm), PL= panicle length (cm), PW= panicle width (cm), PE= panicle exertion (cm), LO= number of plants lodged, SD= 100 seed mass (g), GY=grain yield ($tha^{-1}$), ns= not significant at $P \leq 0.05$, *, **, *** significant at $P \leq 0.05$, $P \leq 0.01$ and $P \leq 0.001$ probability levels respectively.

Table 3. 16 Correlation coefficients (r) among 15 sorghum agro-morphological traits evaluated across 3 environments

| | DFL | BY | GY | LL | LW | NTIL | LO | PHT | PE | PL | PW | SD | SS | SG | WB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DFL | - | | | | | | | | | | | | | | |
| BY | 0.0ns | - | | | | | | | | | | | | | |
| GY | -0.4*** | 0.3*** | - | | | | | | | | | | | | |
| LL | -0.2** | 0.2** | 0.2** | - | | | | | | | | | | | |
| LW | 0.2** | 0.2* | -0.1ns | 0.4*** | - | | | | | | | | | | |
| NTIL | 0.2** | -0.2** | -0.1ns | -0.1ns | 0.1ns | - | | | | | | | | | |
| LO | -0.2** | -0.2* | 0.4*** | 0.0ns | -0.2* | -0.1ns | - | | | | | | | | |
| PHT | -0.3*** | 0.5*** | 0.4*** | 0.3*** | 0.2* | 0.0ns | 0.1ns | - | | | | | | | |
| PE | -0.3*** | 0.0ns | 0.1ns | 0.1ns | 0.0ns | 0.4*** | 0.1ns | 0.5*** | - | | | | | | |
| PL | -0.2** | -0.2* | 0.1ns | 0.4*** | 0.3*** | 0.2** | 0.2* | 0.0ns | 0.2* | - | | | | | |
| PW | 0.0ns | -0.2* | 0.0ns | 0.1* | 0.3*** | 0.5*** | 0.1ns | 0.3*** | 0.4*** | 0.4*** | - | | | | |
| SD | -0.1ns | 0.1ns | -0.3*** | 0.1* | 0.2* | 0.4*** | -0.2** | 0.2** | 0.3*** | 0.1ns | 0.3*** | - | | | |
| SS | 0.1ns | -0.2** | 0.3*** | -0.2** | -0.3*** | 0.0ns | 0.2** | -0.1ns | 0.0ns | 0.0ns | 0.0ns | -0.4*** | - | | |
| SG | 0.0ns | 0.2* | -0.1ns | 0.2* | 0.3*** | -0.4*** | -0.2* | -0.3*** | -0.5*** | 0.2* | -0.3*** | -0.1ns | -0.2** | - | |
| WB | -0.3*** | 0.2** | 0.2* | 0.0ns | -0.1 | -0.6*** | 0.0ns | -0.1ns | -0.4*** | -0.2* | -0.5*** | -0.4*** | 0.0ns | 0.5*** | - |

DFL=days to flowering, NTIL=number of productive tillers, BY=biomass yield ($tha^{-1}$), PH= plant height (cm), LL=Leaf length (cm), LW=Leaf width (cm), PL= panicle length (cm), PW= panicle width (cm), PE= panicle exertion (cm), LO= number of plants lodged, SD= 100 seed mass (g), GY=grain yield ($tha^{-1}$), ns= not significant at $P \leq 0.05$, *, **, *** significant at $P \leq 0.05$, $P \leq 0.01$ and $P \leq 0.001$ probability levels respectively.

### 3.3.3.4 Multiple linear regressions

Regression coefficients and probabilities of the estimated independent variables that influence sorghum grain yields are presented in Table 3.17 and Table 3.18. The relative contribution of all yield contributing factors explained 72% ($R^2$) of the total variations in the grain yield and 28% would be due to residual effects. The t- test for the independent variables revealed that days to flowering, stem girth, waxy bloom, biomass yield, plant height, panicle length, panicle width, panicle exertion and 100 seed mass had significant effect ($p<0.001$) on grain yield across environments (Table 3.18). Significant t-test values were recorded in biomass yield, plant height and 100 seed mass at Kiboko 2014LR, whereas at Kiboko 2014-15SR and KYM 2014-15SR only biomass yield recorded significant values.

From the results, the regression model for grain yield (Y) based on significant independent variables across environments is as follows;

$$Y = 10.79 - 0.07(DFL) - 0.79(SG) + 0.24(WB) + 0.19(BY) - 0.01(PH) + 0.06(PL) + 0.12(PW) - 0.03(PE) - 0.53(SD)$$

Where; DFL=days to flowering, SG=stem girth (cm), WB=Waxy bloom, BY=biomass yield ($tha^{-1}$), PH= plant height (cm), PL= panicle length (cm), PW= panicle width (cm), PE= panicle exertion (cm), SD= 100 seed mass (g).

Table 3. 17 Regression statistics for independent variables that influence yields in sorghum

| **Regression Statistics** | **Kiboko 2014LR** | **Kiboko 2014-15SR** | **KYM 2014-15SR** | **Across environments** |
|---|---|---|---|---|
| Multiple R | 0.84 | 0.83 | 0.93 | 0.85 |
| R Square | 0.71 | 0.69 | 0.87 | 0.72 |
| Adjusted R Square | 0.65 | 0.62 | 0.84 | 0.70 |
| Standard Error | 0.60 | 0.61 | 0.26 | 0.69 |
| Observations | 80 | 80 | 80 | 240 |

Table 3. 18 Regression coefficient (B), T value and the Probability of the independent variables predicting sorghum yields across three environments

| | | Kiboko 2014 | | | Kiboko 2014-15 | | | KYM 2014-15 | | | Across environments | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Predictor** | **DF** | **B** | **Tvalue** | **Pvalue** | **B** | **Tvalue** | **Pvalue** | **B** | **Tvalue** | **Pvalue** | **B** | **Tvalue** | **Pvalue** |
| Intercept | 1 | 9.27 | 4.01 | <0.001 | 13.45 | 4.81 | <0.001 | 4.57 | 4.06 | <0.001 | 10.79 | 7.69 | <0.001 |
| DAF | 1 | -0.02 | -0.68 | 0.50 | -0.07 | -2.53 | 0.01 | -0.03 | -2.58 | 0.01 | -0.07 | -5.53 | <0.001 |
| SG | 1 | -0.24 | -1.22 | 0.23 | -0.43 | -2.46 | 0.02 | 0.01 | 0.09 | 0.93 | -0.76 | -8.03 | <0.001 |
| WB | 1 | 0.36 | 2.59 | 0.01 | -0.09 | -0.58 | 0.56 | -0.03 | -0.34 | 0.73 | 0.24 | 3.49 | <0.001 |
| PAS | 1 | -0.89 | -5.10 | <0.001 | -0.67 | -3.35 | <0.001 | -0.58 | -3.98 | <0.001 | -0.61 | -5.38 | <0.001 |
| NTIL | 1 | 0.05 | 2.06 | 0.04 | 0.01 | 0.11 | 0.91 | 0.26 | 1.10 | 0.28 | 0.02 | 1.00 | 0.32 |
| BY | 1 | 0.17 | 5.95 | <0.001 | 0.10 | 2.91 | <0.001 | 0.07 | 3.19 | <0.001 | 0.19 | 9.76 | <0.001 |
| PH | 1 | -0.02 | -3.57 | <0.001 | -0.01 | -1.07 | 0.29 | 0.00 | -0.37 | 0.72 | -0.01 | -3.11 | <0.001 |
| LL | 1 | 0.02 | 0.93 | 0.36 | -0.01 | -0.71 | 0.48 | 0.01 | 1.06 | 0.29 | 0.00 | -0.30 | 0.76 |
| LW | 1 | -0.03 | -0.23 | 0.82 | -0.01 | -0.12 | 0.90 | 0.04 | 0.74 | 0.46 | 0.11 | 1.63 | 0.11 |
| PL | 1 | -0.04 | -1.33 | 0.19 | 0.02 | 0.63 | 0.53 | -0.01 | -0.51 | 0.61 | 0.06 | 3.66 | <0.001 |
| PW | 1 | 0.03 | 0.61 | 0.54 | 0.20 | 2.28 | 0.03 | 0.07 | 1.16 | 0.25 | 0.12 | 3.36 | <0.001 |
| PE | 1 | 0.02 | 0.99 | 0.32 | 0.00 | 0.19 | 0.85 | 0.01 | 1.25 | 0.21 | -0.03 | -2.94 | <0.001 |
| LO | 1 | 0.06 | 1.63 | 0.11 | 0.05 | 1.44 | 0.15 | 0.01 | 1.46 | 0.15 | 0.01 | 0.63 | 0.53 |
| SD | 1 | -0.75 | -3.79 | <0.001 | -0.60 | -2.69 | 0.01 | -0.10 | -1.35 | 0.18 | -0.53 | -4.81 | <0.001 |

DFL=days to flowering, NTIL=number of productive tillers, BY=biomass yield ($tha^{-1}$), PH= plant height (cm), LL=Leaf length (cm), LW=Leaf width (cm), PL= panicle length (cm), PW= panicle width (cm), PE= panicle exertion (cm), LO= number of plants lodged, SD= 100 seed mass (g), GY=grain yield ($tha^{-1}$), significance determined at $P \leq 0.001$ probability level, B=Regression coefficient values .

### 3.3.4 Coefficients of variation, heritability and genetic advance in sorghum hybrids and their parents

#### 3.3.4.1 Genotypic and phenotypic coefficients of variation in sorghum hybrids and their parents at Kiboko

The PCV estimates were higher than the GCV estimates for all the 14 quantitative traits evaluated among the sorghum hybrids and their parents. Number of tillers, biomass yield, plant height, panicle length, panicle width, panicle exertion, number of plants lodged, 100 seed mass and grain yield recorded high PCV scores ranging from 21.1% to 208.8% in hybrids and their parents (Table 3.19). Medium PCV scores were recorded for stem girth, leaf length and leaf width in hybrids and their parents (range= 13% to 20%). Days to 50% flowering recorded the lowest PCV score (7.9%) among the hybrids and their parents (Table 3.19).

High GCV scores ranging from 21.9% to 107.3% were recorded for number of tillers, biomass yield, plant height, panicle exertion and number of lodged plants in hybrids and their parents. Panicle width, panicle length and 100 seed mass recorded medium GCV score. Low GCV scores were recorded in leaf length and days to 50% flowering in sorghum hybrids and parents with a range of 4.9 to 9.8% (Table 3.19).

#### 3.3.4.2 Heritability and genetic advance for sorghum hybrids and their parents at Kiboko

Heritability scores ranged from 10.1% to 90.6% in hybrids and 26.9% to 87.8% in their parents (Table 3.19). High heritability scores (>60%) were recorded for; fresh biomass yield, panicle exertion and plant height in hybrids and their parents. Medium heritability scores (31% - 60%) were recorded in hybrids and their parents for panicle length, panicle width, 100 seed mass, stem girth, leaf width and grain yield. Leaf length and lodged plants recorded low heritability scores (<30%) among the hybrids whereas number of productive tillers recorded low heritability among the parents (Table 3.19).

Medium to high genetic advance scores were recorded in all 14 quantitative traits studied among the parents. GA (%) values ranged from 13.8% in stem girth to 192.9% in panicle exertion (Table 3.19). Grain yield, panicle width, 100 seed mass, plant height, number of

productive tillers, fresh biomass yield, lodged plants and panicle exertion recorded high GA% among the parents (Table 3.19).

Table 3. 19 Estimates of genetic parameters for the studied traits in sorghum hybrids and their parents at Kiboko

| | Parents | | | | | Hybrids | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Trait** | **Means** | **$H^2$** | **PCV%** | **GCV%** | **GA%** | **Means** | **$H^2$** | **PCV%** | **GCV%** |
| DFL | 76 | 87.8 | 7.9 | 7.4 | 14.3 | 72 | 90.6 | 9.1 | 8.6 |
| SG | 5.9 | 46.8 | 14.4 | 9.8 | 13.8 | 5.8 | 58.3 | 14.8 | 11.3 |
| NTIL | 3 | 26.9 | 106.6 | 55.2 | 58.9 | 3 | 38.4 | 95.8 | 59.4 |
| BY | 7.930 | 63.3 | 48.8 | 38.9 | 63.7 | 10.182 | 65.8 | 44.3 | 35.9 |
| PHT | 123.8 | 85.6 | 28.9 | 26.7 | 50.9 | 161.0 | 81.4 | 24.3 | 21.9 |
| LL | 67.7 | 54.0 | 13.0 | 9.5 | 14.4 | 71.4 | 10.1 | 15.5 | 4.9 |
| LW | 8.1 | 48.3 | 20.0 | 13.9 | 19.9 | 8.4 | 42.7 | 14.4 | 9.4 |
| PL | 27.6 | 33.2 | 21.1 | 12.2 | 14.4 | 29.9 | 38.0 | 24.6 | 15.2 |
| PW | 8.0 | 44.7 | 26.1 | 17.4 | 24.0 | 9.0 | 52.3 | 25.2 | 18.2 |
| PE | 3.8 | 76.3 | 122.7 | 107.2 | 192.9 | 9.6 | 82.0 | 95.6 | 86.6 |
| LO | 2 | 32.9 | 187.2 | 107.3 | 126.8 | 2 | 12.3 | 208.8 | 73.3 |
| SD | 2.3 | 59.6 | 25.0 | 19.3 | 30.7 | 2.7 | 58.5 | 20.6 | 15.8 |
| GW | 335.6 | 32.5 | 31.1 | 17.8 | 20.9 | 411.9 | 37.9 | 37.3 | 23.0 |
| GY | 2.927 | 32.1 | 35.7 | 20.2 | 23.6 | 3.195 | 54.2 | 49.8 | 36.7 |

DFL-days to 50% flowering, SG- stem girth, NTIL-number of productive tillers, BY- Fresh biomass yield, PHT- Plant height, LL- leaf length, LW- Leaf width, PL-Panicle length, PW- Panicle width, PE- Panicle exertion, LO- number of lodged plants, SD- 100 seed mass, GW- Grain weight on 5 sampled plants, GY- Grain yield (t/ha), Means- grand means, $\delta^2$g- genotypic variance, $\delta^2$e- environment variance, $\delta^2$p- phenotypic variance, $H^2$- Broad sense heritability, PCV%- Phenotypic coefficient of variation, GCV%- Genotypic coefficient of variation, GA% -Genetic advance as a percentage of the mean.

### 3.3.5 Heterosis in sorghum hybrids

#### 3.3.5.1 Better parent heterosis for yield and its component traits in sorghum hybrids

Heterosis values for days to 50% flowering, plant height and biomass yield are presented because days to flowering (r=-0.4, P≤0.01) and stem biomass (r= 0.4, P≤0.01) were significantly correlated to grain yield. Plant height was significantly correlated to grain yield (r= 0.3, P≤0.01) and stem biomass (r= 0.4, P≤0.01). Variable heterobeltiosis was exhibited by different $F_1$ hybrids for all the traits evaluated (Table 3.20).

Thirty one hybrids exhibited negative heterobeltiosis for days to 50% flowering of up to -16% (Table 3.20). The remaining three hybrids recorded 0% heterosis with the top 2 hybrids involving the male parent ICSR 89058. Nineteen hybrids displayed positive

heterobeltiosis ranging from 1% to 56% for stem biomass (Table 3.20). Eight of these were hybrids involving locally adapted parents Hakika, Macia, IESV 91104DL, KARI Mtama 1 and Wahi (Table 3.20). High positive heterobeltiosis of up to 52% for plant height was recorded in 28 hybrids with six hybrids recording negative heterosis. Nine of these hybrids involved male parents Macia, KARI Mtama 1 and ICSR 160.

Positive heterobeltiosis for grain yield was recorded in 19 hybrids with a range of 3 to 57%. Eight of the hybrids involved both locally adapted and introduced males Macia, ICSR 89058, ICSR 160 and IESV 92172DL. Eleven hybrids ATX 623 x Macia, ICSA 29011 x ICSR 89058, ICSA 11033 x ICSR 160, ICSA 11035 x Macia, ICSA 11004 x ICSR 24008, ICSA 11003 x ICSR 160, ICSA 11040 x IESV 91104 DL, ICSA 228 x Hakika, ICSA 29017 x ICSR 24010, ICSA 101 x ICSR 38 and ICSA 11038 x KARI Mtama 1 displayed positive heterobeltiosis for both biomass and grain yield.

Table 3. 20 Better parent heterosis for 14 traits in 34 F1 sorghum hybrids evaluated at Kiboko and Kampi ya Mawe during the 2014LR and 2014/15SR seasons

| Hybrid name | DFL | BYLD | PHT | LL | LW | PL | PW | NL | PE | SS | LO | SD | GW | GY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ICSA 29011 x ICSR 89058 | -15 | 1 | 22 | 6 | -10 | 8 | 17 | 3 | 68 | -2 | -29 | 8 | 60 | 39 |
| ICSA 75 x ICSR 38 | -11 | -40 | 22 | -5 | -11 | 14 | 8 | -13 | 116 | -1 | 73 | -40 | 47 | 3 |
| ICSA 11004 x ICSR 24008 | -9 | 12 | 17 | 10 | 7 | 20 | 30 | -2 | 130 | -7 | 115 | -5 | 45 | 21 |
| ICSA 11037 x Macia | -11 | -15 | 23 | 3 | 3 | -2 | -12 | -2 | 76 | -13 | 336 | 5 | 43 | 28 |
| ICSA 29015 x ICSR 89058 | -16 | -46 | 17 | 0 | -4 | 1 | 2 | -15 | 179 | 1 | 43 | 2 | 39 | 0 |
| ICSA 29017 x ICSR 24010 | -13 | 12 | 15 | -4 | -16 | 4 | 3 | -8 | 29 | -10 | 47 | 5 | 37 | 9 |
| ICSA 11003 x ICSR 160 | -7 | 21 | 28 | 3 | 10 | 14 | 17 | -7 | 295 | -5 | -3 | -3 | 37 | 20 |
| ICSA 74 x Macia | -12 | -23 | 6 | 3 | 11 | 1 | -7 | -12 | 47 | -59 | -24 | 5 | 32 | -9 |
| ICSA 11034 x Macia | -5 | 0 | 27 | 21 | 11 | -1 | 19 | -6 | 78 | -13 | 144 | 20 | 31 | 17 |
| ATX 623 x Macia | -6 | 27 | 52 | 7 | 12 | 13 | 0 | -22 | 212 | 6 | 287 | 8 | 30 | 57 |
| ICSA 11035 x Macia | -4 | 46 | 38 | 11 | 22 | 28 | 21 | -2 | 35 | -25 | -2 | 15 | 28 | 22 |
| ICSA 101 x ICSR 38 | -6 | 12 | 17 | 1 | -3 | 20 | 27 | -13 | 83 | -31 | -8 | 18 | 26 | 5 |
| ICSA 29001 x ICSV 700 | -6 | -12 | -2 | 8 | 3 | -3 | -2 | -1 | 495 | -1 | 121 | 13 | 26 | 4 |
| ICSA 29002 x ICSV 700 | 0 | -9 | 1 | -3 | 3 | -14 | -10 | -9 | 273 | -51 | -37 | 12 | 26 | 3 |
| ICSA 12 X IESV 92172 DL | -7 | -1 | 36 | 23 | -8 | 5 | -5 | -10 | 385 | -2 | 260 | -5 | 23 | 26 |
| ICSA 228 x Hakika | -11 | 56 | 19 | 6 | -1 | 12 | -12 | -11 | 108 | -75 | -80 | 8 | 19 | 17 |
| ICSA 11038 x KARI Mtama 1 | -11 | 27 | 32 | 0 | 4 | -5 | 4 | -4 | 181 | -100 | 135 | 16 | 18 | 3 |
| ICSA 29004 x ICSR 24010 | -6 | -1 | 12 | 4 | 0 | 11 | 2 | 17 | 314 | -2 | 60 | 7 | 18 | -6 |
| ICSA 11033 x ICSR 160 | -6 | 15 | 25 | 4 | 4 | 13 | 24 | -4 | 84 | -9 | 39 | -18 | 18 | 34 |

DFL-days to 50% flowering, BYLD= Biomass yield ($tha^{-1}$), PHT=plant height (cm), LL=leaf length (cm), LW=leaf width (cm), PL=panicle length (cm), PW=panicle width (cm), NL=number of leaves, PE=panicle exertion (cm), SS=seed set%, LO=number of plants lodged, SD=100 seed mass (g), GW=grain weight per 5 sampled plants (g) and GY= grain yield ($tha^{-1}$).

Table 3.20 Continued'

| Hybrid name | DFL | BYLD | PHT | LL | LW | PL | PW | NL | PE | SS | LO | SD | GW | GY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ICSA 29005 x ICSR 24010 | -5 | -1 | 7 | -5 | 5 | 10 | 14 | -5 | 323 | -7 | 109 | 7 | 17 | 20 |
| ICSA 11039 x KARI Mtama 1 | -11 | -8 | 32 | 2 | 7 | -2 | 5 | -11 | 139 | -94 | -7 | 14 | 12 | -3 |
| ICSA 232 x ICSR 24008 | -8 | 17 | 12 | -4 | 8 | 11 | 20 | -6 | 86 | 0 | -20 | -18 | 10 | 0 |
| ICSA 11018 x Wahi | -9 | -14 | 7 | 9 | 13 | 11 | 16 | -12 | -23 | -10 | 0 | 14 | 4 | -31 |
| ICSA 11040 x IESV 91104 DL | -7 | 19 | 14 | 3 | -2 | -10 | 2 | -13 | 48 | -5 | 105 | 0 | -4 | 18 |
| ICSA 29003 x ICSV 700 | -2 | -7 | -8 | 6 | 2 | -11 | -17 | 3 | -4 | -39 | 175 | 26 | -5 | -23 |
| ICSA 206 x IESV 91104 DL | -7 | 42 | 2 | -12 | -14 | 32 | 0 | -11 | 80 | -17 | 87 | -2 | -6 | -3 |
| ICSA 25002 x IESV 91104 DL | 0 | 21 | -7 | 8 | 6 | 1 | 0 | 4 | -90 | -52 | -77 | -3 | -11 | -48 |
| ICSA 11007 x Wahi | -5 | 9 | 5 | -5 | -8 | 11 | -4 | -13 | 3 | -20 | -36 | 0 | -12 | -3 |
| ICSA 11019 x Hakika | -3 | 38 | 22 | 4 | 7 | 10 | 11 | -2 | 29 | -12 | -60 | 18 | -14 | -12 |
| ICSA 29016 x ICSR 38 | -11 | -19 | 16 | 5 | -13 | 4 | 7 | -19 | 148 | 4 | 113 | -5 | -20 | -11 |
| ICSA 11013 x Hakika | -5 | 13 | 7 | 3 | -2 | 5 | 2 | -10 | -41 | -65 | -83 | 6 | -23 | -22 |
| ICSA 11016 x Wahi | -4 | 31 | -7 | -9 | -10 | -6 | -28 | -26 | -98 | -67 | -91 | 6 | -29 | -9 |
| ICSA 29007 x ICSR 24008 | -12 | -26 | -4 | -18 | -4 | -6 | -9 | 13 | -87 | -2 | -41 | -3 | -31 | 12 |
| ICSA 11036 x KARI Mtama 1 | 0 | 32 | -18 | -4 | 2 | 1 | -23 | -5 | -98 | -82 | -85 | 0 | -42 | -60 |

DFL-days to 50% flowering, BYLD= Biomass yield ($tha^{-1}$), PHT=plant height (cm), LL=leaf length (cm), LW=leaf width (cm), PL=panicle length (cm), PW=panicle width (cm), NL=number of leaves, PE=panicle exertion (cm), SS=seed set%, LO=number of plants lodged, SD=100 seed mass (g), GW=grain weight per 5 sampled plants (g) and GY= grain yield ($tha^{-1}$).

### 3.3.5.2 Mid- parent heterosis for yield and its component traits

Mean heterosis was realised in both positive and negative directions for all the traits evaluated (Table 3.21). Negative mean heterosis for days to 50% flowering was observed in 27 hybrids with a range of -12 to -1% (Table 3.21). The lowest mean heterosis was recorded in hybrids involving ICSR 89058, ICSR 24008 and ICSR 24010 (Table 3.21).

Positive mean heterosis for stem biomass yield was displayed in 27 hybrids with a range of 16% to 158% (Table 3.19). Plant height mean heterosis ranged from -9% to 61% with thirty two hybrids displaying positive mean heterosis. Highest positive mean heterosis for biomass yield and plant height was displayed in hybrids produced from adapted parents IESV 91104 DL, Macia, KARI Mtama 1 and introduced parent ICSV 700. Negative mean heterosis for height was recorded in ICSA 11016 x Wahi and ICSA 11036 x KARI Mtama 1 (Table 3.21).

Panicle exertion recorded the highest mean heterosis values for the studied traits. Positive mean heterosis was recorded in 30 hybrids with a range of 7 to 834%. The highest mean heterosis was recorded in ICSA 232 x ICSR 24008 (834%) and ICSA 29002 x ICSV 700 (549%) (Table 3.21). Positive mean heterosis for grain yield was displayed in 22 of the 34 hybrids with a range of 8 to 57% (Table 3.21). Highest positive mean heterosis for grain (>40%) and stem biomass yield was recorded in four hybrids ATX 623 x Macia, ICSA 29005 x ICSR 24010, ICSA 11033 x ICSR 160, and ICSA 206 x IESV 91104 DL.

Table 3. 21 Mid- parent heterosis for 14 traits in 34 F1 hybrids evaluated at Kiboko and Kampi ya Mawe in 2014LR and 2014/15SR

| Hybrid name | DFL | BYLD | PHT | LL | LW | PL | PW | NL | PE | SS | LO | SD | GW | GY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ATX 623 x Macia | -4 | 43 | 55 | 12 | 12 | 24 | 9 | -14 | 213 | 6 | 319 | 11 | 35 | 57 |
| ICSA 29011 x ICSR 89058 | -10 | 16 | 23 | 6 | 0 | 16 | 30 | -1 | 139 | 6 | 17 | 16 | 65 | 49 |
| ICSA 29005 x ICSR 24010 | -5 | 33 | 39 | 1 | 9 | 16 | 24 | 1 | 387 | 3 | 144 | 16 | 22 | 49 |
| ICSA 11033 x ICSR 160 | -6 | 31 | 26 | 6 | 5 | 16 | 40 | -3 | 268 | -7 | 93 | -11 | 21 | 43 |
| ICSA 206 x IESV 91104 DL | -9 | 158 | 46 | 5 | -5 | 34 | 17 | -2 | 218 | -11 | 274 | 21 | 32 | 42 |
| ICSA 11035 x Macia | -4 | 62 | 55 | 12 | 23 | 29 | 27 | -2 | 134 | -23 | 17 | 19 | 29 | 39 |
| ICSA 12 X IESV 92172 DL | -7 | 21 | 38 | 23 | -2 | 5 | -3 | -11 | 425 | 2 | 233 | 6 | 27 | 38 |
| ICSA 11004 x ICSR 24008 | -6 | 24 | 23 | 11 | 12 | 34 | 32 | 7 | 241 | -6 | 191 | 1 | 49 | 38 |
| ICSA 11003 x ICSR 160 | -6 | 36 | 38 | 8 | 17 | 16 | 23 | -7 | 425 | -4 | 76 | 8 | 41 | 37 |
| ICSA 29017 x ICSR 24010 | -10 | 28 | 36 | 1 | -8 | 12 | 15 | -6 | 97 | -4 | 169 | 11 | 47 | 36 |
| ICSA 11037 x Macia | -7 | -13 | 30 | 13 | 9 | 12 | 6 | -5 | 126 | -11 | 588 | 8 | 59 | 32 |
| ICSA 11034 x Macia | -5 | 36 | 34 | 21 | 10 | 13 | 22 | 1 | 83 | -14 | 137 | 25 | 44 | 32 |
| ICSA 228 x Hakika | -5 | 66 | 32 | 8 | 14 | 17 | 1 | -5 | 316 | -75 | -71 | 24 | 21 | 29 |
| ICSA 11040 x IESV 91104 DL | -5 | 30 | 39 | 8 | 8 | 2 | 9 | -8 | 100 | -4 | 240 | 16 | 16 | 25 |
| ICSA 101 x ICSR 38 | -4 | 28 | 22 | 4 | 1 | 22 | 30 | -8 | 90 | -29 | 78 | 23 | 39 | 24 |
| ICSA 232 x ICSR 24008 | -7 | 29 | 25 | 1 | 12 | 19 | 33 | -1 | 834 | 1 | 49 | -13 | 23 | 19 |
| ICSA 29001 x ICSV 700 | 2 | 60 | 61 | 3 | 9 | -13 | 8 | 10 | -11 | -1 | 43 | 18 | 50 | 19 |
| ICSA 11038 x KARI Mtama 1 | -8 | 43 | 47 | 0 | 5 | 3 | 5 | -4 | 248 | -100 | 170 | 29 | 15 | 14 |
| ICSA 29015 x ICSR 89058 | -12 | -40 | 23 | 1 | 3 | 7 | 10 | -9 | 200 | 4 | 187 | 10 | 42 | 13 |
| ICSA 29007 x ICSR 24008 | -10 | -16 | 18 | -4 | 10 | 20 | 21 | -12 | 100 | -4 | 215 | 5 | 66 | 13 |
| ICSA 29002 x ICSV 700 | 1 | 18 | 25 | 4 | 4 | -6 | -5 | -7 | 549 | -49 | -12 | 16 | 42 | 9 |
| ICSA 75 x ICSR 38 | -9 | -22 | 31 | 0 | -2 | 23 | 10 | -4 | 158 | 2 | 144 | -7 | 53 | 8 |
| ICSA 11039 x KARI Mtama 1 | -8 | 12 | 48 | 2 | 9 | 5 | 11 | -10 | 168 | -97 | 6 | 39 | 18 | -1 |
| ICSA 74 x Macia | -7 | -2 | 24 | 8 | 14 | 17 | -1 | -7 | 58 | -58 | 24 | 13 | 38 | -3 |
| ICSA 11016 x Wahi | 0 | 40 | -6 | -9 | -5 | -5 | -19 | -23 | -96 | -66 | -89 | 12 | -18 | -4 |
| ICSA 29004 x ICSR 24010 | -5 | 19 | 38 | 6 | 0 | 16 | 7 | 21 | 334 | -2 | 103 | 16 | 29 | -5 |
| ICSA 11019 x Hakika | 0 | 49 | 23 | 7 | 12 | 13 | 17 | 2 | 67 | -6 | -67 | 11 | 0 | -6 |

DFL-days to 50% flowering, SG=stem girth (cm), NTIL=number of productive tillers, BYLD= Biomass yield ($tha^{-1}$), PHT=plant height (cm), LL=leaf length (cm), LW=leaf width (cm), PL=panicle length (cm), PW=panicle width (cm), NL=number of leaves, PE=panicle exertion (cm), SS=seed set%, LO=number of plants lodged, SD=100 seed mass (g), GW=grain weight per 5 sampled plants (g) and GY= grain yield ($tha^{-1}$).

Table 3.21 (Continued)

| Hybrid name | DFL | BYLD | PHT | LL | LW | PL | PW | NL | PE | SS | LO | SD | GW | GY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ICSA 29016 x ICSR 38 | -9 | -1 | 20 | 4 | -3 | 5 | 5 | -11 | 213 | 5 | 288 | 5 | -6 | -7 |
| ICSA 11013 x Hakika | -1 | 24 | 12 | 5 | 12 | 14 | 20 | -6 | 7 | -65 | -72 | 15 | -6 | -15 |
| ICSA 29003 x ICSV 700 | 1 | 23 | 19 | 12 | 4 | -4 | -9 | 5 | 84 | -32 | 300 | 28 | -5 | -21 |
| ICSA 11018 x Wahi | -4 | -3 | 13 | 11 | 17 | 18 | 18 | -4 | 11 | -6 | -44 | 30 | 20 | -23 |
| ICSA 25002 x IESV 91104 DL | 5 | 44 | 19 | 9 | 15 | 15 | 6 | 5 | -82 | -52 | -59 | 13 | 3 | -35 |
| ICSA 11036 x KARI Mtama 1 | 7 | 44 | -9 | -2 | 4 | 1 | -20 | 4 | -97 | -82 | -74 | 12 | -41 | -57 |

DFL-days to 50% flowering, SG=stem girth (cm), NTIL=number of productive tillers, BYLD= Biomass yield ($tha^{-1}$), PHT=plant height (cm), LL=leaf length (cm), LW=leaf width (cm), PL=panicle length (cm), PW=panicle width (cm), NL=number of leaves, PE=panicle exertion (cm), SS=seed set%, LO=number of plants lodged, SD=100 seed mass (g), GW=grain weight per 5 sampled plants (g) and GY= grain yield ($tha^{-1}$).

### 3.3.5.3 Standard heterosis for yield and its component traits

Standard heterosis values expressed by the $F_1$ sorghum hybrids over the commercial OPV check, Seredo for yield and its associated traits are presented in Table 3.22. Standard heterosis was recorded with both negative and positive magnitude for most of the studied traits. However, standard heterosis for days to 50% flowering, stem girth and leaf width occurred with only positive magnitude (Table 3.22). Days to 50% flowering had a standard heterosis range of 0% to 24%.

High positive (preferred) standard heterosis was expressed in 27 hybrids for biomass yield with a range of 2% to 87%. Plant height showed high positive standard heterosis in 25 of the 34 hybrids with a range of 1 to 48% (Table 3.22). Negative standard heterosis for plant height ranged from -3 to -32%. $F_1$ hybrids developed from male parents; Wahi and Hakika exhibited low standard heterosis whereas the ones from ICSR 24010 displayed high standard heterosis for height (Table 3.22).

Desired standard heterosis for grain yield was exhibited in 16 hybrids with a range of 7 to 48%. Hybrids involving male parents Macia, ICSR 24008, ICSR 24010 and ICSR 160 displayed high positive standard heterosis for grain yield. Sorghum hybrids with high positive standard heterosis for grain and biomass yield were ATX 623 x Macia, ICSA 29005 x ICSR 24010, ICSA 29011 x ICSR 89058, ICSA 11040 x IESV 91104 DL and ICSA 29017 x ICSR 24010. All hybrids developed from restorer lines ICSR 38, ICSV 700, Wahi and Hakika displayed negative standard heterosis for grain yield (Table 3.22).

Table 3. 22 Standard heterosis for 14 traits in 34 F1 hybrids evaluated at Kiboko and Kampi ya Mawe in 2014LR and 2014/15SR

| Hybrid name | DFL | BYLD | PHT | LL | LW | PL | PW | NL | PE | SS | LO | SD | GW | GY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ATX 623 x Macia | 5 | 40 | 14 | 17 | 24 | 4 | -5 | 7 | 157 | 2 | 211 | 4 | 55 | 48 |
| ICSA 11004 x ICSR 24008 | 6 | 8 | 7 | 13 | 21 | 31 | 33 | 17 | 20 | -9 | 238 | 0 | 94 | 47 |
| ICSA 11033 x ICSR 160 | 5 | -14 | 10 | 16 | 18 | 9 | 59 | 6 | -6 | -10 | 271 | -13 | 55 | 41 |
| ICSA 29005 x ICSR 24010 | 7 | 48 | 38 | 10 | 23 | -6 | 28 | 7 | 137 | -9 | 236 | 1 | 31 | 41 |
| ICSA 29011 x ICSR 89058 | 3 | 16 | 14 | 11 | 15 | 9 | 28 | 2 | 203 | -2 | 75 | 6 | 79 | 39 |
| ICSA 11040 x IESV 91104 DL | 8 | 57 | 33 | 25 | 27 | -11 | 11 | 6 | 59 | -6 | 186 | 23 | 47 | 35 |
| ICSA 11037 x Macia | 9 | -6 | 3 | 23 | 27 | -1 | 26 | 8 | 44 | -12 | 250 | 1 | 97 | 28 |
| ICSA 12 X IESV 92172 DL | 4 | 2 | 1 | 32 | 1 | 3 | -7 | -1 | 170 | -2 | 221 | 0 | 34 | 28 |
| ICSA 29017 x ICSR 24010 | 6 | 67 | 48 | 9 | 20 | -8 | 16 | 8 | 131 | -12 | 136 | -6 | 53 | 27 |
| ICSA 11003 x ICSR 160 | 4 | -6 | 12 | 16 | 21 | 7 | 27 | 2 | 101 | -6 | 161 | 10 | 72 | 26 |
| ICSA 232 x ICSR 24008 | 10 | 17 | 3 | 6 | 30 | 10 | 28 | 14 | 28 | 0 | 25 | -13 | 47 | 22 |
| ICSA 11035 x Macia | 7 | 62 | 4 | 10 | 37 | -3 | 15 | 8 | 11 | -25 | -21 | 11 | 41 | 15 |
| ICSA 29004 x ICSR 24010 | 7 | 48 | 44 | 10 | 17 | -7 | 16 | 40 | 132 | -4 | 157 | 0 | 59 | 12 |
| ICSA 11034 x Macia | 7 | 11 | -4 | 19 | 22 | 0 | 13 | 3 | 53 | -18 | 96 | 16 | 45 | 10 |
| ICSA 29007 x ICSR 24008 | 12 | -5 | 10 | 7 | 27 | 7 | 12 | 7 | 56 | -6 | 164 | -4 | 94 | 9 |
| ICSA 11038 x KARI Mtama 1 | 0 | 47 | 27 | 11 | 16 | -13 | 10 | -4 | 149 | -100 | 93 | 49 | 33 | 7 |
| ICSA 29015 x ICSR 89058 | 0 | -42 | 9 | 8 | 14 | 2 | 3 | -5 | 135 | 2 | 254 | 1 | 62 | 0 |
| ICSA 29001 x ICSV 700 | 19 | 53 | 30 | 4 | 18 | -20 | -5 | 23 | -65 | 0 | 89 | 5 | 49 | -1 |
| ICSA 29002 x ICSV 700 | 23 | 58 | 34 | 4 | 18 | -20 | -2 | 13 | -16 | -50 | -46 | 3 | 49 | -2 |
| ICSA 206 x IESV 91104 DL | 2 | 87 | 18 | 6 | 12 | 1 | 9 | -4 | 94 | -18 | 160 | 22 | 45 | -2 |
| ICSA 101 x ICSR 38 | 8 | 2 | -3 | 13 | 10 | 9 | 21 | -4 | 64 | -34 | 104 | 3 | 30 | -2 |
| ICSA 75 x ICSR 38 | 3 | -22 | 17 | 12 | 13 | 22 | 3 | 4 | 165 | -4 | 282 | -3 | 54 | -3 |
| ICSA 228 x Hakika | 9 | 52 | -7 | 14 | 38 | 9 | 5 | 7 | -33 | -76 | -96 | 25 | 14 | -5 |

DFL-days to 50% flowering, SG=stem girth (cm), NTIL=number of productive tillers, BYLD= Biomass yield ($tha^{-1}$), PHT=plant height (cm), LL=leaf length (cm), LW=leaf width (cm), PL=panicle length (cm), PW=panicle width (cm), NL=number of leaves, PE=panicle exertion (cm), SS=seed set%, LO=number of plants lodged, SD=100 seed mass (g), GW=grain weight per 5 sampled plants (g) and GY= grain yield ($tha^{-1}$).

Table 3. 22 (Continued)

| Hybrid name | DFL | BYLD | PHT | LL | LW | PL | PW | NL | PE | SS | LO | SD | GW | GY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ICSA 11019 x Hakika | 12 | 58 | -4 | 17 | 23 | -3 | -4 | 11 | -59 | -13 | -93 | 21 | 10 | -18 |
| ICSA 29016 x ICSR 38 | 3 | -12 | 2 | 10 | 15 | -5 | 2 | -3 | 105 | 0 | 371 | -7 | 10 | -9 |
| ICSA 74 x Macia | 11 | 50 | 12 | 14 | 30 | 6 | 2 | 10 | 20 | -60 | -39 | 19 | 46 | -14 |
| ICSA 11039 x KARI Mtama 1 | 1 | 7 | 27 | 13 | 19 | -14 | 11 | -9 | 112 | -97 | 0 | 46 | 25 | -16 |
| ICSA 11016 x Wahi | 12 | 23 | -32 | -4 | 12 | -11 | -20 | -17 | -98 | -68 | -96 | 23 | -10 | -19 |
| ICSA 11007 x Wahi | 13 | 4 | -8 | 0 | 9 | 8 | -16 | -7 | -17 | -21 | -18 | 15 | 17 | -22 |
| ICSA 29003 x ICSV 700 | 20 | 60 | 22 | 9 | 18 | -19 | -2 | 28 | -25 | -39 | 136 | 20 | 12 | -27 |
| ICSA 11018 x Wahi | 10 | 5 | -13 | 14 | 35 | 6 | 5 | 9 | -38 | -10 | -82 | 32 | 31 | -30 |
| ICSA 11013 x Hakika | 12 | 10 | -17 | 12 | 36 | 10 | 27 | 4 | -81 | -65 | -86 | 23 | 10 | -37 |
| ICSA 25002 x IESV 91104 DL | 20 | 60 | 8 | 30 | 38 | -2 | 9 | 12 | -89 | -53 | -68 | 20 | 37 | -47 |
| ICSA 11036 x KARI Mtama 1 | 24 | 83 | -21 | 7 | 18 | -22 | -11 | 15 | -98 | -82 | -88 | 28 | -33 | -62 |

DFL-days to 50% flowering, SG=stem girth (cm), NTIL=number of productive tillers, BYLD= Biomass yield ($tha^{-1}$), PHT=plant height (cm), LL=leaf length (cm), LW=leaf width (cm), PL=panicle length (cm), PW=panicle width (cm), NL=number of leaves, PE=panicle exertion (cm), SS=seed set%, LO=number of plants lodged, SD=100 seed mass (g), GW=grain weight per 5 sampled plants (g) and GY= grain yield ($tha^{-1}$).

### 3.3.6 Combining ability analysis

#### 3.3.6.1 Estimates of combining ability and genetic parameters

##### 3.3.6.1.1 General combining ability effects for male parents at Kiboko

General combining ability effects of male parents evaluated at Kiboko are shown in Table 3.23. Male parents with desirable GCA effects for flowering were ICSR 89058 (-2.45) and ICSR 38 (-1.39). High positive GCA effects for biomass yield were recorded in ICSR 24010 (2.64), KARI Mtama 1 (1.52) and ICSV 700 (1.44). Desirable GCA effects for grain yield were exhibited in half of the males with ICSR 24010 (0.62) being the most desirable. Desirable positive GCA effects for panicle exertion were recorded in ICSR 89058 (6.05) and ICSR 24010 (5.04).

Most of the males with desirable GCA effects for panicle length had positive GCA effects for panicle width except Wahi (Table 3.23). ICSR 24008 (2.66) and ICSR 160 (1.59) had the most desirable GCA effects for panicle length and width respectively. Positive GCA effects for plant height were recorded in four of the 12 males with ICSR 24010 (42.39), ICSV 700 (18.18) and IESV 91104DL (10.88) displaying the most desirable effects. The highest GCA score was recorded in ICSR 24010. The lowest GCA effect for plant height was recorded by Wahi (-29.99) and Hakika (-21.87).

The most desirable positive GCA effects for seed set was displayed by ICSR 89058 (17.05). Positive GCA effects for 100 seed mass was exhibited in four male parents with KARI Mtama 1 (0.54) being the most desirable (Table 3.23).

##### 3.3.6.2.2. General combining ability effects for male parents at Kampi ya Mawe in 2014-15SR

Estimates of general combining ability for yield and its component traits at Kampi ya Mawe are presented in Table 3.24. Desirable GCA effects for days to flowering was displayed by six of the 12 male parents. Good general combiners for days to flowering were ICSR 89058 (-1.59) and ICSR 160 (-1.49) whereas the worst was ICSV 700 (2.76). Good general combiners for biomass yield were ICSV 700 (2.34) and Hakika (2.11). Low GCA effects were recorded for grain yield with ICSR 160 exhibiting the highest positive GCA effect among the males. IESV 91104DL displayed a GCA score of 2.30 for leaf

length. Three males; Hakika, Wahi and KARI Mtama 1 showed desirable GCA effects for number of lodged plants with GCA scores of -8.92, -7.61 and -4.43 respectively.

Male parent IESV 92172DL had the highest positive GCA value for panicle length. Male parents ICSR 24010 and ICSV 700 had the highest GCA scores for plant height at 27.18 and 26.19 respectively. Most desirable GCA effects for plant height and 100 seed mass were displayed in Wahi (-25.25; 0.3) and Hakika (-21.30; 0.26).

**3.3.6.2.3. General combining ability effects for male parents across sites**

Most desirable general combiners for days to 50% flowering were ICSR 89058 (-2.26) and ICSR 38 (-1.57). Poorest general combiner for days to flowering was ICSV 700 (4.50). Male parents, ICSV 700 (1.84) and ICSR 24010 (1.83) had the highest GCA effect for biomass yield (Table 3.25). Most desirable GCA effects for grain yield were shown by male parents, ICSR 24010 (0.54), ICSR 24008 (0.46) and ICSR 160 (0.38). Macia was a good general combiner for both leaf length and leaf width with GCA effects of 1.24 and 0.36 respectively.

Good general combiners for panicle exertion were ICSR 89058 and ICSR 24010 with GCA effects of 4.26 and 3.74 respectively (Table 3.25). ICSR 38 (2.07) and ICSR 24008 (2.12) had the highest positive GCA effects for panicle length. Half of the 12 male parents had positive GCA effects for plant height. The highest and lowest GCA effects for plant height were recorded in ICSR 24010 (38.23) and Wahi (-29.1) respectively. Best general combiners for seed set were, ICSR 89058 (16.92) and ICSR 24008 (16.05).

Table 3. 23 Estimates of general combining ability for 14 traits in 12 hybrid male parents at Kiboko

| **Parents** | **DFL** | **BYLD** | **GY** | **LL** | **LW** | **LO** | **NTIL** | **PE** | **PL** | **PW** | **PH** | **SS** | **SD** | **SG** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hakika | 0.59 | 0.39 | -0.42 | 0.63 | 0.34 | -1.17 | 1.17 | -6.44 | 1.76 | 0.02 | -21.87 | -19.82 | 0.21 | 0.01 |
| ICSR160 | -0.97 | -1.54 | 0.28 | 0.51 | -0.03 | 1.15 | 0.29 | -0.21 | 1.79 | 1.59 | -0.43 | 11.75 | -0.26 | 0.00 |
| ICSR24008 | 0.23 | -1.46 | 0.39 | -0.40 | 0.21 | 1.27 | -0.09 | -1.73 | 2.66 | 1.05 | -1.50 | 16.14 | -0.22 | 0.00 |
| ICSR24010 | -0.86 | 2.64 | 0.62 | -0.60 | 0.03 | -0.02 | 0.44 | 5.04 | -1.13 | 0.63 | 42.39 | 12.37 | -0.19 | -0.01 |
| ICSR38 | -1.39 | -1.45 | -0.05 | -0.31 | -0.26 | 1.75 | -0.01 | 3.47 | 2.39 | 0.10 | -3.48 | 9.26 | -0.26 | -0.01 |
| ICSR89058 | -2.45 | -1.78 | 0.24 | -0.29 | -0.20 | 0.20 | 0.39 | 6.05 | 1.35 | 0.18 | 1.43 | 17.05 | -0.18 | -0.01 |
| ICSV700 | 5.29 | 1.44 | -0.30 | -1.70 | 0.03 | -1.13 | -0.67 | -5.89 | -3.85 | -0.85 | 18.18 | -3.93 | -0.06 | 0.00 |
| IESV91104DL | 0.29 | 1.27 | -0.18 | 1.43 | 0.10 | -0.47 | 0.07 | -0.90 | -2.49 | -0.17 | 10.88 | 1.35 | 0.28 | 0.00 |
| IESV92172DL | -1.19 | -0.28 | 0.23 | -0.51 | -0.36 | 0.01 | -0.42 | 4.66 | -0.10 | -0.71 | -9.66 | 12.23 | -0.07 | 0.00 |
| KARI Mtama1 | -0.53 | 1.52 | -0.72 | -0.41 | -0.12 | -0.65 | 0.07 | 0.33 | -3.91 | -0.70 | -1.46 | -52.13 | 0.54 | 0.00 |
| Macia | -0.34 | 0.42 | 0.31 | 1.42 | 0.29 | 0.12 | -0.43 | 1.12 | 0.40 | 0.07 | -4.50 | 1.90 | -0.02 | 0.01 |
| Wahi | 1.34 | -1.16 | -0.40 | 0.22 | -0.03 | -1.04 | -0.80 | -5.51 | 1.14 | -1.20 | -29.99 | -6.17 | 0.22 | 0.01 |

DFL-days to 50% flowering, SG=stem girth (cm), NTIL=number of productive tillers, BYLD= Biomass yield ($tha^{-1}$), PH=plant height (cm), LL=leaf length (cm), LW=leaf width (cm), PL=panicle length (cm), PW=panicle width (cm), PE=panicle exertion (cm), SS=seed set%, LO=number of plants lodged, SD=100 seed mass (g), GW=grain weight per 5 sampled plants (g) and GY= grain yield ($tha^{-1}$)

Table 3. 24 Estimates of general combining ability for 12 traits in 12 hybrid male parents at Kampi ya Mawe

| **Parents** | **DFL** | **BYLD** | **GY** | **LL** | **LW** | **LO** | **NTIL** | **PL** | **PW** | **PH** | **SD** | **SG** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hakika | 1.37 | 2.11 | -0.31 | -0.15 | 0.39 | -8.92 | -0.02 | 0.53 | -0.14 | -21.30 | 0.26 | 0.19 |
| ICSR160 | -1.49 | -1.38 | 0.25 | 0.80 | -0.05 | 3.55 | 0.03 | 1.38 | 0.40 | 2.53 | -0.12 | -0.06 |
| ICSR24008 | 0.19 | -0.08 | 0.16 | -0.93 | 0.12 | 0.19 | 0.08 | 0.61 | 0.06 | -5.69 | -0.48 | 0.11 |
| ICSR24010 | -0.42 | -0.26 | 0.04 | -1.20 | -0.15 | 4.46 | -0.02 | -1.57 | 0.06 | 27.18 | -0.30 | -0.40 |
| ICSR38 | -1.60 | -1.97 | -0.07 | 0.09 | -0.31 | 5.56 | -0.02 | 1.19 | -0.25 | -12.76 | -0.22 | -0.03 |
| ICSR89058 | -1.59 | -1.27 | -0.08 | -1.23 | -0.12 | 2.76 | -0.02 | 0.73 | 0.10 | 0.45 | 0.00 | -0.25 |
| ICSV700 | 2.76 | 2.34 | -0.13 | 0.54 | -0.10 | -0.23 | -0.03 | -3.05 | -0.04 | 26.19 | 0.04 | -0.18 |
| IESV91104DL | 0.23 | 0.22 | 0.08 | 2.30 | 0.15 | 0.94 | 0.08 | -0.74 | 0.00 | 15.53 | 0.25 | 0.19 |
| IESV92172DL | -0.73 | -1.61 | 0.01 | -0.07 | -0.23 | 3.99 | 0.04 | 1.21 | -0.09 | -4.93 | -0.27 | 0.02 |
| KARI Mtama1 | 0.64 | 0.90 | 0.07 | -1.02 | -0.15 | -4.43 | -0.03 | -1.79 | 0.13 | 7.37 | 0.56 | -0.11 |
| Macia | -0.46 | 0.63 | 0.16 | 0.72 | 0.22 | -0.27 | -0.04 | 0.32 | -0.13 | -9.31 | -0.03 | 0.10 |
| Wahi | 1.09 | 0.38 | -0.19 | 0.14 | 0.23 | -7.61 | -0.03 | 1.19 | -0.10 | -25.25 | 0.30 | 0.41 |

DFL-days to 50% flowering, SG=stem girth (cm), NTIL=number of productive tillers, BYLD= Biomass yield ($tha^{-1}$), PH=plant height (cm), LL=leaf length (cm), LW=leaf width (cm), PL=panicle length (cm), PW=panicle width (cm), PE=panicle exertion (cm), SS=seed set%, LO=number of plants lodged, SD=100 seed mass (g), GW=grain weight per 5 sampled plants (g) and GY= grain yield ($tha^{-1}$)

Table 3. 25 Estimates of general combining ability for 14 traits in 12 hybrid male parents grown across sites

| **Parents** | **DFL** | **BYLD** | **GY** | **LL** | **LW** | **LO** | **NTL** | **PE** | **PL** | **PW** | **PH** | **SS** | **SD** | **SG** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hakika | 1.0 | 1.0 | -0.5 | 0.4 | 0.5 | -4.2 | 0.7 | -4.8 | 1.4 | -0.1 | -23.3 | -20.1 | 0.3 | 0.1 |
| ICSR 160 | -1.2 | -1.6 | 0.4 | 0.6 | -0.1 | 2.2 | 0.2 | 0.0 | 1.7 | 1.1 | 0.4 | 11.7 | -0.2 | 0.0 |
| ICSR 24008 | 0.3 | -1.1 | 0.5 | -0.7 | 0.3 | 0.9 | 0.0 | -0.7 | 2.1 | 0.7 | -2.9 | 16.1 | -0.3 | 0.0 |
| ICSR 24010 | -0.7 | 1.8 | 0.5 | -0.9 | 0.0 | 1.6 | 0.2 | 3.7 | -1.5 | 0.4 | 38.2 | 12.5 | -0.3 | -0.2 |
| ICSR 38 | -1.6 | -1.7 | -0.1 | -0.2 | -0.4 | 3.3 | 0.0 | 2.6 | 2.1 | -0.1 | -7.4 | 9.1 | -0.3 | -0.1 |
| ICSR 89058 | -2.3 | -1.7 | 0.2 | -0.6 | -0.3 | 1.2 | 0.2 | 4.3 | 1.2 | 0.1 | 0.9 | 16.9 | -0.1 | -0.1 |
| ICSV 700 | 4.5 | 1.8 | -0.3 | -1.0 | 0.0 | -0.9 | -0.4 | -3.9 | -3.8 | -0.5 | 21.8 | -4.0 | 0.0 | 0.0 |
| IESV 91104DL | 0.3 | 1.0 | -0.1 | 1.9 | 0.2 | 0.0 | 0.1 | -1.4 | -2.0 | -0.1 | 13.3 | 1.5 | 0.3 | 0.0 |
| IESV 92172DL | -1.1 | -0.8 | 0.2 | -0.4 | -0.6 | 1.6 | -0.2 | 3.2 | 0.6 | -0.5 | -8.0 | 12.6 | -0.2 | 0.0 |
| KARI Mtama1 | -0.2 | 1.4 | -0.5 | -0.6 | -0.2 | -2.1 | 0.0 | 0.5 | -3.4 | -0.3 | 2.4 | -51.9 | 0.6 | 0.0 |
| Macia | -0.4 | 0.5 | 0.4 | 1.2 | 0.4 | 0.0 | -0.3 | 0.7 | 0.3 | -0.1 | -6.5 | 2.0 | 0.0 | 0.1 |
| Wahi | 1.2 | -0.7 | -0.6 | 0.2 | 0.1 | -3.5 | -0.5 | -4.3 | 1.3 | -0.8 | -29.1 | -6.4 | 0.3 | 0.2 |

DFL-days to 50% flowering, SG=stem girth (cm), NTIL=number of productive tillers, BYLD= Biomass yield ($tha^{-1}$), PH=plant height (cm), LL=leaf length (cm), LW=leaf width (cm), PL=panicle length (cm), PW=panicle width (cm), NL=number of leaves, PE=panicle exertion (cm), SS=seed set%, LO=number of plants lodged, SD=100 seed mass (g), WB=waxy bloom (1-9) GW=grain weight per 5 sampled plants (g) and GY= grain yield ($tha^{-1}$).

### 3.3.6.2.4 Specific combining ability effects for sorghum hybrids at Kiboko

The specific combining ability for yield and its component traits are shown in Table 3.26. The most desirable negative SCAs for days to 50% flowering were recorded in hybrids ICSA 206 x IESV 91104DL (-5.5), ICSA 11038 x KARI Mtama1 (-5.0), and ICSA 11039 x KARI Mtama1 (-4.2) with 19 hybrid combinations recording negative SCA effects. Hybrids ICSA 11040 x IESV 91104DL (2.0) and ICSA11036 x KARI Mtama1 (2.0) recorded the highest positive SCAs for biomass yield (Table 3.26).

Cross combinations ATX 623 x Macia (0.8), ICSA 11040 x IESV 91104DL (0.8) and ICSA 29011 x ICSR 89058 (0.4) recorded higher magnitude of positive SCA effect for grain yield. Positive SCA effects for plant height were observed in half of the cross combinations (Table 3.26). The highest SCA effects for plant height were noted in ICSA 11040 x IESV 91104DL (24.4) and ICSA11038 x KARI Mtama1 (23.4) whereas hybrids ICSA11016 x Wahi (-36.7) and ICSA11036 x KARI Mtama1 (-35.6) revealed the lowest SCA scores for plant height. Seed set showed positive SCA effects in 21 cross combinations with ICSA 11019 x Hakika (24.4) and ICSA 29001 x ICSV 700 (24.3) recording the highest SCA effects for seed set.

### 3.3.6.2.5. Specific combining ability effects for sorghum hybrids at Kampi ya Mawe

SCA effects for the 34$F_1$ hybrids evaluated at Kampi ya Mawe are given in Table 3.27. Specific combiners for days to flowering with negative SCA values were ICSA 206 x IESV 91104DL (-4.20), ICSA 11038 x KARI Mtama 1(-3.72) and ICSA 11039 x KARI Mtama1 (-3.47). Among the 34 hybrids studied, cross combinations *viz.*, ICSA 11035 x Macia (1.71) and ICSA 74 x Macia (1.11) and ICSA 228 x Hakika (0.79) showed highest positive SCA effects for biomass yield.

Highest positive SCA estimates for grain yield among the studied hybrids was manifested in ICSA 206 x IESV 91104DL (0.22) and ICSA 11035 x Macia (0.20). Cross combinations, ICSA 29004 x ICSR 24010 (6.17), ICSA 75 x ICSR 38 (5.10) and ICSA 11039 x KARI Mtama 1 (5.09) had high SCA effects for panicle exertion. Hybrid ICSA 29011 x ICSR 89058 had high SCA effects for panicle length and panicle width at 2.04 and 0.37 respectively. The highest and lowest SCA effects for plant height were recorded in ICSA 11039 x KARI Mtama 1 (30.25) and ICSA 11036 x KARI Mtama 1 (-39.28).

### 3.3.6.2.6 Specific combining ability effects for yield and its related traits across locations

Results of the combined SCA effects are shown in Table 3.28. The SCA effects for days to 50% flowering was recorded in desirable direction by 20 of the 34 hybrids. The lowest SCA estimates were manifested in hybrids ICSA 206 x IESV 91104DL (-5.69), ICSA 11038 x Mtama1 (-4.96) and ICSA 11039 x KARI Mtama 1 (-4.18). The results further revealed that the hybrid ICSA 11036 x KARI Mtama 1 which recorded the highest SCA effect for days to 50% flowering also displayed the highest positive SCA effect for biomass yield.

High SCA effects for grain yield were recorded in ATX 623 x Macia (0.29), ICSA 11040 x IESV 91104DL (0.25) and ICSA 29011 x ICSR 89058 (0.17). However the SCA scores were of lower magnitude. Hybrid ICSA 25002 x IESV 91104DL recorded the highest SCA effects for leaf length (5.65), leaf width (0.23) and stem girth (0.39). Eighteen hybrids recorded positive SCA effects for panicle exersion.

Hybrids ICSA 75 x ICSR 38 (1.88) and ICSA 11007 x Wahi (1.76) displayed the highest SCA effects for panicle length. High SCA effects for plant height were recorded in ICSA 11038 x KARI Mtama 1 (21.66), ICSA 11039 x KARI Mtama 1 (20.89) and ICSA 11040 x IESV 91104DL (16.40) whereas the lowest SCA effects for plant height were recorded in ICSA 11036 x KARI Mtama 1 (-41.02) and ICSA 11016 x Wahi (-27.12).

Table 3. 26 Specific combining ability effects for females in male parents at Kiboko

| Hybrid name | DFL | BY | GY | PE | PL | PW | PH | SS |
|---|---|---|---|---|---|---|---|---|
| ICSA11013 x Hakika | 0.7 | -1.0 | -0.5 | -1.2 | 0.9 | 0.5 | -14.2 | -8.7 |
| ICSA11019 x Hakika | 1.0 | 1.0 | 0.0 | -1.3 | -1.1 | -0.3 | 4.2 | 24.4 |
| ICSA228 x Hakika | -0.6 | 0.3 | 0.0 | -0.2 | 1.1 | -0.1 | -4.8 | -30.1 |
| ICSA11003 x ICSR160 | -1.0 | -0.6 | 0.0 | 1.7 | 0.2 | -0.1 | 0.1 | 6.0 |
| ICSA11033 x ICSR160 | -0.7 | -0.7 | 0.3 | -1.8 | 0.7 | 0.6 | -0.4 | 2.6 |
| ICSA11004 x ICSR24008 | -1.7 | -0.8 | 0.3 | -0.7 | 0.2 | 0.4 | -2.7 | 2.4 |
| ICSA232 x ICSR24008 | 0.0 | 0.2 | 0.3 | -0.3 | 1.2 | 0.2 | -4.5 | 7.2 |
| ICSA29007 x ICSR24008 | 2.1 | -0.5 | -0.2 | 0.3 | 0.0 | -0.2 | 6.2 | 2.2 |
| ICSA29004 x ICSR24010 | -0.2 | -0.2 | 0.0 | -0.4 | -0.4 | -0.1 | 12.9 | 6.7 |
| ICSA29005 x ICSR24010 | -0.5 | 0.3 | 0.4 | 1.2 | -0.3 | 0.3 | 3.7 | 2.3 |
| ICSA29017 x ICSR24010 | -0.8 | 2.0 | 0.2 | 1.3 | 0.0 | 0.1 | 12.0 | 0.0 |
| ICSA101 x ICSR38 | 0.8 | 0.5 | -0.1 | -1.2 | 0.5 | 0.3 | -10.7 | -15.8 |
| ICSA29016 x ICSR38 | -1.8 | -0.5 | 0.3 | 0.8 | -1.9 | -0.1 | -2.8 | 13.2 |
| ICSA75 x ICSR38 | -1.5 | -1.2 | -0.2 | 1.8 | 2.6 | -0.2 | 11.1 | 9.3 |
| ICSA29011 x ICSR89058 | -1.3 | 0.7 | 0.4 | 1.8 | 0.5 | 0.2 | 2.7 | 4.8 |
| ICSA29015 x ICSR89058 | -3.0 | -2.1 | -0.2 | 0.7 | 0.2 | -0.2 | -1.7 | 7.6 |
| ICSA29001 x ICSV700 | 2.5 | 0.1 | -0.1 | -0.7 | -1.6 | -0.1 | 17.0 | 24.3 |
| ICSA29002 x ICSV700 | 3.9 | 0.4 | 0.1 | -1.7 | 0.9 | 0.0 | 2.3 | -18.6 |
| ICSA29003 x ICSV700 | 2.8 | 0.7 | -0.3 | 0.0 | -1.3 | -0.2 | -6.9 | -8.6 |
| ICSA11040 x IESV91104DL | -1.2 | 2.2 | 0.8 | 1.8 | -0.5 | 0.0 | 24.4 | 14.5 |
| ICSA206 x IESV91104DL | -5.5 | -2.4 | -0.3 | 2.7 | -1.8 | 0.0 | 1.4 | 12.1 |
| ICSA25002 x IESV91104DL | 7.2 | 1.2 | -0.6 | -4.8 | 1.0 | -0.1 | -18.5 | -25.6 |
| ICSA12 x IESV92172DL | -2.1 | -0.2 | 0.3 | 1.9 | -0.1 | -0.2 | -6.5 | 8.9 |
| ICSA11036 x KARI Mtama1 | 8.3 | 2.2 | -0.7 | -5.6 | -0.8 | -0.4 | -35.6 | -1.9 |
| ICSA11038 x KARI Mtama1 | -5.0 | 0.2 | 0.1 | 3.8 | -0.3 | 0.1 | 23.4 | -18.7 |
| ICSA11039 x KARI Mtama1 | -4.2 | -1.2 | -0.2 | 1.9 | -0.9 | 0.1 | 11.2 | -17.3 |
| ATX623 x Macia | -1.7 | 1.2 | 0.8 | 3.9 | 0.4 | -0.3 | 14.3 | 21.0 |
| ICSA11034 x Macia | -0.1 | -0.8 | 0.1 | -0.2 | 0.0 | 0.1 | -15.2 | 4.5 |
| ICSA11035 x Macia | -0.8 | 0.5 | -0.2 | -1.4 | -1.9 | 0.0 | -6.7 | -1.7 |
| ICSA11037 x Macia | 0.1 | -0.9 | 0.3 | 0.0 | 0.3 | 0.5 | -0.2 | 9.1 |
| ICSA74 x Macia | 1.9 | 0.3 | -0.6 | -1.9 | 1.4 | -0.2 | 4.8 | -31.5 |
| ICSA11007 x Wahi | 1.6 | -0.7 | -0.2 | 0.8 | 3.3 | -0.2 | 17.4 | 8.3 |
| ICSA11016 x Wahi | 0.1 | 0.0 | 0.2 | -2.4 | -3.8 | -0.4 | -36.7 | -31.1 |
| ICSA11018 x Wahi | 0.6 | -0.2 | -0.3 | -0.7 | 1.0 | 0.2 | -1.0 | 18.3 |

DFL-days to 50% flowering, SG=stem girth (cm), BY= Biomass yield ($tha^{-1}$), PH=plant height (cm), PL=panicle length (cm), PW=panicle width (cm), PE=panicle exertion (cm), SS=seed set%, SD=100 seed mass (g) and GY= grain yield ($tha^{-1}$).

Table 3. 27 Specific combining ability effects for females in male parents at Kampi ya Mawe

| Genotype | DFL | BY | GY | NTIL | PE | PL | PW | PH |
|---|---|---|---|---|---|---|---|---|
| ICSA11013 x Hakika | 2.41 | -0.18 | -0.12 | -0.02 | -5.3 | 1.51 | -0.04 | -15.78 |
| ICSA11019 x Hakika | 1.42 | 0.25 | -0.15 | -0.01 | -1.95 | -1.57 | -0.14 | 1.54 |
| ICSA228 x Hakika | -0.22 | 0.79 | -0.04 | -0.01 | -0.29 | 0.63 | -0.04 | -1.78 |
| ICSA11003 x ICSR160 | -2.19 | -0.01 | 0.13 | -0.02 | 2.31 | 0.73 | 0.09 | 2.37 |
| ICSA11033 x ICSR160 | -1.74 | -0.55 | 0.11 | 0.06 | -2.3 | 0.73 | 0.57 | -0.47 |
| ICSA11004 x ICSR24008 | -2.61 | -0.22 | 0.18 | 0.02 | 0.39 | 0.58 | 0.09 | -8.15 |
| ICSA232 x ICSR24008 | 2.28 | 0.24 | -0.01 | -0.03 | -0.48 | -0.3 | 0.09 | -3.64 |
| ICSA29007 x ICSR24008 | 0.82 | -0.06 | -0.01 | 0.13 | 0.77 | 0.36 | -0.1 | 7.51 |
| ICSA29004 x ICSR24010 | -1.17 | 0.36 | 0.08 | -0.01 | 6.17 | 0.04 | 0.19 | 8.32 |
| ICSA29005 x ICSR24010 | 0.44 | -0.37 | -0.13 | -0.02 | -0.21 | 0.04 | 0.09 | -2.84 |
| ICSA29017 x ICSR24010 | -0.38 | -0.1 | 0.09 | -0.01 | -1.2 | -1.73 | -0.19 | 14.96 |
| ICSA101 x ICSR38 | 0.41 | -0.02 | -0.06 | -0.01 | -2.05 | 0.42 | -0.01 | -12.14 |
| ICSA29016 x ICSR38 | -2.4 | -0.45 | -0.12 | -0.02 | -0.51 | -2.44 | -0.3 | -10 |
| ICSA75 x ICSR38 | -2.25 | -0.34 | 0.11 | -0.01 | 5.1 | 3.28 | -0.1 | 12.54 |
| ICSA29011 x ICSR89058 | -1.33 | 0.16 | 0.07 | -0.01 | 4.77 | 2.04 | 0.37 | 6.93 |
| ICSA29015 x ICSR89058 | -2.86 | -0.68 | -0.15 | -0.01 | 0.48 | -1.27 | -0.21 | -6.59 |
| ICSA29001 x ICSV700 | 1.42 | 0.22 | 0.02 | -0.01 | -4.93 | -0.53 | -0.16 | -6.4 |
| ICSA29002 x ICSV700 | 4.63 | 0.73 | -0.05 | -0.02 | 4.49 | -0.97 | 0.22 | 26.11 |
| ICSA29003 x ICSV700 | 1.24 | 0.01 | -0.1 | -0.02 | -1.55 | -1.71 | -0.12 | -0.01 |
| ICSA11040 x IESV91104DL | 1.01 | 0.02 | -0.03 | -0.03 | -2.67 | -0.95 | 0.01 | 1.19 |
| ICSA206 x IESV91104DL | -4.2 | -0.11 | 0.22 | 0.19 | 1.59 | 0.37 | 0.01 | 12.58 |
| ICSA25002 x IESV91104DL | 3.8 | 0.18 | -0.12 | -0.04 | -3.82 | -0.19 | -0.03 | -2.09 |
| ICSA12 x IESV92172DL | -1.92 | -0.66 | 0.01 | 0.06 | 2.59 | 1.28 | -0.15 | -3.71 |
| ICSA11036 x KARI Mtama1 | 8.86 | 0.34 | -0.24 | -0.01 | -2.79 | -3.34 | -0.22 | -39.28 |
| ICSA11038 x KARI Mtama1 | -3.72 | 0.1 | 0.16 | -0.02 | 1.42 | 0.4 | 0.17 | 14.58 |
| ICSA11039 x KARI Mtama1 | -3.47 | -0.07 | 0.15 | -0.01 | 5.09 | 1.06 | 0.26 | 30.25 |
| ATX623 x Macia | -1.45 | -0.88 | 0.07 | -0.01 | 0.42 | 0.77 | -0.23 | 2.97 |
| ICSA11034 x Macia | -2.28 | -0.58 | 0.01 | -0.01 | -0.79 | -0.33 | -0.04 | -9.85 |
| ICSA11035 x Macia | 1.29 | 1.71 | 0.2 | -0.01 | 0.75 | 1.65 | 0.34 | 2.25 |
| ICSA11037 x Macia | 0.26 | -1.1 | -0.07 | -0.01 | -3.08 | -1.65 | -0.14 | -11.03 |
| ICSA74 x Macia | 0.98 | 1.11 | -0.05 | -0.03 | 3.72 | -0.11 | -0.14 | 8.66 |
| ICSA11007 x Wahi | 0.92 | 0.07 | -0.05 | -0.01 | -2.35 | 1.52 | -0.05 | 4.11 |
| ICSA11016 x Wahi | 3.26 | 0.61 | -0.14 | -0.02 | -3.6 | 0.42 | -0.05 | -10.13 |
| ICSA11018 x Wahi | -1.29 | -0.52 | 0 | -0.01 | -0.16 | -0.68 | -0.05 | -12.97 |

DFL-days to 50% flowering, SG=stem girth (cm), BY= Biomass yield ($tha^{-1}$), PH=plant height (cm), LL=leaf length (cm), LW=leaf width (cm), PL=panicle length (cm), PW=panicle width (cm), PE=panicle exertion (cm), SS=seed set%, SD=100 seed mass (g), and GY= grain yield ($tha^{-1}$).

Table 3. 28 Specific combining ability effects for sorghum hybrids across locations

| Genotype | DAF | BY | GY | LL | LW | PE | PL | PH | SS |
|---|---|---|---|---|---|---|---|---|---|
| ICSA11013 x Hakika | 1.26 | -0.62 | -0.19 | -0.87 | 0.14 | -1.92 | 0.59 | -15.93 | -8.92 |
| ICSA11019 x Hakika | 1.12 | 0.65 | -0.02 | 1.67 | -0.1 | -0.93 | -0.76 | 3.75 | 24.32 |
| ICSA228 x Hakika | -0.44 | 0.47 | 0.03 | 0.27 | 0.16 | -0.01 | 0.56 | -2.59 | -30.06 |
| ICSA11003 x ICSR160 | -1.52 | -0.26 | 0.02 | 0.92 | 0.02 | 2.05 | 0.2 | 1.47 | 6.31 |
| ICSA11033 x ICSR160 | -0.89 | -0.54 | 0.12 | 0.91 | -0.04 | -2.03 | 0.31 | -1.18 | 2.22 |
| ICSA11004 x ICSR24008 | -2.1 | -0.49 | 0.13 | 0.58 | -0.08 | -0.39 | 0.22 | -4.02 | 2.59 |
| ICSA232 x ICSR24008 | 0.81 | 0.23 | 0.09 | -2.35 | 0.09 | -0.25 | 0.48 | -3.94 | 6.88 |
| ICSA29007 x ICSR24008 | 1.97 | -0.29 | -0.06 | -0.1 | 0.09 | 0.24 | -0.08 | 6.13 | 2.27 |
| ICSA29004 x ICSR24010 | -0.5 | -0.05 | 0.01 | -0.79 | -0.06 | 1.45 | -0.05 | 12.22 | 6.82 |
| ICSA29005 x ICSR24010 | -0.26 | -0.06 | 0.07 | -0.61 | 0.05 | 0.53 | 0.04 | 0.6 | 2.43 |
| ICSA29017 x ICSR24010 | -0.61 | 1.03 | 0.11 | -1.09 | 0 | 0.28 | -0.43 | 11.46 | -0.15 |
| ICSA101 x ICSR38 | 0.74 | 0.33 | -0.07 | 0.36 | -0.09 | -1.39 | 0.27 | -12.33 | -15.84 |
| ICSA29016 x ICSR38 | -1.91 | -0.44 | 0.04 | -0.94 | -0.01 | 0.36 | -1.54 | -5.86 | 13.26 |
| ICSA75 x ICSR38 | -2.03 | -0.76 | -0.01 | -0.01 | -0.04 | 2.57 | 1.88 | 13.51 | 9.21 |
| ICSA29011 x ICSR89058 | -1.32 | 0.51 | 0.17 | -0.16 | -0.03 | 2.49 | 0.62 | 4.82 | 5.03 |
| ICSA29015 x ICSR89058 | -3.3 | -1.39 | -0.12 | -1.63 | -0.06 | 0.07 | -0.27 | -4.24 | 7.35 |
| ICSA29001 x ICSV700 | 2.27 | 0.11 | -0.01 | -3.12 | -0.06 | -1.67 | -0.75 | 6.76 | 23.98 |
| ICSA29002 x ICSV700 | 4.26 | 0.47 | 0.03 | 0.73 | 0.13 | 0.03 | 0.34 | 13.11 | -18.64 |
| ICSA29003 x ICSV700 | 2.66 | 0.35 | -0.13 | -0.65 | -0.06 | -0.68 | -0.7 | -6.03 | -8.25 |
| ICSA11040 x IESV91104DL | -0.66 | 1.25 | 0.25 | 3.68 | 0.06 | 0.94 | -0.46 | 16.4 | 14.49 |
| ICSA206 x IESV91104DL | -5.69 | -1.45 | -0.04 | -3.86 | -0.21 | 2.41 | -0.66 | 7.08 | 12.43 |
| ICSA25002 x IESV91104DL | 6.93 | 0.71 | -0.24 | 5.65 | 0.23 | -4.19 | 0.53 | -15.02 | -25.8 |
| ICSA12 x IESV92172DL | -2.19 | -0.38 | 0.07 | -1.06 | -0.21 | 1.91 | 0.18 | -5.09 | 9.25 |
| ICSA11036 x KARI Mtama1 | 8.8 | 1.36 | -0.32 | -2.1 | -0.02 | -5.53 | -1.01 | -41.02 | -2.27 |
| ICSA11038 x KARI Mtama1 | -4.96 | 0.12 | 0.12 | -0.35 | -0.05 | 2.97 | 0.06 | 21.66 | -18.9 |
| ICSA11039 x KARI Mtama1 | -4.18 | -0.77 | 0.01 | 0.67 | 0.01 | 2.86 | -0.04 | 20.89 | -16.81 |
| ATX623 x Macia | -1.9 | 0.29 | 0.29 | 0.93 | -0.05 | 3 | 0.32 | 11.3 | 21.25 |
| ICSA11034 x Macia | -0.75 | -0.67 | 0 | 1.76 | -0.08 | -0.14 | -0.06 | -13.11 | 5.12 |
| ICSA11035 x Macia | -0.36 | 1 | 0 | -1.88 | 0.18 | -1.22 | -0.47 | -4.59 | -1.8 |
| ICSA11037 x Macia | 0.5 | -0.97 | 0.1 | 3.24 | 0.02 | -0.77 | -0.31 | -4.94 | 8.69 |
| ICSA74 x Macia | 1.76 | 0.61 | -0.27 | -0.45 | 0.06 | -0.45 | 0.6 | 7.22 | -31.81 |
| ICSA11007 x Wahi | 1.53 | -0.33 | -0.08 | -1.2 | -0.03 | 0.08 | 1.76 | 13.27 | 7.9 |
| ICSA11016 x Wahi | 1.09 | 0.27 | -0.02 | 1.36 | -0.16 | -2.29 | -1.54 | -27.12 | -31.25 |
| ICSA11018 x Wahi | -0.13 | -0.31 | -0.09 | 0.48 | 0.22 | -0.4 | 0.16 | -4.63 | 18.69 |

DFL-days to 50% flowering, SG=stem girth (cm), BY= Biomass yield ($tha^{-1}$), PH=plant height (cm), LL=leaf length (cm), LW=leaf width (cm), PL=panicle length (cm), PW=panicle width (cm), PE=panicle exertion (cm), SS=seed set%, SD=100 seed mass (g), and GY= grain yield ($tha^{-1}$).

### 3.3.6.3 Estimates of components of variance for yield and its related traits across locations

Additive variance was higher than dominance variance in most of the evaluated traits as shown in Table 3.29. Degree of dominance was more than unity in days to 50% flowering, leaf length and stem girth with values of 1.02, 1.38 and 1.1 respectively.

Table 3. 29 Estimates of genetic parameters in the 34 sorghum hybrids across locations

| Parameter | Additive Variance | Dominance Variance | Environmental Variance | Broad Heritability | Narrow Heritability | Degree of Dominance |
|---|---|---|---|---|---|---|
| DAF | 22.5 | 23.4 | 3.1 | 0.9 | 0.5 | 1 |
| BY | 11.3 | 0 | 5.3 | 0.7 | 0.7 | 0 |
| GY | 1 | 0 | 0.7 | 0.6 | 0.6 | 0 |
| LL | 8.6 | 16.3 | 10 | 0.7 | 0.3 | 1.4 |
| LW | 0.6 | 0 | 0.5 | 0.6 | 0.6 | 0 |
| PE | 54.2 | 0 | 14.2 | 0.8 | 0.8 | 0 |
| PL | 22.5 | 0 | 6.1 | 0.8 | 0.8 | 0 |
| PW | 1.8 | 0 | 2.4 | 0.4 | 0.4 | 0 |
| PH | 1719 | 0 | 117.1 | 0.9 | 0.9 | 0 |
| SS | 2044 | 0 | 102.8 | 1 | 1 | 0 |
| SD | 0.4 | 0 | 0.1 | 0.8 | 0.8 | 0 |
| SG | 0.1 | 0.2 | 0.2 | 0.6 | 0.3 | 1.1 |

DFL-days to 50% flowering, SG=stem girth (cm), BY= Biomass yield ($tha^{-1}$), PH=plant height (cm), LL=leaf length (cm), LW=leaf width (cm), PL=panicle length (cm), PW=panicle width (cm), PE=panicle exertion (cm), SS=seed set%, SD=100 seed mass (g), and GY= grain yield ($tha^{-1}$).

## 3.4 Discussion

### 3.4.1 Analysis of variance for yield and its component traits

The results showed that large variability exists within the germplasm which can be utilized in development of new cultivars with high grain and biomass yield potential. Previous research work on sorghum by Abdus *et al* 2012; Nyadanu and Dikera 2014; Taye *et al* 2016; Ahmadikhah and Marufinia, 2016 reported significant differences among studied traits.

The results clearly showed that yields and agronomic performance of sorghum hybrids and their parents were greatly influenced by the environment where they were grown. The three environments were highly variable. The variation between environments was due to the differences in climatic factors prevailing between the three environments. From the results the temperatures and rainfall amounts were varied hence might have caused the variation in yields.

The significant genotype by environment interaction revealed that there was differential performance of genotypes for yield and its components across the testing

environments. Therefore, evaluation and selection of genotypes for these traits should be done in multiple environments. Similar results among sorghum hybrids were reported by Ezzat *et al*, 2010 in Egypt and Kenga *et al* 2003 in Cameroon.

### 3.4.2 Agronomic performance of the sorghum hybrids and their parents at Kiboko and Kampi ya Mawe

Significant differences were noted among genotypes for days to flowering. Hybrid parents flowered earlier at Kiboko than Kampi ya Mawe. The variation might have been caused by the differences in weather conditions *viz* rainfall and temperature. Tesfamichael (2015) reported that plants respond to moisture stress by delaying the growth. Munamava and Riddoch (2001) observed that drought after panicle initiation delayed flowering in sorghum. Sorghum hybrids were also early flowering than their parents, therefore hybridization is a source of genetic diversity. Xin (2015) reported that flowering time is affected by endogenous and environmental stimuli.

Hybrids and their parents were taller with broad and longer leaves at Kiboko than Kampi ya Mawe. This might have been caused by moisture differences between the locations. According to Assefa *et al* (2010), moisture stress reduces the rate of cell expansion and size which culminates into retarded plant growth, stem elongation, and leaf expansion. This leads to smaller leaf area lowering evapotranspiration hence conferring drought tolerance. Tsuji *et al* (2013) reported that drought tolerance in sorghum is associated with smaller leaf area.

In the current study, panicle length, width and exertion were shorter at Kampi ya Mawe than Kiboko. Decrease in these panicle attributes indicates the sensitivity of the sorghum hybrids and their parents to water stress. Similar results were reported in sorghum by Tesfamichael (2015). Hybrid parents ICSB 11004 and ICSB 75 produced hybrids with longer panicles hence are ideal female parents for improving panicle length.

$F_1$ sorghum hybrids have been reported to be earlier blooming, tall and high yielding than their parents (Mahdy *et al.* 2011; Mindaye *et al*., 2016; Ezzat *et al*., 2010). Terminal drought stress is a major challenge in the ASALs hence apart from high grain yield, farmers in the ASALs would embrace early flowering sorghums able to escape terminal drought. From the current study, the male parents were significantly taller than females hence seed production of the experimental hybrids is feasible.

High yielding hybrids in the current study had good exertion hence grain quality of the developed hybrids will not be compromised. Dogget (1988) and Ringo *et al*, (2015) reported that poor panicle exertion provides conducive conditions at the leaf sheath for fungi and pests to thrive at the base of the panicle and spread to the whole panicle.

Hybrids developed from shorter male parents (Wahi and Hakika) were lodging resistant as depicted from the present study. The two restorers are potential donors for lodging resistance in future hybrid breeding programs. Lodging compromises grain quality due to soiling and sometimes sprouted grain. Good grain quality is an important attribute in the sorghum markets. High grain yielders were more susceptible to lodging. However, the lodging had no effect on fresh biomass yield. Fedenko *et al*., (2015) reported similar findings in sweet sorghum where biomass yields were not different between lodging and non-lodging varieties.

Highly significant differences were noted for grain yield among hybrids and their parents between Kampi ya Mawe (Water stressed) and Kiboko (Supplementary irrigation). Water stress causes reduction in the translocation of photo- assimilates to the grains causing smaller and fewer grains as reported by Menezes *et al*., (2014). The lower grain yield in some hybrids could have been due to fewer and or shriveled grains caused by partial sterility and or poor grain filling due to drought. Although sorghum is relatively drought tolerant, it still requires favourable moisture to give better yields. When drought occurs before anthesis, decrease in yield is due to fewer grains; in case it occurs after anthesis then the low yield is due to small grain as described by Mutava *et al*. (2011). Therefore, high grain yield in hybrids might have been as a result of early flowering which aids in drought escape.

From the current study, the parents ICSR 24008, ICSB 29004, ICSR 24010, ICSB 11040 and ICSR 160 were superior grain yielders whereas ICSB 74, ICSV 700, ICSR 24010 and ICSB 75 were superior biomass producers. Therefore, ICSR 24010 is a dual purpose parent. Superior hybrids in grain yield were ATX 623 x Macia, ICSA 11004 x ICSR 24008, ICSA 29005 x ICSR 24010 and ICSA 11033 x ICSR 160. The male parents to these hybrids were also superior performers hence selection of male hybrid parents should be based on the *perse* performance. However, this should be supported by the combining ability information. Ghorade and Dipali (2007) reported

that per se performance of the restorer lines influenced grain yield performance of the hybrids.

### 3.4.3 Correlation and regression analysis

The knowledge of the relationship between yield and its component traits is important for formulating a breeding program to achieve desired combinations aimed at improving grain and biomass yield. The correlation coefficients provide a measure for distinguishing important relationships between traits (Prakash *et al*., 2010). In the present study, significant negative associations between grain yield and days to 50% flowering suggested that early flowering hybrids and their parents were high grain yielding than late ones. The early genotypes were able to escape terminal drought. Therefore, earliness should be key during development of sorghum cultivars for the ASALs.

The positive association between fresh biomass yield and grain yield in the present study indicated that the two traits can be improved simultaneously. This is in agreement with reports by Prakash *et al*. (2010) and Sanderson *et al*. (1993). This is important in the ASALs where dual purpose sorghums are highly acceptable as food and feed. Even though it is logical to expect high biomass sorghums to have lower grain yields, the association was however found to be positive. The positive association might be due to the high leaf number, and leaf area that gave the plants high photosynthetic capacity producing high photo assimilates used to build both biomass and grain yield (Makanda, 2017).

The positive correlation that existed between grain yield with panicle length, panicle width and plant height at Kampi ya Mawe in the present investigation implies that improvement of sorghum for grain yield can be done by improving those traits simultaneously. The traits can also be used as key selection indices for parents used improving grain yield in the ASALs. The taller plants with longer leaves could have produced higher assimilates which led to greater yields. In Nigeria, Arunah *et al*. (2015) in their study on correlation and path analysis in sorghum found that grain yield was positively correlated to plant height and leaf area index.

From the current study it is evident that plant height was positively correlated with biomass yield. Tall and late maturing plants tend to produce more and larger leaves than those of semi dwarf types as reported by Tesso *et al*., (2011). The tall and late

plants with longer leaves had high net photosynthesis rate during grain filling hence higher grain and biomass yields. The findings are in agreement with those of Kumari et al. (2017) in forage sorghums.

The present study showed that plant height, leaf length and days to flowering are important characters in determining grain and biomass yield in sorghum. Hence they can be used as selection indices in sorghum improvement programs. However, yield is a complex trait which is influenced by many traits some of which are not in this study in addition to environmental influence.

Multiple regression results from the present study revealed that days to flowering, stem girth, waxy bloom, biomass yield, plant height, panicle length, panicle width, panicle exertion and 100 seed mass are variables that contributed significantly to sorghum grain yield. The regression model ($R^2$=0.72) adequately described the variability in grain yield among sorghum genotypes. Mijitaba and Dale (2004) studied the role of epicuticle wax on the rate of water loss from the sorghum plants and concluded that wax cover on sorghum leaves reduces the transpiration water loss and prevents a rapid decrease in plant water potential.

### 3.4.4 Genotypic and phenotypic coefficients of variation in sorghum hybrids and their parents

Days to 50% flowering and plant height had a very close estimate of PCV and GCV scores which showed a lesser influence of environmental effect on these traits hence are highly heritable and their improvement can be done through selection. The other traits in the study had high PCV than GCV scores hence greater environmental influence on the expression of these characters.

The high GCV scores for number of productive tillers, biomass yield, panicle exertion and lodging in the present study suggested that improvement of these characters is possible through direct selection. Badigannavar *et al* (2017) reported high GCV and PCV for plant height, grain yield, panicle length and width in sorghum cultivars adapted to African and Asian conditions. Nyadanu and Dikera (2014) reported high GCV and PCV scores for number of days to flowering, plant height, panicle length and width in sorghums of upper Eastern Ghana. Jain and Patel (2013) reported high GCV and PCV for fodder yield in sorghum in the ASALs of Gujarat. The findings are also in agreement with the results of Kareema *et al* (2017) in sorghum.

However, the coefficient of variation estimates alone were not helpful in determining genetic advance from selection hence it was used together with heritability estimates in increasing the selection efficiency.

### 3.4.5 Heritability and genetic advance for sorghum hybrids and their parents at Kiboko and Kampi ya Mawe

The genotypic coefficient of variation does not offer the full variation that is heritable. Hence, heritability is essential for estimation of genetic control of the expression of a trait. Heritability also determines the efficiency with which the genotypic variability of a trait can be exploited through selection.

High heritability scores were recorded for fresh biomass yield, panicle exertion and plant height in sorghum hybrids and their parents indicating that improvement of these characters through selection would be possible. Moderate and low heritability scores realized in panicle length, panicle width, 100 seed mass, stem girth, leaf length, leaf width and grain yield is an indication that environmental effect constituted a larger portion of the phenotypic variation of these characters hence improvement through selection would be less effective.

The utility of heritability scores is more important when used with genetic advance as a percentage of the mean (Badigannavar *et al*., 2017). In the present study, high heritability coupled with high genetic advance as a percentage of the mean was observed for fresh biomass yield, plant height and panicle exertion for sorghum hybrid parents. This is an indication that additive gene effects controlled inheritance of these traits. Therefore, genetic gains can be achieved through selection.

High heritability and low genetic advance as a percentage of the mean for days to 50% flowering in sorghum hybrids and their parents indicated that the inheritance of the trait was caused by non-additive gene effects. Hence, its improvement through selection would be ineffective. Badigannavar *et al*. (2017) reported high heritability and genetic advance for grain yield, days to flowering and plant height in sorghum. High heritability and genetic advance in sorghum was also reported by Jain and Patel (2013).

### 3.4.6 Better parent, mid parent and standard heterosis for grain and fresh biomass yield and their component traits in sorghum hybrids

Exploitation of heterosis is important in improving grain and biomass yields in sorghum. Hybrids with wider adaptation are key in sorghum improvement. Commercialization of sorghum hybrids is a profitable venture for the farming communities and seed companies. It is important to compare new hybrids with the released varieties or hybrids than merely comparing it with parents.

Heterosis values are key in selection of superior crosses in sorghum. Drought limits sorghum production in the ASALs of Kenya. Therefore, early flowering sorghums are preferred because they escape terminal drought. In this study, more than 91% of the hybrids had negative better parent heterosis for days to flowering indicating that they were earlier maturing than their parents. Mindaye *et al*. (2016) reported an average better parent heterosis of -9% for days to flowering in sorghum hybrids adapted to lowlands of Ethiopia.

Positive better parent heterosis for stem girth is important in increasing the succulence of stems and lodging resistance in sorghums. In this study, 50% of the hybrids had positive better parent heterosis, 59% had positive mid parent heterosis for stem girth showing the predominance of non-additive gene action in controlling the trait. All hybrids had positive standard heterosis for the trait. The results were in agreement with those of Vinaykumar *et al*., (2012) who reported positive better parent and standard heterosis for stem girth in sweet sorghum hybrids at Bengaluru. However, non- significant better parent heterosis was reported in forage sorghum hybrids for the same trait by Pandey and Shrotria (2012).

Dual purpose sorghums play an important role in integrated crop livestock production systems. Farmers prefer sorghum hybrids that produce high grain and above ground biomass yields. From this study, high positive better parent and mid parent heterosis for biomass yield and its contributory traits such as plant height, leaf length and width were recorded. Heterosis for biomass yield manifests as the cumulative effect of its contributory traits. Longer and wider leaves have higher photosynthetic efficiency hence produce higher assimilates. The results are in agreement with the findings of Meenu and Shrotria (2005) who reported significant positive heterobeltiosis, relative

and standard heterosis for green fodder yield, leaf length and width, plant height and stem diameter in forage sorghums.

In the current study, most of the hybrids had positive heterosis for plant height hence its improvement can be accomplished through hybrid development. The findings are in agreement with the results of Meenu and Shrotria (2005) in forage sorghums. Mindaye *et al*. (2016) reported mean better parent heterosis of 11% for plant height in lowland sorghum hybrids. Vinaykumar *et al*. (2012) reported significant positive heterobeltiosis and standard heterosis for plant height in sweet sorghums.

Panicle length is one of the yield contributing factors in sorghum. In the present study, desirable heterobeltiosis for panicle length was exhibited in 70% of hybrids. Blum (2013) reported that most growth heterosis in sorghum is invested in the panicle. The results are in agreement with the findings of Makanda (2009) in grain sorghum hybrids for the lowland and mid altitude environments of Zimbabwe. Mindaye *et al* (2016) also reported similar results in sorghum hybrids for the lowland environments of Ethiopia.

Panicle exertion had the highest heterobeltiosis among the studied traits. Most of the hybrids had positive better parent, mid parent and standard heterosis for panicle exertion. Panicle exertion is an important trait with farmers preferring positive exertion. Well exerted sorghums produce better quality grain. Poor panicle exertion is disadvantageous because the leaf sheath of the boot leaf provide conducive microclimate for growth of fungal pathogens that cause grain molds. The boot leaf sheath can also harbor sucking bugs that lower the grain quality. Ringo *et al* (2015) reported positive heterosis for panicle exertion in sorghum hybrids for the lowlands and sub humid environments of East Africa.

Seed set percent is an important factor to consider in sorghum hybrid production. A good sorghum hybrid should be able to restore fertility. Four hybrids ATX 623 x Macia, ICSA 29016 x ICSR 38, ICSA 232 x ICSR 24008 and ICSA 29015 x ICSR 89058 recorded positive better parent, mid parent and standard heterosis for seed set% hence would be fit for commercialization.

In the present study, better parent, mid parent and standard heterosis for grain yield were realized with both positive and negative magnitude. This shows the greater effect of non- additive gene action (dominance and epistasis) in inheritance of the

trait. Drought stress limits sorghum production in the semi-arid areas of Kenya. Therefore, drought tolerant, high yielding sorghums are preferred by the farmers. Sorghum hybrids; ATX 623 x Macia, ICSA 29011 x ICSR 89058, ICSA 11033 x ICSR 160, ICSA 12 x IESV 92172DL and ICSA 11035 x Macia had high positive magnitudes of the 3 types of heterosis. Therefore, these hybrids can be fast tracked for on-farm testing and possible release for cultivation in the semi-arid areas of Kenya.

Ashok *et al*. (2011) reported negative and positive better parent and mid parent heterosis for grain yield in white grained mold resistant sorghum hybrids. In another study, Ringo *et al*. (2015) reported heterobeltiosis and mean heterosis for grain yield in sorghum hybrids at 81.9% and 77.18% respectively. Premalatha *et al*. (2006) reported sorghum grain yield heterosis of 90%, 86.89% and 33.45% for mid parent, better parent and standard heterosis respectively. Jayalakshimi *et al*. (2006) reported mid parent and better parent heterosis for grain yield per plant in sorghum hybrids with a range of -44.2 to 71.3% and -47.7 to 65% respectively. This is a clear indication that for realization of high sorghum yields in the dry areas of Kenya, production of hybrids by is essential.

### 3.4.7 Gene action and combining ability effects

In this study, additive gene action was predominant over non-additive gene action for grain yield as well as, for biomass yield, leaf width, number of plants lodged, and number of tillers, panicle length, panicle width, panicle exertion, plant height, 100 seed mass and seed set. Kale and Desai (2016) reported preponderance of additive gene action in sorghum for grain yield per plant, plant height, panicle length, harvest index and 1000 seed mass in India. Riyazaddin *et al*., (2015) reported additive gene action for days to flowering and plant height during post rainy season in India. Mungra *et al*., (2011) reported preponderance of additive gene action in control of days to 50% flowering, stem girth and protein content in sorghum.

However, the ratio between dominance and additive variances was above unity for days to 50% flowering, leaf length and stem girth indicating the predominance of non-additive gene action in controlling the expression of these traits. Muturi (2013) reported significant non-additive gene action for panicle emergence and panicle length in Kenya. Results in a study by Mungra *et al*., (2011) showed that non-additive gene action played a major role in the inheritance of plant height and stem fodder

yield. This shows that both additive and non-additive gene action are important in governing inheritance of yield and its component traits. Hence, there is a possibility of improving traits through heterosis.

Genotypes with desirable GCAs are expected to transmit genes with desirable effects to their progenies when used as parents in a crop improvement program. It was observed that none of the male parents was a good general combiner for all traits. Among the male parents, ICSR 24010 was found to have good *per se* performance for grain and biomass yield and a good general combiner for grain yield, biomass yield, number of tillers, and plant height, therefore it is a good source of favorable genes for increasing grain and forage yield in dual purpose hybrids.

The male parents ICSR 89058, ICSR 38 and ICSR 160 recorded desirable GCA for days to 50% flowering showing that these parents are good sources of genes for earliness. However, they were poor combiners for biomass yield. Male parents ICSR 160, ICSR 24008 and ICSR 24010 exhibited desirable GCA for grain yield and its component trait panicle length. Hence, they are potential donors for genes in improving grain yield in hybrids. Genotypes, ICSV 700, ICSR 24010 and KARI Mtama 1 recorded desirable GCA values for biomass yield hence could provide good sources of genes for fodder improvement.

Male parents ICSR 160, Macia and ICSR 24008 were the best general combiners for grain yield at Kampi ya Mawe whereas ICSR 24010, ICSR 24008, and Macia were the best combiners for grain yield at Kiboko. Makanda (2009) reported that environment plays a critical role in influencing the expression of additive and non-additive gene effects. Therefore, selection of parents should be done after testing them in different environments to classify them for general and specific adaptation.

The estimates of SCA effects of females within males revealed that no cross combination was superior for all characters. Hybrids, ICSA 206 x IESV 91104DL, ICSA 11038 x KARI Mtama 1, ICSA 11039 x KARI Mtama 1 and ICSA 29015 x ICSR 89058 exhibited the most desirable SCA for days to 50% flowering. The hybrids were developed from one or both parents who were superior in flowering. SCA estimates for biomass yield varied between locations showing the presence of interaction between the SCA and environments. Positive correlation between the SCA for days to 50% and biomass showed that improvement for high biomass in sorghum

hybrids can be accomplished through selection of late hybrids. Hybrids ICSA 11040 x IESV 91104DL, ICSA 29017 x ICSR 24010 and ICSA 29011 x ICSR 89058 with high SCA effects for grain and biomass yield can also be fast tracked for onfarm testing and possible release. Late hybrid ICSA 11036 x KARI Mtama 1 had the highest SCA for biomass yield and lowest SCA for grain yield making it a good forage sorghum however its acceptance in the semi-arid areas where earliness is key would be low.

### 3.5 Conclusions

From the study, it can be concluded that environment affected the genotypic expression of hybrids and their parents for most of the traits. Therefore, selection of new hybrids and their parents should be done on the basis of specific and broad adaptation. Hybrids were early maturing and had higher grain and biomass yields than the inbred lines hence hybrid breeding will improve grain and biomass yields in the semi-arid areas of Kenya. Grain and biomass yield can be improved simultaneously through hybrid development. In the present study, additive gene action influenced the expression of grain yield, biomass yield, number of tillers, panicle length, width and exertion, plant height, seed set percent and 100 seed mass. However, non-additive gene action controlled the inheritance of plant height, leaf length and stem girth. Development of early, high yielding dual purpose sorghum hybrids is possible through exploitation of heterosis. Sorghum hybrids; ATX 623 x Macia, ICSA 29011 x ICSR 89058, ICSA 11033 x ICSR 160, ICSA 12 x IESV 92172DL and ICSA 11035 x Macia were high yielding hence could be recommended for on farm testing. Male parents, ICSV 700 and ICSR 160 were good general combiners for biomass and grain yield respectively hence can be used effectively in sorghum improvement. An understanding of the association between grain yield and other characters will enable development of high yielding cultivars with the desired plant type.

# CHAPTER FOUR

## EVALUATION OF GRAIN YIELD STABILITY AND ADAPTATION OF SORGHUM HYBRIDS IN SEMI- ARID AREAS OF KENYA


### 4.0 Abstract

Development of high yielding and stable sorghum varieties or hybrids with wide adaption is one of the main objectives of plant breeders. However, genotype by environment interaction which greatly affects the yields has remained a major challenge to breeders. Thirty four sorghum hybrids derived from NCD I and a check variety Seredo were evaluated in three environments in eastern Kenya; Kiboko 2014, Kiboko 2014-15 and Kampi ya Mawe 2014-15 for yield stability and adaptation. The experiment was conducted in a 5x7 alpha lattice trial design. The trials at Kiboko were supplied with supplementary irrigation while the trial at Kampi ya Mawe was rain fed. The AMMI (Additive Multiplicative Main Interaction) analysis and Genotype main effects and genotype by environment effect (GGE) biplot analysis were used to determine stability. The combined ANOVA for grain yield showed significant effects of genotypes, environment and genotype by environment interaction for grain yield. The sum of squares showed that environment caused 58% of the variation in grain yield indicating the need for multi locational trials or testing over seasons of sorghum hybrids. The AMMI analysis of variance also revealed significant genotype, environmental and genotype by environment interaction (GEI) effects at $P \leq 0.01$ indicating that genotypes responded differently to changes in test environments and environments discriminated genotypes with different magnitudes. The mean grain yield of the genotypes across the locations showed that G31 (ATX 623 x Macia) had the highest yield at 4.017tha$^{-1}$ and G24 (ICSA 11036 x KARI Mtama 1) the lowest at 1.116tha$^{-1}$. The AMMI Stability value (ASV) and AMMI biplots revealed that hybrid G33 (ICSA 11016 x Wahi), G6 (ICSA 11004 x ICSR 24008) and G27 (ICSA 11034 x Macia) were stable and less influenced by the environments. The GGE biplot models showed that the three environments used in the study belonged to two mega environments. The winning genotypes in the two mega environments were; G5 (ICSA 11033 x ICSR 160) for Kiboko 2014-15 and KYM 2014-15 and G15 (ICSA 29011 x ICSR 89058) and G31 (ATX 623 x Macia) were the best genotypes in KBK 2014. In the current study, the most desirable genotypes were G10 (ICSA 29005 x ICSR 24010), G6 (ICSA 11004 x ICSR 24008), G5 (ICSA 11033 x ICSR 160), G31 (ATX 623 x Macia), G23 (ICSA 12 X IESV 92172 DL). It was also evident that different seasons at Kiboko could be considered differently when testing sorghum hybrids for grain yield. The sorghum hybrid G31 (ATX 623 x Macia) released in Tanzania together with G6 (ICSA 11004 x ICSR 24008), G5 (ICSA 11033 x ICSR 160), and G23 (ICSA 12 X IESV 92172 DL) can are potential hybrid releases in the semi- arid areas of Kenya due to their superior performance.



Key words: *AMMI model, GGE biplots, correlation, principal component analysis, stability, mega environments*

## 4.1 Introduction

One of the main objectives of a crop breeding program is the development of high yielding and stable varieties or hybrids adapted to wide growing conditions. At the same time plant breeders are faced with a task of identifying the best environments for growing the newly developed genotypes. However, this has remained a major challenge to most researchers due to the phenomenon of G x E interaction which greatly affects yield stability.

The phenotypic performance of a genotype in one location or season is not the same in another season or location. The varied performance of a genotype is influenced by environment (E), genotype (G) and the genotype by environment interaction (GEI) (Manyasa *et al*., 2009). Some of the environmental factors causing varied performance are; variations in temperatures, moisture, humidity, soils, altitude, photoperiods, pests and diseases.

Sorghum is an important crop in the semi-arid areas due to its drought tolerance nature and ability to withstand long periods of high temperatures. The crop can also withstand some levels of water logging. Sorghum confers drought resistance through; its deep and extensive root system which is able to draw water from deeper zones, leaf rolling, epicuticle wax and stomata closure which reduces evapotranspiration, some varieties contain stay green genes which promote photosynthesis during the dry periods (Krupa *et al*., 2017).

According to Ngugi *et al*. (2015), *Striga hermontheca* and water deficit are the main factors limiting sorghum productivity in Kenya. Sorghum yields have remained low at less than $1tha^{-1}$ yet the consumption has been on increase. The low yields in the farmers' fields are mainly attributed to use of unstable landraces or traditional varieties. To remedy this, development of high yielding drought tolerant sorghum hybrids adapted to the semi- arid areas is needed.

In a study on stability of different populations of sorghum hybrids in Makueni by Haussmann *et al*. (2000), the genotype by environment interaction was more important than the genotypic effects. In another study in Kenya, sorghum cane and juice yield were significantly affected by genotype, environment and genotype by

environment interaction (Rono *et al*., 2016). Heterozygosity in sorghum hybrids makes them more stable than their parents (Haussmann *et al*., 2012).

Promising genotypes for release evaluated in one environment in one season or year does not remain productive if the environmental conditions change (Filho *et al*., 2014). Therefore, recommendation of varieties for release remains a challenge due to this instability. Performance of different genotypes under different environments is called Genotype by Environment interaction (Filho *et al*., 2014). According to Mariotti *et al*., (1976), stability of a genotype is associated with the performance of the genotype under varying environmental conditions and its potential to adjust to environmental stimuli. Drought is one of the stresses that cause the instability in sorghum yields across East Africa.

Researchers have recommended use of different methods in the analysis of genotype by environment interaction (GEI) (Cruz and Regazzi, 1997). These methods should be used concurrently to capture the stability and adaptability information in an integrated manner (Filho *et al*., 2014). Some of the proposed methods are; regression coefficient (Finlay and Wilkinson, 1963), sum of squares from regression (Eberhart and Russel, 1966), stability variance (Shukla, 1972), Additive Main Effects and Multiplicative Interaction (AMMI) model (Zobel, 1988) and the GGE biplot method proposed by Yan 1999.

AMMI and GGE biplot analysis have been used in stability and adaptation studies in many crops such as; barley (Jalata, 2011), chickpea (Ezatollah *et al*., 2013), sorghum (Rono *et al*., 2016), maize (Beyene *et al*., 2011; Nzuve *et al*., 2013), pearl millet (Vir and Singh 2016) and Beans (Gebeyehu and Assefa, 2002).

The objective of this study was to identify the grain and biomass yield stability among the sorghum genotypes (hybrids) and the ideal environments for their cultivation in the semi-arid Kenya.

## 4.2 Materials and Methods

### 4.2.1 Experimental sites

The experiments were conducted at two Kenya Agricultural and Livestock Research Organization (KALRO) sites at; Kiboko and Kampi ya Mawe in 2014LR and 2014-

15SR planting seasons. Important characteristics of the test sites are presented in table 4.1 and described in detail under section 3.2.3.

Table 4. 1 Agro climatic conditions of the experimental sites

| Site | Longitude | Latitude | Altitude (m asl) | Rainfall (mm) | TMin (ºC) | TMax (ºC) | Soils |
|---|---|---|---|---|---|---|---|
| Kiboko | $37.75^0$E | $3.15^0$S | 975 | 530 | 14.3 | 35.1 | Sandy loams |
| Kampi ya Mawe | $37^0$40'E | $1^0$57'S | 1125 | 643 | 14 | 31 | Chromic luvisols |

M asl= metres above sea level, mm=millimeters, ºC=Degrees Celsius, TMin=Minimum temperature, TMax=Maximum temperature

*Adopted from Siderius and Muchena, 1977, and Gicheru and Ita, 1987, Manyasa et al., 2009.*

### 4.2.2 Sorghum germplasm

The genetic materials included 34 sorghum hybrids and a check (Seredo) shown in table 4.2. The hybrids were generated using the method described under section 3.2.2.

Table 4. 2 List of sorghum hybrids and a commercial check used in the study

| Entry no | Genotype | Status |
|---|---|---|
| G1 | ICSA 11019 x Hakika | Hybrid |
| G2 | ICSA 11013 x Hakika | Hybrid |
| G3 | ICSA 228 x Hakika | Hybrid |
| G4 | ICSA 11003 x ICSR 160 | Hybrid |
| G5 | ICSA 11033 x ICSR 160 | Hybrid |
| G6 | ICSA 11004 x ICSR 24008 | Hybrid |
| G7 | ICSA 232 x ICSR 24008 | Hybrid |
| G8 | ICSA 29007 x ICSR 24008 | Hybrid |
| G9 | ICSA 29004 x ICSR 24010 | Hybrid |
| G10 | ICSA 29005 x ICSR 24010 | Hybrid |
| G11 | ICSA 29017 x ICSR 24010 | Hybrid |
| G12 | ICSA 101 x ICSR 38 | Hybrid |
| G13 | ICSA 29016 x ICSR 38 | Hybrid |
| G14 | ICSA 75 x ICSR 38 | Hybrid |
| G15 | ICSA 29011 x ICSR 89058 | Hybrid |
| G16 | ICSA 29015 x ICSR 89058 | Hybrid |
| G17 | ICSA 29001 x ICSV 700 | Hybrid |
| G18 | ICSA 29002 x ICSV 700 | Hybrid |
| G19 | ICSA 29003 x ICSV 700 | Hybrid |
| G20 | ICSA 11040 x IESV 91104 DL | Hybrid |
| G21 | ICSA 206 x IESV 91104 DL | Hybrid |
| G22 | ICSA 25002 x IESV 91104 DL | Hybrid |
| G23 | ICSA 12 X IESV 92172 DL | Hybrid |

Table 4. 2 List of sorghum hybrids and a commercial check used in the study

| Entry no | Genotype | Status |
|---|---|---|
| G24 | ICSA 11036 x KARI Mtama 1 | Hybrid |
| G25 | ICSA 11038 x KARI Mtama 1 | Hybrid |
| G26 | ICSA 11039 x KARI Mtama 1 | Hybrid |
| G27 | ICSA 11034 x Macia | Hybrid |
| G28 | ICSA 11035 x Macia | Hybrid |
| G29 | ICSA 11037 x Macia | Hybrid |
| G30 | ICSA 74 x Macia | Hybrid |
| G31 | ATX 623 x Macia | Hybrid |
| G32 | ICSA 11007 x Wahi | Hybrid |
| G33 | ICSA 11016 x Wahi | Hybrid |
| G34 | ICSA 11018 x Wahi | Hybrid |
| G35 | Seredo | OPV Check |

G= Genotype

### 4.2.3 Experimental layout and design

Thirty four sorghum hybrids and a check (Seredo) were sown at KALRO Kiboko and Kampi ya Mawe in 5 by 7 alpha lattice trial design in 3 replications. The sowing at Kiboko was done on 19$^{th}$ May, 2014 (long rains) and on 11$^{th}$ November, 2014 (short rains) while at Kampi ya Mawe the sowing was done on 4$^{th}$ November, 2014 (short rains). The sowing was done in 2 row plots of 4m length with inter row spacing of 0.75m and intra row spacing of 0.20m. Fertilizer was applied at the rate of 46kg $P_2O_5$/ha and 54kgN/ha using Di-ammonium phosphate (DAP) at planting and Urea at 40 days after emergence.

Plants were thinned to 1 plant per hill at 21 days after emergence. First weeding was done after thinning then second weeding was done after top dressing. Confidor liquid (Imidacloprid 200SL 17.8%w/w) systemic pesticide was applied to prevent damage from chaffer grubs and shootfly. Bulldock granules (Cyfluthrin 5g/Kg) were placed in the funnels of the plants during active vegetative growth to control stalk borers. The trial at Kiboko 2014LR was irrigated 8 times with each irrigation providing 30mm of water. Weather parameters rainfall amount, humidity and temperature were monitored on daily basis and data collected as shown in Appendix 4.

### 4.2.4 Data Collection

Data collection for grain yield and biomass yield is highlighted in Table 4.3. Data collection procedures were followed as described in IBPGR and ICRISAT (1993).

Table 4. 3 Description of the traits and how they were measured

| Trait | Description and scoring of the trait |
|---|---|
| Fresh biomass yield ($tha^{-1}$) | Net plot weight of the harvested stalks converted to $tha^{-1}$ |
| Grain yield ($tha^{-1}$) | Net plot weight of the threshed sorghum grain at 12.5% moisture content converted to $tha^{-1}$ |

### 4.2.5 Data Analysis

#### 4.2.5.1 Analysis of Variance for yield stability

Analysis of variance (ANOVA), means, and variances for each trait were carried out in alpha lattice design using Genstat v18.1 (Table 4.4; Equation 4.1). Analysis of variance was done for each environment and a combined analysis for all the sites. The results from the three environments were subjected to combined analysis of variance (ANOVA) to determine the G x E effects. Both analyses were done in GenStat v18.1 (VSN International, 2011). In this model, the genotypic effects were fixed and environment effects random (Piepho, 1994).

Equation 4. 1: Analysis of variance of a lattice design by Bondari (2013)

$$Y_{ijk} = \mu + G_i + E_j + GE_{ij} + B_{jk} + g_{ijk}$$

Where; $Y_{ijk}$ is the yield of the $i^{th}$ genotype in the $k^{th}$ block of the $j^{th}$ environment, $\mu$ is the mean, $G_i$ is the effect of the $i^{th}$ genotype, $E_j$ is the effect of the $j^{th}$ environment, $GE_{ij}$ is the interaction of the $i^{th}$ genotype with the $j^{th}$ Environment, $B_{jk}$ is the effect of the $k^{th}$ block in the $j^{th}$ environment, and $g_{ijk}$ is the random error (Bondari, 2013).

Table 4. 4 Outline of the combined analysis of variance for yield

| Source of variation | DF | SS | MS | (VR) | Fpr |
|---|---|---|---|---|---|
| Environment (E) | e-1 | $SS_E$ | $MS_E$ | $MS_E/ MS_e$ | |
| Replication (R) | r-1 | $SS_R$ | $MS_R$ | $MS_R/ MS_e$ | |
| Genotype (G) | a-1 | $SS_G$ | $MS_G$ | $M_{SG}/ MS_e$ | |
| GXE | (e-1)(a-1) | $SS_{GE}$ | $MS_{GE}$ | $MS_{GE}/ MS_e$ | |
| Error (e) | By subtraction | $SS_e$ | $MS_e$ | | |
| Total | (aer-1) | | | | |

DF=Degrees of freedom, SS=Sum of squares, MS= Mean Sum of Squares, Variance Ratio, GXE=genotype by environment interaction

#### 4.2.5.2 Additive Main Effect and Multiplicative Interaction (AMMI) Analysis

Genotype by environment (G x E) effects were evaluated using the AMMI model which combines the ANOVA and the first 2 Principal components (PCA). To carry out the stability analysis, an equation proposed by Purchase (1997) was used (Equation 4.2).

Equation 4. 2: AMMI Stability value formula (Purchase, 1997).

$$ASV = \sqrt{\left[\frac{SS_{IPCA1}}{SS_{IPCA2}}(IPCA1_{Score})\right]^2 + (IPCA2_{Score})^2}$$

Where: ASV=AMMI stability value; IPCA1= Interaction principal component analysis 1; IPCA2= Interaction principal component analysis 2; $SS_{IPCA1}$ = Sum of squares for interaction principal component analysis 1; $SS_{IPCA2}$ = Sum of squares for interaction principal component analysis 2.

#### 4.2.5.3 GGE biplot analysis

GGE biplots were constructed to display the G x E interaction, the stable genotypes, the ideal environments for cultivation and the best genotype per environment as shown in equation 4.3 (Rao, 2011). The GGE-biplot analysis was performed on summarized means estimated from analysis of variance from the 3 environments. The GGE biplots were constructed using GenStat v18.1 software.

Equation 4. 3 The GGE model (Rao, 2011).

$$Y_{ij} - \mu - B_j = a_i + j_{ij}$$

Where; $Y_{ij}$ is the measured mean of $i^{th}$ genotype in $j^{th}$ environment, $\mu$ is the grand mean, $a_i$ is the main effect of $i^{th}$ genotype, *ßj* is the main effect of $j^{th}$ environment, $j_{ij}$ is interaction between $i^{th}$ genotype and $j^{th}$ environment.

### 4.3 Results

#### 4.3.1 Weather characteristics of the study environments

Monthly rainfall and temperature data recorded in the three study environments is shown in Table 4.5. The total amount of water provided to Kiboko 2014LR environment was approximately 286.2mm (26.2mm rainfall and 240mm from irrigation). Kiboko and Kampi ya Mawe 2014-15SR received 463.5mm and 366.9mm

of rainfall respectively. The total rainfall amount varied greatly across the environments with these areas receiving most of the rainfall before flowering (most hybrids flowered in January 2015). There was moderate variation in the mean minimum and mean maximum temperature across the three environments. Kiboko 2014-15SR had the highest mean maximum temperature whereas Kampi ya Mawe 2014-15 had the lowest mean minimum temperature.

Table 4. 5 Crop growing season temperature and rainfall amount

| Environment | Year | Month | Tmax (°C) | Tmin (°C) | Rain (mm) | Avg. Tmax°C | Avg. Tmin°C | Total Rain (mm) |
|---|---|---|---|---|---|---|---|---|
| | 2014 | May | 28 | 18 | 21.8 | 27.6 | 16.8 | 26.2 |
| **Kiboko 2014LR** | 2014 | June | 27 | 17 | 2.9 | | | |
| | 2014 | July | 27 | 16 | 0 | | | |
| | 2014 | August | 28 | 16 | 0 | | | |
| | 2014 | September | 28 | 17 | 1.5 | | | |
| | 2014 | November | 31 | 18.7 | 147 | 31.8 | 17.8 | 463.5 |
| **Kiboko 2014-15SR** | 2014 | December | 29.6 | 18.4 | 199.5 | | | |
| | 2015 | January | 32.1 | 16.2 | 0 | | | |
| | 2015 | February | 33.5 | 17.9 | 52.5 | | | |
| | 2015 | March | 32.6 | 17.9 | 64.5 | | | |
| **KYM 2014-15SR** | 2014 | November | 28 | 16 | 161.6 | 29.7 | 14.1 | 366.9 |
| | 2014 | December | 27 | 10.5 | 166.3 | | | |
| | 2015 | January | 30 | 16 | 20.3 | | | |
| | 2015 | February | 32 | - | 0 | | | |
| | 2015 | March | 31.3 | - | 18.7 | | | |

Tmax= average monthly maximum temperature, Tmin= average monthly minimum temperature, Avg. =average, SR=Short rains season, LR=Long rains season, KYM= Kampi ya Mawe

### 4.3.2 Analysis of variance for grain and biomass yield

The combined analysis of variance showed that the grain and biomass yield of sorghum hybrids were significantly ($p<0.01$) affected by genotype, environment and genotype by environment interaction (Tables 4.6 and 4.7). Environment contributed 32.8% and 13.3% of the total variation in grain yield and biomass yield respectively.

Genotypes contributed to 22.2% and 18.1% variation in grain and biomass yield respectively. GXE contributed 27.7% and 18.1% of the total variation in biomass and grain yield respectively.

Table 4. 6 Analysis of variance for grain yield of 34 sorghum hybrids and a check

| Source of variation | D.F. | s.s. | m.s. | v.r. | F pr. | % Variation explained |
|---|---|---|---|---|---|---|
| Rep | 2 | 17.5 | 8.8 | 9.1 | | |
| Genotype (G) | 34 | 157.2 | 4.6 | 4.8 | <.001 | 22.2 |
| Environment (E) | 2 | 232.2 | 116.1 | 120.5 | <.001 | 32.8 |
| G X E | 67 | 128.4 | 1.9 | 2 | <.001 | 18.1 |
| Error | 202 | 194.6 | 1 | | | |
| Total | 307 | 708.1 | | | | |

D.F-Degrees of freedom, ss-sum of squares, ms- mean sum of squares, vr-variance ratio, coefficient of variation=36.8%, G X E=Genotype by Environment Interaction.

Table 4. 7 Analysis of variance for biomass yield of 34 sorghum hybrids and a check

| Source of variation | D.F. | s.s. | m.s. | v.r. | F pr. | % Variation explained |
|---|---|---|---|---|---|---|
| Rep | 2 | 138.6 | 69.3 | | | |
| Environment (E) | 2 | 1305.8 | 652.9 | 34.7 | <.001 | 13.3 |
| Genotype (G) | 34 | 1777.6 | 52.3 | 2.78 | <.001 | 18.1 |
| GXE | 68 | 2712.8 | 39.9 | 2.12 | <.001 | 27.7 |
| Error | 207 | 3895 | 18.8 | | | |
| Total | 313 | 9811 | | | | |

D.F-Degrees of freedom, ss-sum of squares, ms- mean sum of squares, vr-variance ratio, coefficient of variation=36.8%, G X E=Genotype by Environment Interaction.

### 4.3.2 The AMMI analyses of variance for 34 sorghum hybrids and a check for grain yield

The genotypes, environments and genotype by environment interaction (GEI) effects were significant in the AMMI analysis of variance (Tables 4.8 and 4.9). The main effect of Genotype (G) and environment (E) accounted for 24.4% and 21% of the variation in grain yield respectively.

The main effects of genotype and environment accounted for 26.3% and 24.6% of variation in biomass yield. Interaction accounted for 19.1% and 26.2% of the total variation in grain and biomass yield respectively. The first principal component (IPCA1) captured 11.1% of interaction sum of squares whereas IPCA 2 captured 7.9% of GEI for grain yield. The IPCA 1 and IPCA 2 captured 20.6% and 5.6% GEI sum of squares respectively for biomass yield.

Table 4. 8 AMMI analysis of variance for grain yield of 34 sorghum hybrids and a check

| Source | d.f. | s.s. | m.s. | v.r. | % of total variation |
|---|---|---|---|---|---|
| Total | 314 | 683.1 | 2.176 | | |
| Treatments | 104 | 441.1 | 4.242** | 4.24 | 64.6 |
| Genotypes | 34 | 167.1 | 4.915** | 4.91 | 24.5 |
| Environments | 2 | 143.5 | 71.767** | 9.8 | 21.0 |
| Block | 6 | 43.9 | 7.322** | 7.32 | 6.4 |
| Interactions | 67 | 130.5 | 1.948** | 1.95 | 19.1 |
| IPCA 1 | 35 | 76.1 | 2.176** | 2.17 | 11.1 |
| IPCA 2 | 33 | 54.3 | 1.647 | 1.65 | 7.9 |
| Residuals | <0.001 | 0 | 0 | 0 | |
| Error | 198 | 198.1 | 1 | | |

NB: the block source of variation refers to blocks within environments
**= significant at p<0.01

Table 4. 9 AMMI analysis of variance for biomass yield of 34 sorghum hybrids and a check

| Source | df | SS | MS | VR | % of total variation |
|---|---|---|---|---|---|
| Total | 314 | 6298 | 20.1 | | |
| Treatments | 104 | 4860 | 46.7** | 7.24 | 77.2 |
| Genotypes | 34 | 1658 | 48.8** | 7.55 | 26.3 |
| Environments | 2 | 1551 | 775.7** | 38.59 | 24.6 |
| Block | 6 | 121 | 20.1** | 3.11 | 1.9 |
| Interactions | 68 | 1651 | 24.3** | 3.76 | 26.2 |
| IPCA 1 | 35 | 1296 | 37** | 5.74 | 20.6 |
| IPCA 2 | 33 | 354 | 10.7* | 1.66 | 5.6 |
| Residuals | 0 | 0 | 0 | 0 | |
| Error | 204 | 1317 | 6.5 | | |

### 4.3.3 AMMI Biplot analysis

AMMI biplot summarizes the information on main and interaction effects of genotypes and environments simultaneously (Figure 4.1). The IPCA 1 scores of genotypes and environment were plotted against their respective means in AMMI 1 biplot. The IPCA1 scores are shown on the y- axis and the genotype and environment means are shown on the x- axis (Figure 4.1). In the AMMI 2 biplot, the IPCA 1 and IPCA 2 scores of genotypes and environments were plotted against each other (Figure 4.2).

Genotypes or environments on the right side of the biplot beyond the midpoint of the perpendicular line have higher yields than the ones on the left side of the

perpendicular line (Grand mean). Genotypes G31 (ATX 623 x Macia), G6 (ICSA 11004 x ICSR 24008), G5 (ICSA 11033 x ICSR 160), G15 (ICSA 29011 x ICSR 89058) and G10 (ICSA 29005 x ICSR 24010) were superior grain yielders with high additive main effects (Figure 4.1).

Genotypes, G33 (ICSA 11016 x Wahi), G29 (ICSA 11037 x Macia), G27 (ICSA 11034 x Macia) and G6 (ICSA 11004 x ICSR 24008) recorded IPCA 1 scores close to Zero hence were the most stable. However, G33 gave below average yields (Figure 4.1). Genotype G18 (ICSA 29002 x ICSV 700) and G8 (ICSA 29007 x ICSR 24008) were well adapted to Kiboko 2014-15SR, genotypes G26 (ICSA 11039 x KARI Mtama 1) and G21 (ICSA 206 x IESV 91104 DL) were adapted to KYM 2014/15SR and genotypes G1 (ICSA 11019 x Hakika) and G15 (ICSA 29011 x ICSR 89058) were adapted to Kiboko 2014LR (Figure 4.2).

Figure 4. 1 AMMI 1 biplot for grain yield (tha$^{-1}$) of 34 sorghum hybrids (G) at three environments (E) using genotypic and environmental scores

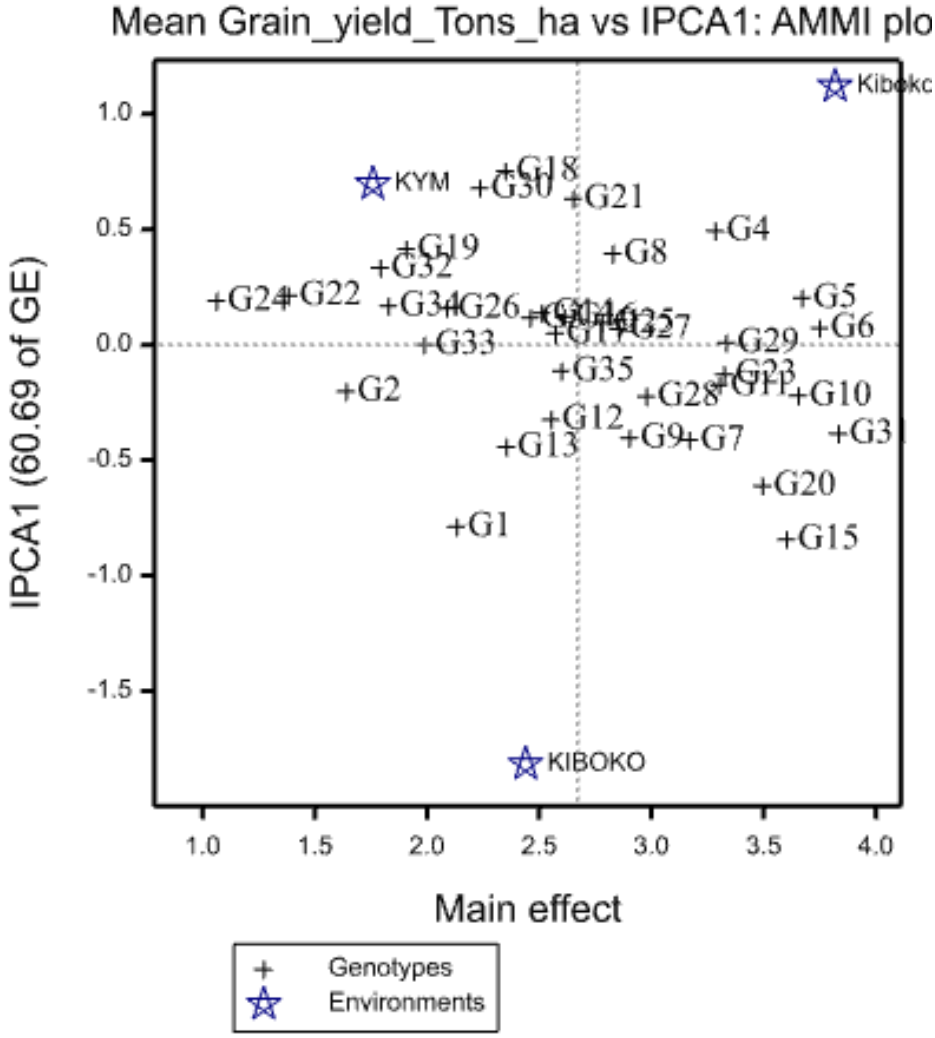
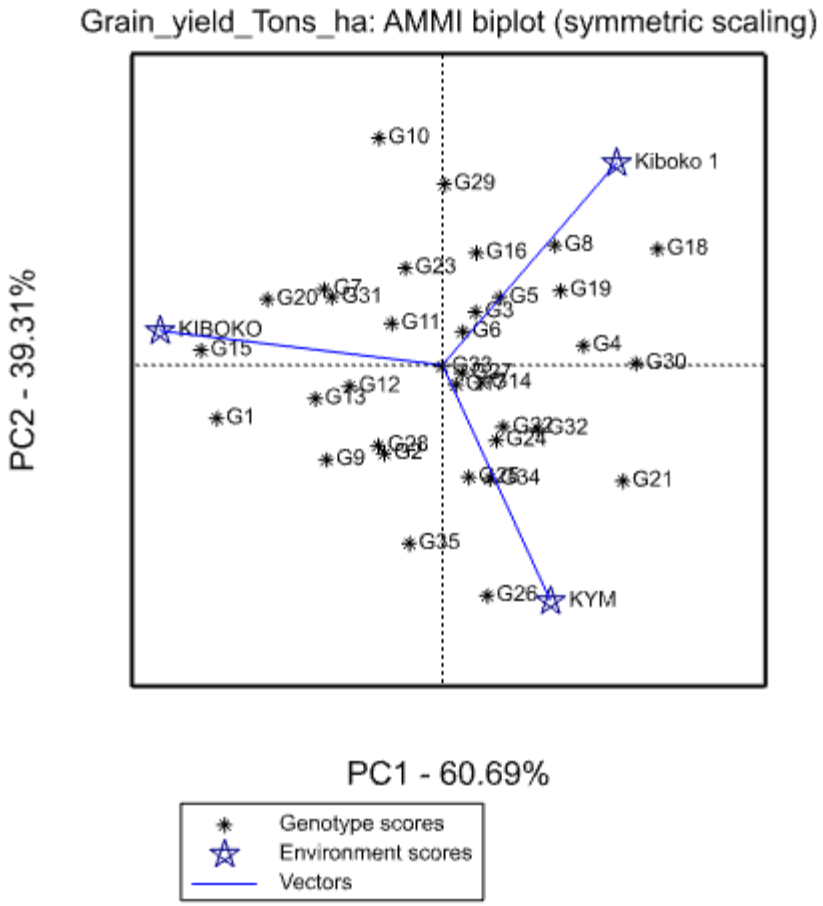


Figure 4. 2 AMMI 2 biplot for grain yield (tha$^{-1}$) of 34 sorghum genotypes (G) at three environments (E) using genotypic and environmental scores.




### 4.3.4 AMMI stability value (ASV) analysis

AMMI stability values combine the two PCAs (PCA1 and PCA 2) where, the genotype with the lowest ASV value is the most stable. According to the ranking in Tables 4.10 and 4.11, the genotypes with the lowest ASV values for grain yield were G33 (ICSA 11016 x Wahi), G17 (ICSA 29001 x ICSV 700), G27 (ICSA 11034 x Macia) and G6 (ICSA 11004 x ICSR 24008) with ASV value of 0.064, 0.101 0.125 and 0.147 respectively. Lowest ASV values for biomass yield were recorded in G29 (ICSA 11037 x Macia), G25 (ICSA 11038 x KARI Mtama 1), G12 (ICSA 101 x ICSR 38) and G6 (ICSA 11004 x ICSR 24008). The most unstable genotypes for grain yield were, G15 (ICSA 29011 x ICSR 89058) and G1 (ICSA 11019 x Hakika) with ASV scores of 1.159 and 1.134 respectively (Table 4.10). The most unstable hybrids for biomass yield were, G18 (ICSA 29002 x ICSV 700) and G33 (ICSA 11016 x Wahi) as shown in Table 4.11.

Table 4. 10 AMMI stability values for grain yield in 35 sorghum genotypes in three environments between 2014 and 2015

| Genotype | Mean | IPCAg1 | IPCAg2 | ASV | Rank |
|---|---|---|---|---|---|
| G33 | 2.038 | 0.00045 | -0.06396 | 0.064 | 1 |
| G17 | 2.718 | 0.05623 | 0.06306 | 0.101 | 2 |
| G27 | 3.02 | 0.0832 | 0.04641 | 0.125 | 3 |
| G6 | 3.973 | 0.10318 | -0.02428 | 0.147 | 4 |
| G14 | 2.658 | 0.14214 | 0.04406 | 0.204 | 5 |
| G3 | 2.565 | 0.07175 | -0.23466 | 0.255 | 6 |
| G24 | 1.116 | 0.16217 | 0.11641 | 0.255 | 7 |
| G11 | 3.468 | -0.17734 | -0.08657 | 0.263 | 8 |
| G22 | 1.459 | 0.19327 | 0.09607 | 0.287 | 9 |
| G5 | 3.879 | 0.20944 | -0.17275 | 0.341 | 10 |
| G2 | 1.726 | -0.20033 | 0.25006 | 0.376 | 11 |
| G23 | 3.466 | -0.16364 | -0.30246 | 0.380 | 12 |
| G28 | 3.176 | -0.16141 | 0.35733 | 0.423 | 13 |
| G34 | 1.967 | 0.20297 | 0.3452 | 0.447 | 14 |
| G16 | 2.698 | 0.04381 | -0.44912 | 0.453 | 15 |
| G12 | 2.675 | -0.32366 | 0.09026 | 0.462 | 16 |
| G32 | 1.912 | 0.33634 | 0.13696 | 0.491 | 17 |
| G25 | 2.997 | 0.17366 | 0.44067 | 0.503 | 18 |
| G31 | 4.017 | -0.38167 | -0.12147 | 0.549 | 19 |
| G19 | 1.971 | 0.33385 | -0.39235 | 0.611 | 20 |
| G9 | 3.089 | -0.33926 | 0.41472 | 0.631 | 21 |
| G13 | 2.458 | -0.44657 | 0.12399 | 0.638 | 22 |
| G29 | 3.439 | -0.07969 | -0.63533 | 0.645 | 23 |
| G8 | 2.947 | 0.32888 | -0.47216 | 0.660 | 24 |
| G7 | 3.29 | -0.4481 | -0.21931 | 0.665 | 25 |
| G35 | 2.821 | -0.00386 | 0.69227 | 0.692 | 26 |
| G4 | 3.502 | 0.51947 | -0.04262 | 0.729 | 27 |
| G20 | 3.636 | -0.62763 | -0.13461 | 0.890 | 28 |
| G10 | 3.75 | -0.32847 | -0.7679 | 0.895 | 29 |
| G26 | 2.311 | 0.28245 | 0.82564 | 0.916 | 30 |
| G30 | 2.382 | 0.66758 | -0.09176 | 0.940 | 31 |
| G18 | 2.45 | 0.67362 | -0.52875 | 1.082 | 32 |
| G21 | 2.893 | 0.71854 | 0.40965 | 1.087 | 33 |
| G1 | 2.206 | -0.7967 | 0.19928 | 1.134 | 34 |
| G15 | 3.765 | -0.82466 | 0.08801 | 1.159 | 35 |

Table 4. 11 AMMI stability values for biomass yield in 35 sorghum genotypes in three environments between 2014 and 2015

| Genotype | Means | IPCAg[1] | IPCAg[2] | ASV | Rank |
|---|---|---|---|---|---|
| G29 | 6.857 | -0.044 | -0.199 | 0.256 | 1 |
| G25 | 10.784 | 0.029 | -0.306 | 0.323 | 2 |
| G12 | 7.482 | -0.055 | -0.309 | 0.368 | 3 |
| G6 | 6.926 | 0.150 | 0.583 | 0.802 | 4 |
| G35 | 7.32 | 0.203 | 0.455 | 0.872 | 5 |
| G1 | 11.549 | -0.254 | -0.127 | 0.940 | 6 |
| G4 | 6.901 | 0.259 | 0.359 | 1.015 | 7 |
| G19 | 11.716 | -0.291 | -0.397 | 1.136 | 8 |
| G27 | 8.094 | -0.350 | -0.317 | 1.321 | 9 |
| G9 | 10.829 | 0.353 | -0.307 | 1.328 | 10 |
| G7 | 8.531 | 0.345 | 0.562 | 1.383 | 11 |
| G11 | 12.223 | 0.073 | -1.555 | 1.578 | 12 |
| G34 | 7.691 | -0.452 | -0.245 | 1.673 | 13 |
| G14 | 5.704 | 0.448 | 0.358 | 1.678 | 14 |
| G28 | 11.852 | 0.397 | 1.169 | 1.864 | 15 |
| G3 | 11.137 | -0.514 | 0.483 | 1.944 | 16 |
| G23 | 7.494 | 0.540 | -0.523 | 2.045 | 17 |
| G2 | 8.056 | -0.562 | 0.623 | 2.150 | 18 |
| G21 | 6.922 | -0.561 | 0.662 | 2.159 | 19 |
| G16 | 4.241 | 0.542 | 0.920 | 2.187 | 20 |
| G20 | 11.49 | 0.580 | -0.617 | 2.213 | 21 |
| G10 | 10.802 | 0.571 | -0.975 | 2.307 | 22 |
| G26 | 7.829 | -0.650 | 0.300 | 2.399 | 23 |
| G5 | 6.278 | 0.691 | 0.274 | 2.546 | 24 |
| G8 | 6.968 | -0.711 | 0.221 | 2.614 | 25 |
| G17 | 11.176 | -0.901 | -0.310 | 3.313 | 26 |
| G32 | 7.642 | -0.965 | 0.124 | 3.535 | 27 |
| G24 | 13.765 | 0.981 | -0.665 | 3.652 | 28 |
| G13 | 6.42 | 1.078 | 0.331 | 3.960 | 29 |
| G31 | 10.259 | 1.120 | -0.630 | 4.150 | 30 |
| G15 | 8.488 | 1.148 | 0.497 | 4.230 | 31 |
| G30 | 10.975 | -1.320 | -0.182 | 4.834 | 32 |
| G22 | 11.691 | 1.476 | 0.028 | 5.403 | 33 |
| G33 | 8.154 | -1.535 | 0.170 | 5.623 | 34 |
| G18 | 11.566 | -1.817 | -0.455 | 6.668 | 35 |

G=Genotype, ASV=AMMI stability values, IPCA1= interactive principal components analysis 1, IPCA2= interactive principal components analysis 2

### 4.3.5 GGE Biplot analysis of 35 sorghum genotypes evaluated in three environments

#### 4.3.5.1 Visualization of which won where pattern in multi environments

The genotypes at the vertices of the polygon delineate the best performing genotypes in one or more environments where they were tested. A polygon was generated which connected the genotypes with the longest vectors located furthest from the biplot origin. Rays are lines that divide the polygon into sectors and are perpendicular to the sides of the polygon.

In the current study, the rays divided the polygon into 8 sectors. The winning genotypes for each sector are situated at the vertex. In the current study, the best genotypes for grain yield at Kiboko 2014-15 and KYM 2014-15 were G5 (ICSA 11033 x ICSR 160) and G15 (ICSA 29011 x ICSR 89058) with G29 (ICSA 11037 x Macia) and G6 (ICSA 11004 x ICSR 24008) yielding higher in these environments. Genotypes G15 (ICSA 29011 x ICSR 89058) and G31 (ATX 623 x Macia) were the best genotypes in KBK 2014 with G28 (ICSA 11035 x Macia), G7 (ICSA 232 x ICSR 24008), G9 (ICSA 29004 x ICSR 24010), and G20 (ICSA 11040 x IESV 91104 DL) recording better yields in this location (Figure 4.3).

Two mega environments were delineated by the biplot with respect to biomass yield; KYM 2014-15SR and KBK 2014LR forming mega environment 1 and KBK 2014-15SR forming the 2$^{nd}$ mega environment (Figure 4.4). The best genotype for biomass yield at mega environment 1 was 18 (ICSA 29002 x ICSV 700) whereas for mega environment 2, the best genotypes were 22 (ICSA 25002 x IESV 91104 DL) and 24 (ICSA 11036 x KARI Mtama 1).

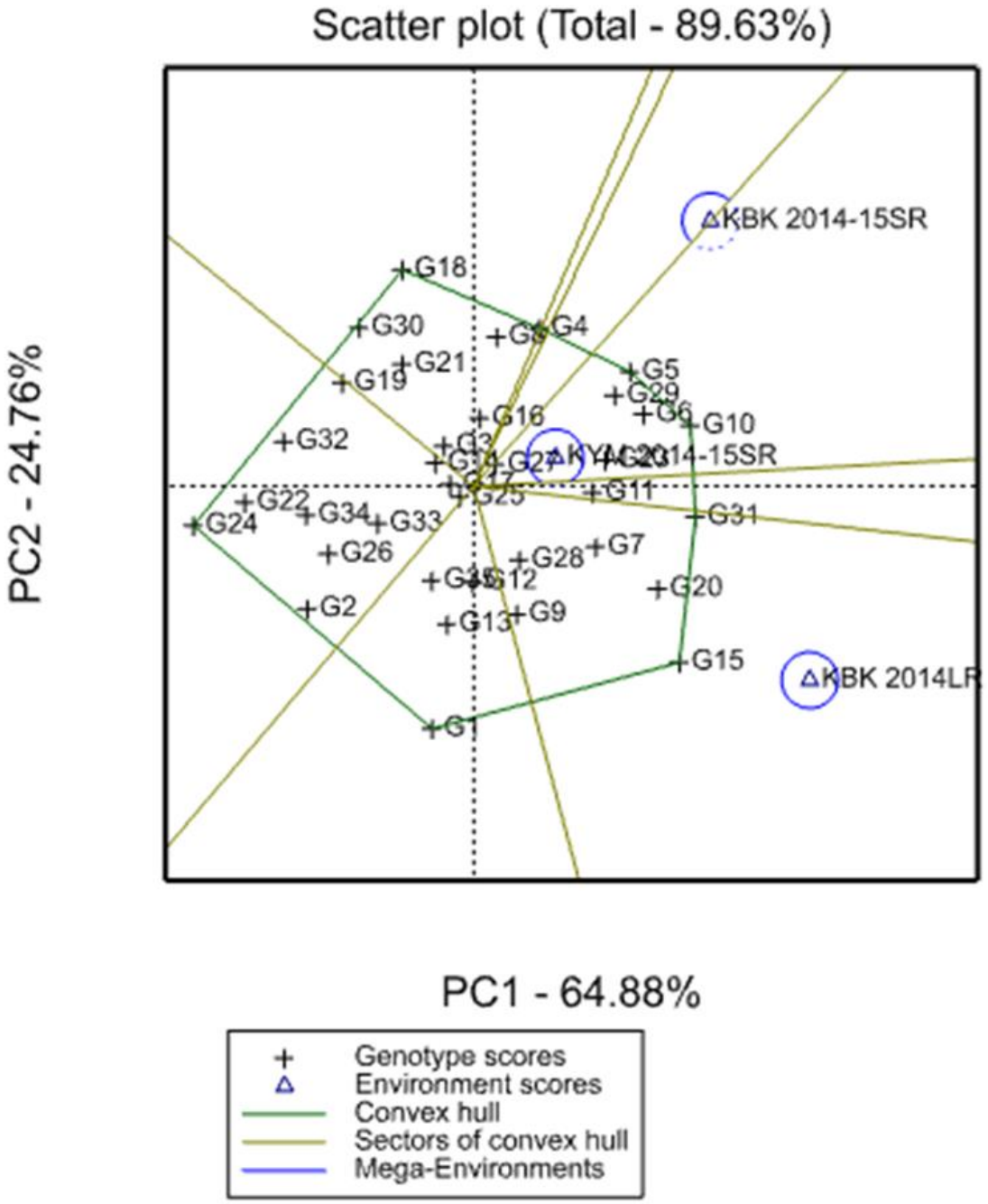



Figure 4. 3 Which won where and mega environment delineation GGE biplot for grain yield of 35 sorghum genotypes evaluated in three environments in 2014 and 2014/15 season

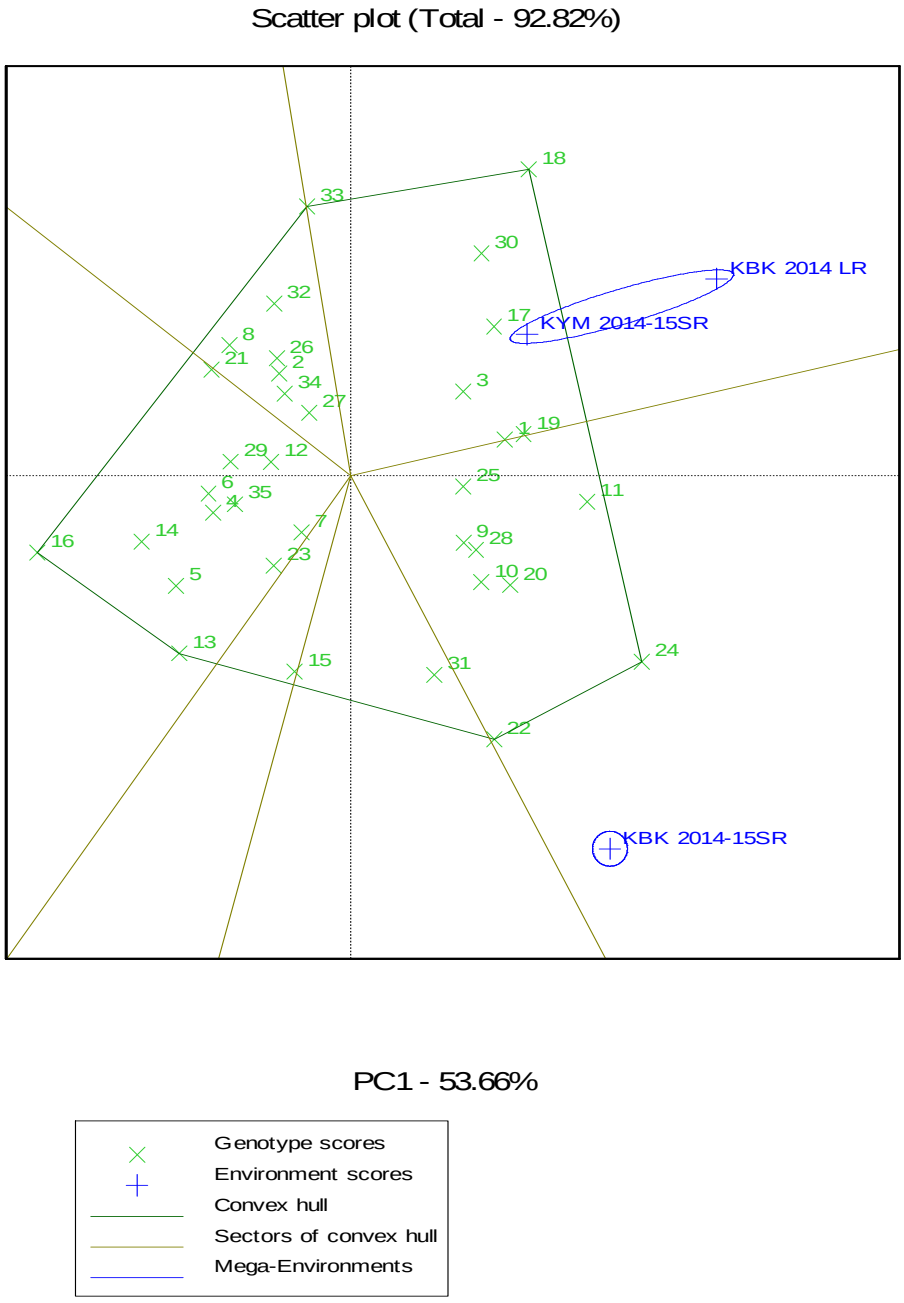



Figure 4. 4 Which won where and mega environment delineation GGE biplot for biomass yield of 35 sorghum genotypes evaluated in three environments in 2014 and 2014/15 season

### 4.3.5.2 Relationship among test environments for their discriminating ability on sorghum hybrids

The environment vector view of the GGE biplot (Figures 4.5 and 4.6) describes the relationship between test environments. The biplots explained 89.6% and 92.8% of the total variation in grain and biomass yield respectively. From the current study, the relationship between environments KBK 2014-15 and KYM 2014-15 was positive for grain yield. The angle between KBK 2014 and KBK 2014-15 is close to 90$^{o}$ indicating

that there was no correlation between them (Figure 4.5). The biplot for biomass yield shows that KBK 2014LR was positively correlated with KYM 2014-15SR whereas KBK 2014-15 had no correlation with the other two environments (Figure 4.6).

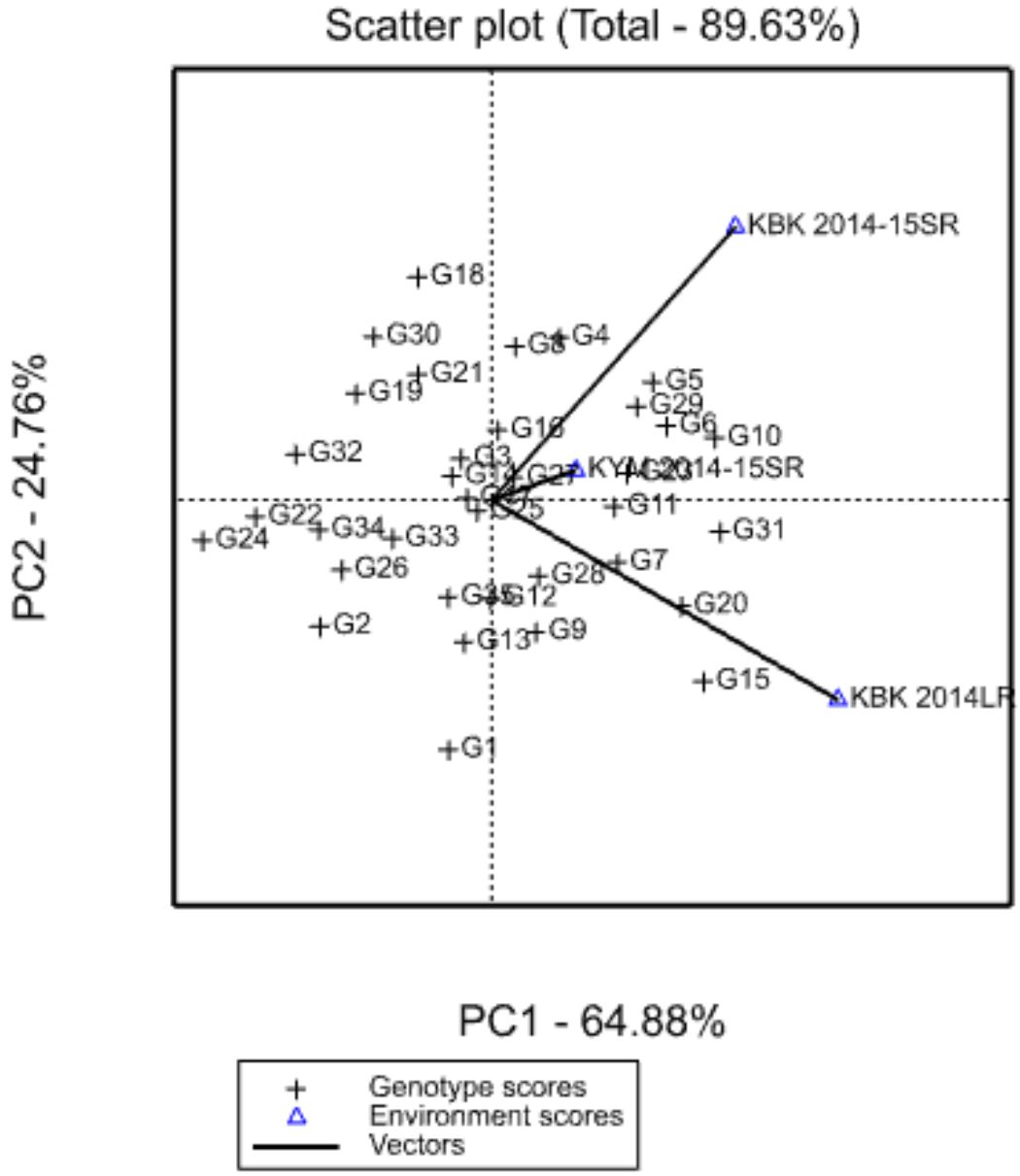



Figure 4. 5 GGE biplot for grain yield based on environment focused scaling for 35 sorghum genotypes evaluated in three environments

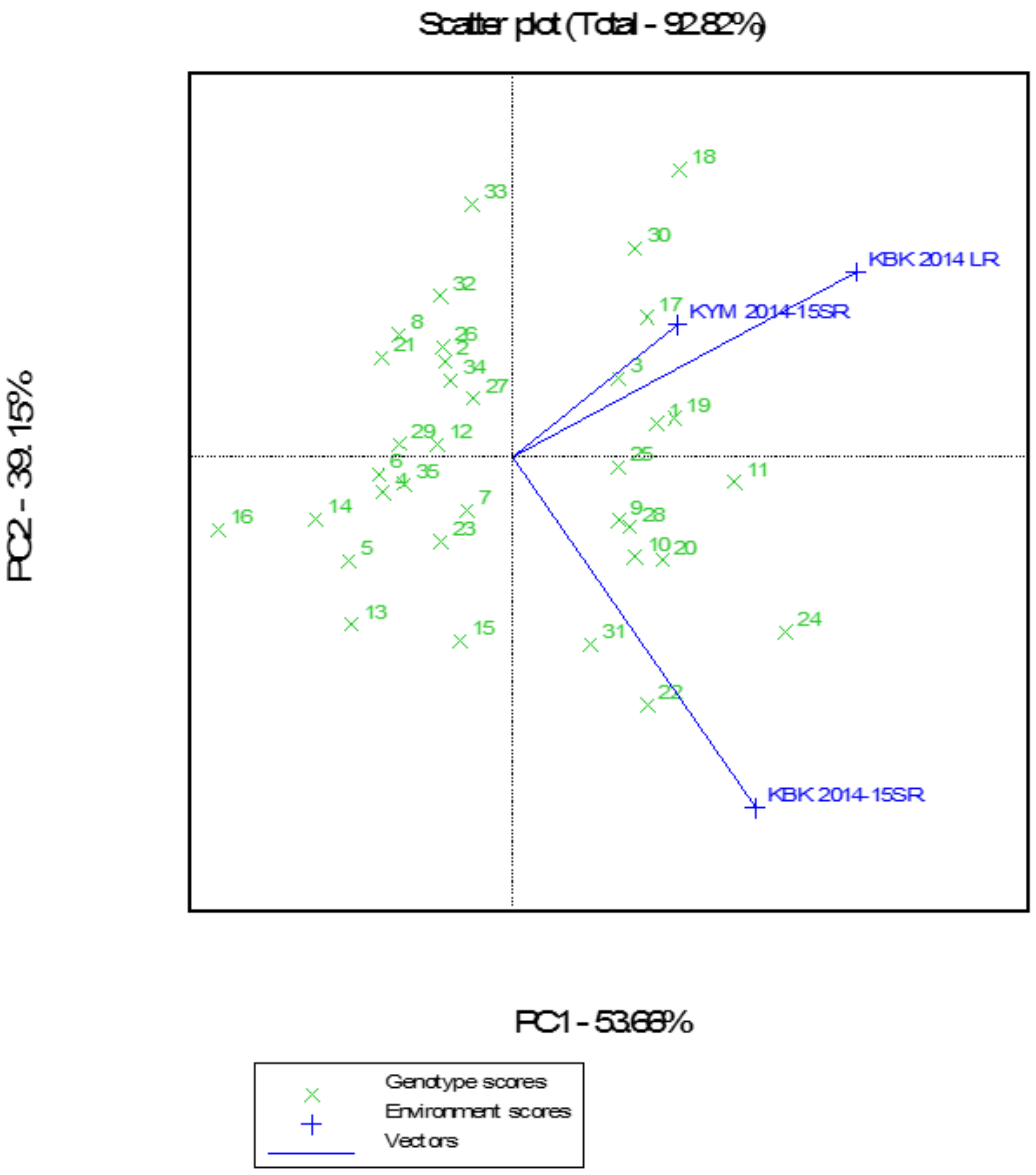



Figure 4. 6 GGE biplot for biomass yield based on environment focused scaling for 35 sorghum genotypes evaluated in three environments

#### 4.3.5.3 Mean performance and stability of sorghum genotypes relative to the ideal genotype

In the GGE biplot, ideal genotypes are stable with a high mean performance and are situated at the center of the concentric circles. Concentric circles were drawn to help visualize the distance between each genotype with the ideal genotype and the genotypes closer to the ideal genotype are desirable. Ideal genotype has large PC1 score (high grain yield) and small PC2 score (high stability). The genotype at the centre of the concentric circles in the GGE biplot have zero contribution to both G and GE whereas the ones situated furthest have the largest contribution to G and GE.

In the current study, genotypes G10 (ICSA 29005 x ICSR 24010), G6 (ICSA 11004 x ICSR 24008), G5 (ICSA 11033 x ICSR 160), G31 (ATX 623 x Macia), and G29 (ICSA 11037 x Macia) were the most desirable for grain yield (Figure 4.7). The most undesirable genotypes for grain yield were G24 (ICSA 11036 x KARI Mtama 1), G22 (ICSA 25002 x IESV 91104 DL), G2 (ICSA 11013 x Hakika), G32 (ICSA 11007 x Wahi), and G34 (ICSA 11018 x Wahi).

Genotypes 11 (ICSA 29017 x ICSR 24010), 19 (ICSA 29003 x ICSV 700), 24 (ICSA 11036 x KARI Mtama 1) and 1 (ICSA 11019 x Hakika) were the most desirable genotypes for biomass yield (Figure 4.8). The most undesirable genotypes for biomass yield were; 16 (ICSA 29015 x ICSR 89058), 14 (ICSA 75 x ICSR 38), 13 (ICSA 29016 x ICSR 38) and 5 (ICSA 11033 x ICSR 160).

#### 4.3.5.4 Evaluation of sorghum growing environments relative to ideal environment

In the current study, the GGE biplot in figure 4.9 shows KBK 2014LR and KBK 2014-15SR as the most desirable environments for evaluating sorghum genotypes for grain yield. The two environments are located next to the ideal environment. An Ideal environment is situated next to the origin of the biplot hence the most discriminating to the genotypes yet most representative of the other environments. The most ideal environment for selecting sorghum hybrids for biomass yield was KBK 2014LR (Figure 4.10).

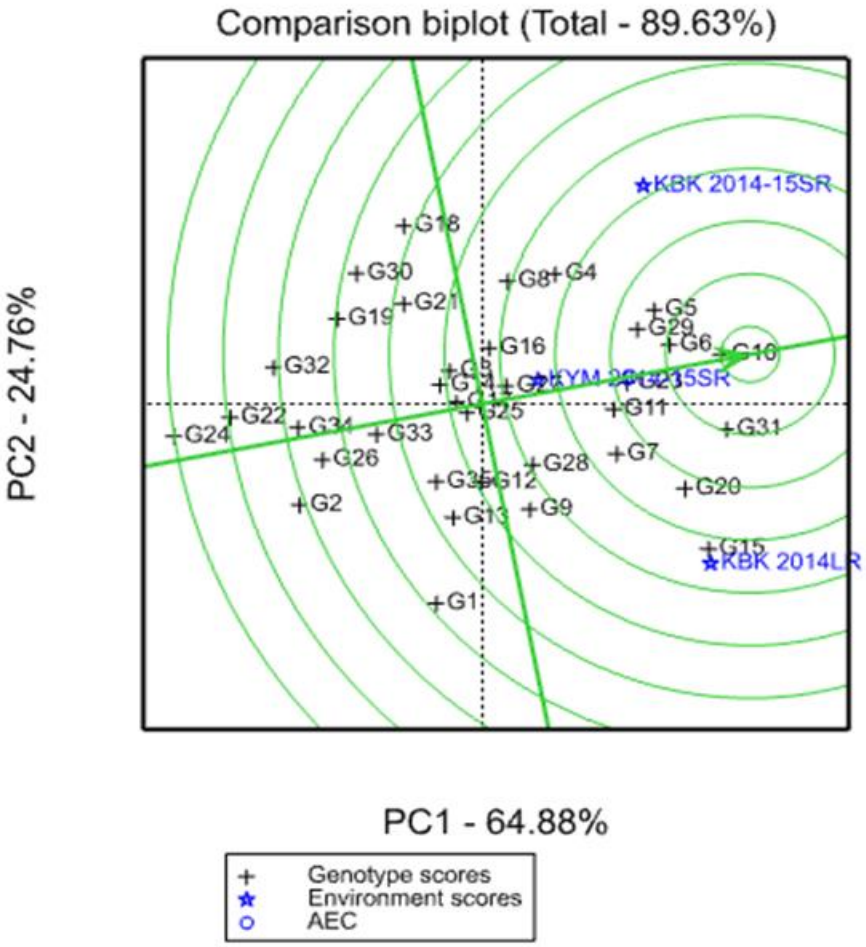



Figure 4. 7 GGE biplot based on genotype focused scaling for comparison of genotypes to the ideal genotype for grain yield in 35 sorghum genotypes evaluated in three environments

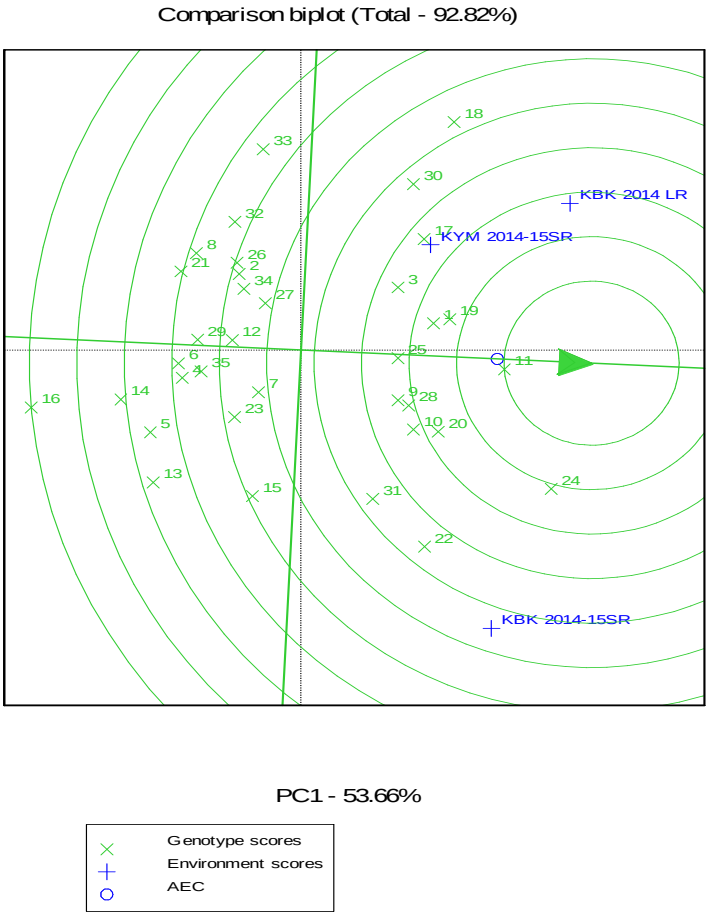



Figure 4. 8 GGE biplot based on genotype focused scaling for comparison of genotypes to the ideal genotype for biomass yield in 35 sorghum genotypes evaluated in three environments

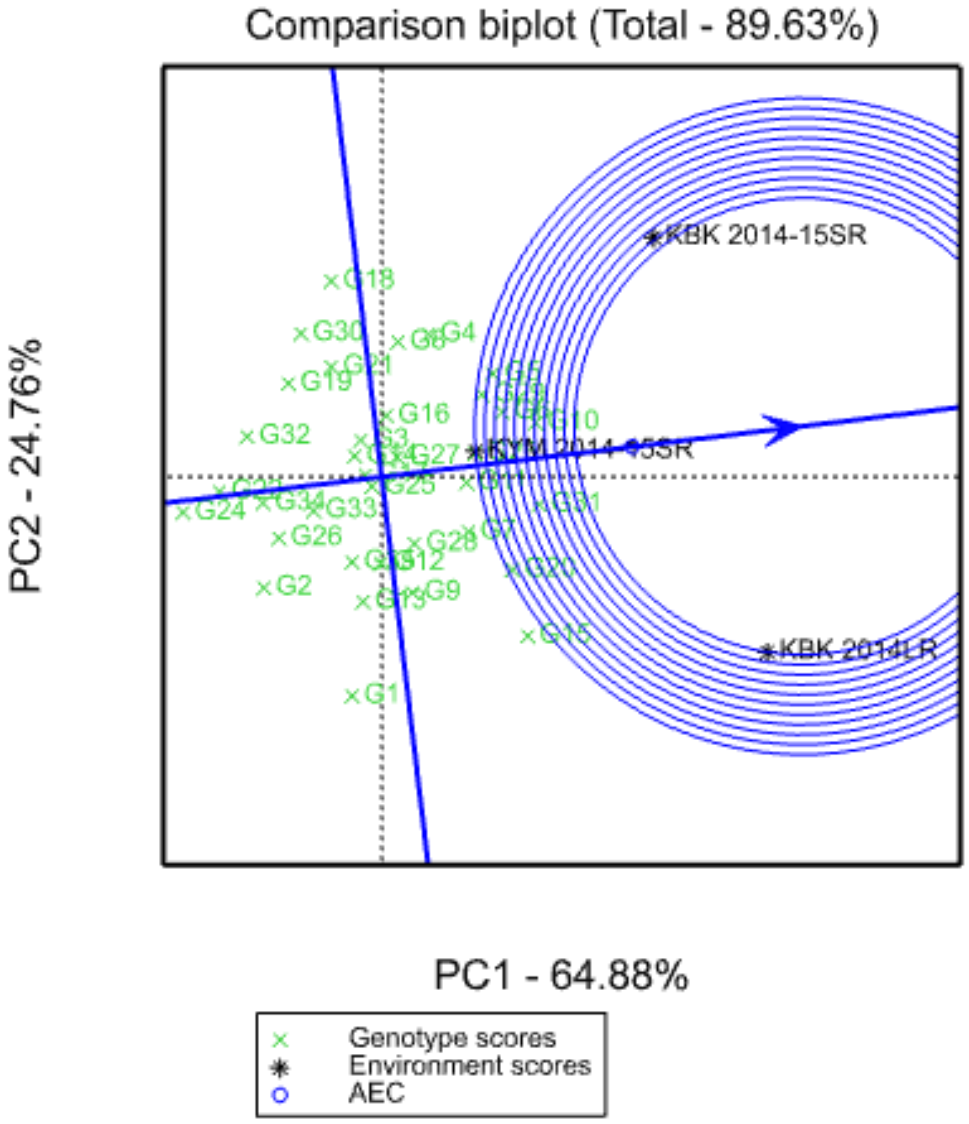



Figure 4. 9 GGE biplot based on environment focused scaling for comparison of environments to the ideal environment for grain yield in 35 sorghum genotypes evaluated in three environments

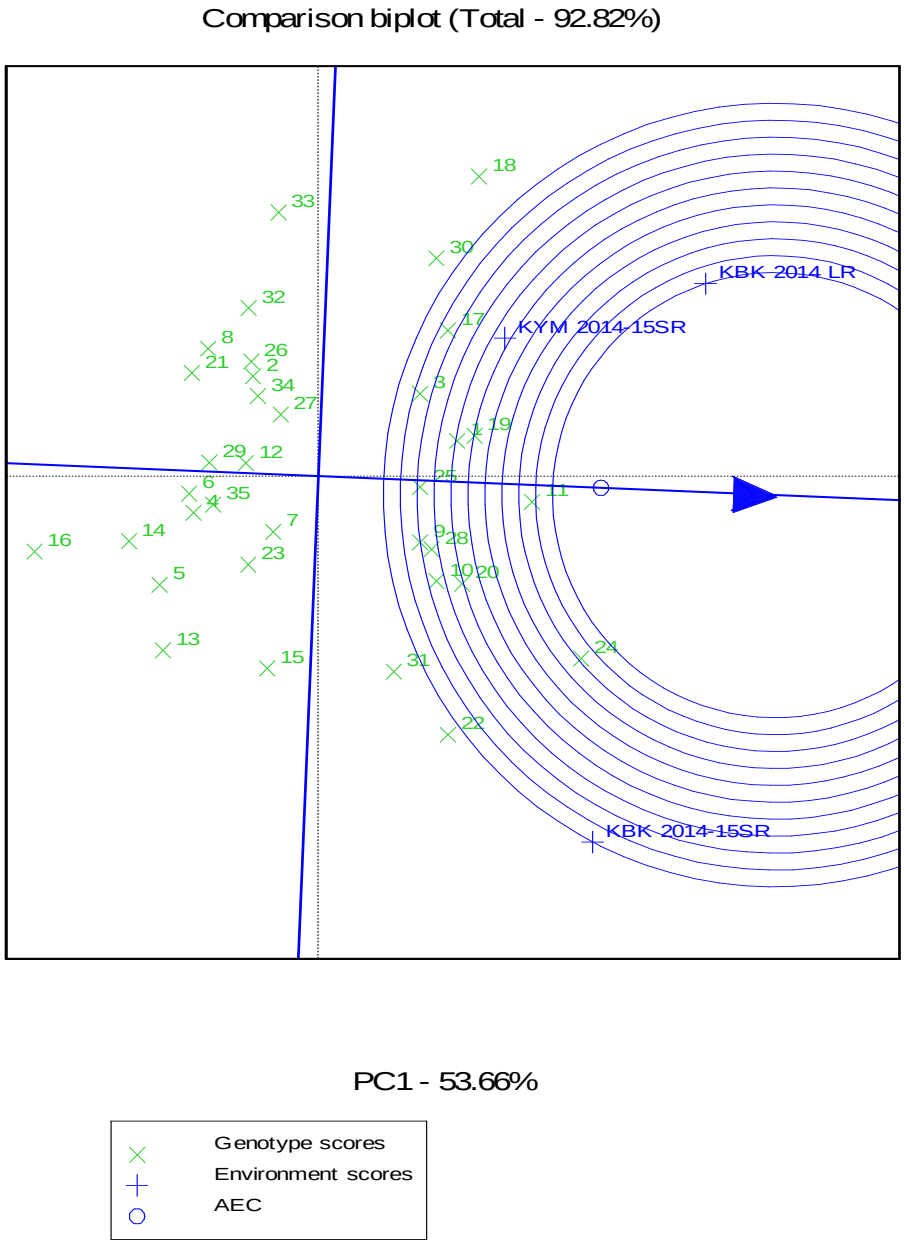



Figure 4. 10 GGE biplot based on environment focused scaling for comparison of environments to the ideal environment for biomass yield in 35 sorghum genotypes evaluated in three environments

## 4.4 Discussion

### 4.4.1 Analysis of variance for grain and biomass yield

The variation among genotypes, environments and their interactions caused the grain and biomass yield differences in sorghum hybrids. The results showed variations in both hybrids and test environments. Sorghum hybrids had varied performance for biomass and grain yield in different environments. The three environments had variation in temperature, rainfall amount and distribution. These differences in

weather conditions could be the cause of varied performance of the hybrids for biomass and grain yield.

Therefore, sorghum hybrids have to be tested over a range of environments or seasons before meaningful conclusions about genotypic selection can be reached. Significant GEI in sorghum grain yield were reported in various studies by; Asfaw, (2007); Thirumala *et al*., (2013); Ezzat *et al*., (2010), and Ghazy *et al.*, (2012).The effect of location was more important than that of genotypes and GEI for grain yield. Contrary to that, GEI effect influenced biomass yields more than genotype and environment effects. The findings indicated that the grain and biomass yields of sorghum hybrids are affected by environment in a different way.

### 4.4.2 The AMMI analyses of variance for 34 sorghum hybrids and a check for grain yield

Significant genotype (G), environmental (E), genotype by environment (GEI), PCA1 and PCA2 effects were recorded in the AMMI analysis. This indicates that environments and genotypes differed significantly and that the genotypes had varied biomass and grain yield at different environments. The results show that the hybrids were diverse. Therefore, different sorghum hybrids could be selected for specific agro- ecologies. Similar findings have been reported in previous studies by Rad *et al*., (2013) in wheat; Anowara *et al*., (2015) in rice and Muez *et al*., (2014) in barley.

The small variation between the sum of squares for genotypes and environments indicated the greater part played by genotype and environment in influencing the grain and biomass yield of the sorghum hybrids. The effect of environment on the grain yield could be attributed to differences in rainfall and mean temperature during growth. Genotype effect on the yields of sorghum hybrids may have been attributed to the diversity of the hybrid parents and heterozygosity of the hybrids. The presence of significant GEI shows the necessity of testing sorghum hybrids in multiple locations before release for cultivation in Kenya.

#### 4.4.3 AMMI Biplot Analysis

According to Muez *et al*., (2014), genotypes that group together have similar adaptation and environments that group together influence genotypes the same way. The best genotypes were, G31 (ATX 623 x Macia), G6 (ICSA 11004 x ICSR 24008) and G5 (ICSA 11033 x ICSR 160) because they were placed on the right hand side of

the perpendicular line (grand mean). Therefore, they are potential candidates for on farm testing and later release in Kenya. Genotypes G35 (Seredo), G33 (ICSA 11016 x Wahi) and G6 (ICSA 11004 x ICSR 24008) were the most stable due to their location on the AMMI biplot and were less influenced by the environments.

Sorghum variety, Seredo (G35) was released in the East African countries. Hence, G33 and G6 can be promoted for release in similar agro ecologies on the strength of their stability. Kiboko 2014-15 was the most favorable environment for testing the sorghum hybrids. Genotypes close to each other on the biplot have similar yield in all test locations. Therefore, genotypes near the origin of the biplot are not sensitive to environmental interaction. From the present study, the most responsive genotypes to the environment were; G10 (ICSA 29005 x ICSR 24010), G26 (ICSA 11039 x KARI Mtama 1) and G35 (Seredo), since they occurred far away from the origin.

### 4.4.4 AMMI stability value (ASV) analysis

The AMMI stability values proposed by Purchase *et al* 2000 were used to quantify and classify genotypes based on their stability values which is the measure of the distance of the genotype from the point zero of the scatter diagram (Eder *et al*., 2014). It has been described as the most appropriate single method of describing genotypic stability (Rad *et al*., 2013). Grain and biomass yield are important selection criterion used by farmers in the semi-arid areas. Therefore, a good hybrid should be high yielding and stable.

From the present study, genotypes G27 (ICSA 11034 x Macia) and G6 (ICSA 11004 x ICSR 24008) had high grain yield and were stable. Genotypes, G29 (ICSA 11037 x Macia), and G25 (ICSA 11038 x KARI Mtama 1) were stable with high biomass yield. Genotype G6 had low ASV value for biomass and grain yield hence it is a good dual purpose hybrid. AMMI stability values have been used in classifying genotypes as stable in sorghum by; Al-Naggar *et al*., (2018); Sintayehu and Tesfaye (2017); and Filho et al., (2014.

### 4.4.5 Stable and specifically adapted genotypes

Two mega environments were realized from the GGE biplot for grain and biomass yield. However, the ranking was different. Kiboko 2014-15 and KYM 2014-15 formed mega environment 1 and Kiboko 2014 formed the 2$^{nd}$ mega environment for

grain yield. The clustering was different for biomass yield with KBK 2014LR clustering together with KYM 2014-15SR in mega environment 1. The winning genotypes for the mega environments were different for grain and biomass yield.
Hybrids G15 and G31 are specifically adapted to KBK 2014LR whereas G5 and G10 have wide adaptation for grain yield. Hybrids G22 and G24 are specifically adapted for biomass yield to KBK 2014-15SR whereas G18 has broad adaptation for biomass yield to KBK 2014LR and KYM 2014-15SR. Sorghum hybrids G5, G15 and G31 can be promoted for release in the ASALs of Kenya. Similar results were reported by Teodoro *et al*., (2016); Rono *et al*., (2016) and Akter *et al*., (2014).

An ideal/ superior genotype is the one that has high yield and is stable across the test environments (Yan and Kang, 2003). Desirable genotypes are situated next to ideal genotypes in the GGE biplots. Most desirable genotypes for grain yield were G10 (ICSA 29005 x ICSR 24010), G6 (ICSA 11004 x ICSR 24008), G5 (ICSA 11033 x ICSR 160), G31 (ATX 623 x Macia), and G23 (ICSA 12 X IESV 92172 DL. Genotypes G11 (ICSA 29017 x ICSR 24010), and G19 (ICSA 29003 x ICSV 700) were the most desirable for biomass yield. It is evident that the GGE biplot is a good method of identifying stable, ideal and desirable genotypes as reported previously (Akter *et al*., 2014; Ding and Tier, 2008; Rad *et al*., 2013; and Yan and Tinker 2006).

### 4.4.6 Evaluation of sorghum growing environments relative to ideal environment

The GGE biplots for grain yield and biomass yield explained 84.6% and 92.8% of the total variation respectively. Therefore relationships between environments can be deduced from these biplots. Lines that connect environments to the biplot origin are called environmental vectors and the angle between the environments vectors is related to correlation coefficient if the fit is perfect (Kroonenberg, 1995).

KBK 2014-15SR and KYM 2014-15SR are closely related hence provide similar information about the genotypes. Testing hybrids in both locations would increase the costs of evaluation without adding much information on the cultivar performance. Environments, KBK 2014-15 and KBK 2014 which had the longest vectors from the biplot origin, were the most discriminating sites. The two seasons in Kiboko (short and long rains) can be used jointly as discriminating sites for testing hybrids. Discriminating and representative sites are the best for selecting high yielding hybrids while discarding the poor yielders.

Environment, KBK 2014LR was the most ideal environment for selecting sorghum hybrids for grain and biomass yield performance due to its closeness to the average environment. This reduces the costs and increases the breeding efficiency. The most undesirable environment for grain yield performance was KYM 2014-15SR whereas for biomass yield the most undesirable was KBK 2014-15SR. Comparable results were reported by Akter *et al*., (2014); Kamau, (2013); Maji *et al*., (2015) & Ding and Tier, (2008).

## 4.5 Conclusion

Grain yield in sorghum hybrids was found to be strongly influenced by the environment, the genotype and GEI. The significant GEI for grain yield observed in the AMMI ANOVA in the present study showed that sorghum hybrids respond differently when grown in different environments. Both AMMI and GGE biplots designated genotype G6 (ICSA 11004 x ICSR 24008) a stable hybrid with superior performance across the test environments. The best performing genotypes were, G31 (ATX 623 x Macia), G6 (ICSA 11004 x ICSR 24008) and G5 (ICSA 11033 x ICSR 160). It is evident that the grain yields of sorghum hybrids are greatly determined by the genetic make-up and the environment where they are grown. KBK 2014LR was the most ideal environment for selecting sorghum hybrids. Under resource constraints evaluation of hybrids can be done at Kiboko during the long rains and short rains. AMMI analysis and GGE biplot analysis were able to delineate stable and adapted genotypes and mega environments for sorghum hybrid cultivation. Further testing of these sorghum hybrids in additional locations for more seasons is encouraged.

# CHAPTER FIVE

## 5.0 GENERAL DISCUSSION, CONCLUSIONS AND RECOMENDATIONS

### 5.1 General discussion

From the results of the current study, significant genotypic variances for yield and its related traits showed the existence of variability within the germplasm which can be used in development of new cultivars with superior yields. High grain yielding male parents produced high yielding hybrids hence selection of restorer parents for hybrid development should be based on their *per se* performance. Similar findings were reported by Ghorade and Dipali (2007). Hybrids were early flowering and high yielding than the parents which might have been due to drought escape caused by their earliness.

The significant negative relationship between grain yield and days to 50% flowering in the present study reaffirmed the importance of earliness when developing sorghum hybrids for the semi-arid areas. The positive correlation between grain and biomass yield demonstrates that some of the developed hybrids are dual purpose hence will be accepted in the semi-arid areas for food and feed. The results in present study showed that plant height, leaf length and days to flowering greatly influences grain and biomass yield in sorghum. Hence they can be used as selection indices in sorghum improvement.

Results from the current study showed high heritability for biomass yield, plant height and panicle exertion in sorghum hybrids and their parents showing the influence of additive gene effect in inheritance of these traits. Therefore, improvement of these traits can be done through direct selection. Direct selection for grain yield in sorghum would be less effective due to greater environmental influence as shown by medium heritability scores.

Sorghum hybrids; ATX 623 x Macia, ICSA 29011 x ICSR 89058, ICSA 11033 x ICSR 160, ICSA 12 x IESV 92172DL and ICSA 11035 x Macia were high yielding and had high positive magnitudes of better parent, mid parent and standard heterosis for grain yield. These hybrids can be exploited for grain yield production in semi-arid

areas of Kenya. Hybrids with high grain and biomass yields from current study were; ICSA 11040 x IESV 91104DL, ICSA 29017 x ICSR 24010 and ICSA 11035 x Macia hence can be promoted as dual purpose hybrids. Realization of better parent, mean and standard heterosis for grain yield in both positive and negative direction shows greater effect of non- additive gene action (dominance and epistasis) in inheritance of the trait. Therefore, both additive and non-additive gene actions are important in governing inheritance of yield and its component traits.

From the present study, none of the male parents was a good general combiner for all traits. Male parent, ICSR 24010 had a good *per se* performance and a good general combiner for grain yield and biomass yield. Therefore, it could serve as a good source of favourable genes for improving grain and forage yields in sorghum hybrids. The male parents ICSR 89058, ICSR 38 and ICSR 160 recorded desirable GCA for days to 50% flowering hence they are good sources of genes for earliness. Male parents ICSR 160, ICSR 24008 and ICSR 24010 exhibited desirable GCA scores for grain yield and its component trait panicle length. Hence, they are potential donors for genes in improving grain yield in hybrids. Male parents ICSV 700, ICSR 24010 and KARI Mtama 1 recorded desirable GCA for biomass yield hence could provide good sources of genes for fodder improvement.

Male parents ICSR 160, Macia and ICSR 24008 were the best general combiners for grain yield at Kampi ya Mawe whereas ICSR 24010, ICSR 24008, and Macia were the best combiners for grain yield at Kiboko. The differential ranking of parents for GCA showed that seasonality affects the GCA of male parents. Makanda (2009) reported that environment plays a critical role in influencing the expression of additive and non- additive gene effects. Therefore, selection of parents should be done after testing them in different environments to classify them for general and specific adaptation.

The estimates of SCA effects of females within males revealed that no cross combination was superior for all characters. Hybrids ICSA 11040 x IESV 91104DL, ICSA 29017 x ICSR 24010 and ICSA 29011 x ICSR 89058 with high SCA effects for grain and biomass yield can be fast tracked for on farm testing and possible release. There was variation between genotypes, environments and their interactions in the current study. Therefore, different sorghum hybrids could be selected for

specific agro- ecologies. Hybrids G27 (ICSA 11034 x Macia) and G6 (ICSA 11004 x ICSR 24008) were high yielding and stable whereas the most desirable hybrids were, G10 (ICSA 29005 x ICSR 24010), G6 (ICSA 11004 x ICSR 24008), G5 (ICSA 11033 x ICSR 160), G31 (ATX 623 x Macia), and G23 (ICSA 12 X IESV 92172 DL. Kiboko 2014LR was the most ideal environment for selecting sorghum hybrids. Selection of hybrids in this environment was more effective.

### 5.2 General conclusion

From the current study, it is evident that selection of sorghum hybrid parents should be based on their *perse* performance and their general combining ability. Development of high yielding dual purpose sorghum hybrids adapted to the semi-arid conditions of Kenya is possible using seed parents from India. Hybrids were superior to their parental lines in grain and biomass yield hence yield improvement can be accomplished through hybrid development. Additive and non-additive gene effects were shown to control inheritance of days to 50% flowering, leaf length, stem girth, grain yield, biomass yield, leaf width, number of plants lodged, tiller number, panicle length, panicle width, panicle exertion, plant height, 100 seed mass and seed set in sorghum. Restorer parent, ICSR 24010 was identified as a good general combiner for grain yield, biomass yield and panicle exertion whereas ICSR 89058 was a good general combiner for days to flowering and panicle exertion. The best SCA effects for grain yield were demonstrated in hybrid combinations ATX 623 x Macia, ICSA 11040 x IESV 91104DL and ICSA 29011 x ICSR 89058. The study also confirmed earlier reports that environment greatly affects the performance of sorghum hybrids hence multi locational testing is important before commercialization of the hybrids. Both AMMI and GGE biplots designated hybrid ICSA 11004 x ICSR 24008 as the most stable with superior performance across the test environments. The best performing genotypes were, G31 (ATX 623 x Macia), G6 (ICSA 11004 x ICSR 24008) and G5 (ICSA 11033 x ICSR 160). It is evident that the grain yields of sorghum hybrids are greatly determined by the genetic make-up and the environment where they are grown.

### 5.3 Recommendations

- The best hybrids for grain yield, ATX 623 x Macia, ICSA 11040 x IESV 91104DL and ICSA 29011 x ICSR 89058 can be tested further through on

farm trials across the semi-arid agro ecologies and finally recommended for commercialization.

- The hybrid with the highest biomass yield was developed from a male parent KARI Mtama 1 whose hybrids are sterile or partially sterile. Further breeding has to be done to find CGMS lines which are heterotic to this line and able to produce hybrids with full fertility restoration.
- There was lack of CGMS A-lines developed in the region hence the female parents used were exotic. Future breeding should be geared towards developing female parents using local germplasm to solve adaptation related problems. There is need to characterize the hybrid parents to place them in heterotic groups for use in future hybridization programs.

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# APPENDICES

Appendix 1: Mean performance of sorghum hybrid parents evaluated at Kiboko 2014LR and 2014/15 Short rains

| GYLD rank | Genotype | Status | DFL | SG | NTIL | BYLD | PHT | LL | LW | PL | PW | PE | LO | SD | GY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | ICSR 24008 | Male | 77.0 | 5.6 | 2.0 | 7.6 | 137.6 | 62.8 | 7.9 | 27.0 | 8.1 | 1.5 | 7.0 | 2.2 | 4.1 |
| 2 | ICSB 29004 | Female | 75.0 | 6.1 | 4.0 | 8.0 | 127.4 | 66.5 | 8.1 | 26.1 | 8.6 | 3.7 | 2.0 | 2.2 | 4.0 |
| 3 | ICSR 24010 | Male | 73.0 | 5.1 | 2.0 | 12.2 | 193.8 | 63.8 | 8.1 | 22.9 | 9.1 | 3.3 | 2.0 | 1.7 | 3.8 |
| 4 | ICSB 11040 | Female | 77.0 | 6.0 | 4.0 | 9.4 | 111.4 | 70.3 | 7.3 | 29.8 | 7.5 | 2.8 | 1.0 | 2.4 | 3.7 |
| 5 | ICSR 160 | Male | 75.0 | 5.5 | 2.0 | 7.4 | 136.3 | 71.7 | 7.9 | 28.9 | 8.1 | 4.2 | 3.0 | 1.9 | 3.6 |
| 6 | IESV 92172 DL | Male | 73.0 | 6.3 | 1.0 | 9.2 | 116.3 | 67.0 | 7.9 | 30.6 | 7.7 | 4.6 | 2.0 | 2.6 | 3.5 |
| 7 | ICSB 11038 | Female | 74.0 | 5.9 | 2.0 | 7.7 | 112.8 | 70.0 | 7.8 | 27.4 | 8.5 | 4.5 | 1.0 | 2.5 | 3.5 |
| 8 | ICSB 11018 | Female | 80.0 | 6.4 | 7.0 | 10.3 | 124.6 | 63.9 | 8.4 | 26.2 | 7.2 | 2.6 | 1.0 | 2.2 | 3.5 |
| 9 | ICSB 29016 | Female | 76.0 | 6.2 | 4.0 | 8.6 | 132.2 | 68.6 | 9.6 | 28.3 | 8.3 | 3.3 | 0.0 | 2.3 | 3.4 |
| 10 | ICSR 89058 | Male | 71.0 | 5.7 | 1.0 | 7.1 | 143.0 | 68.2 | 7.3 | 30.4 | 7.1 | 6.0 | 7.0 | 2.1 | 3.4 |
| 11 | ICSB 11037 | Female | 81.0 | 6.0 | 3.0 | 8.3 | 121.8 | 75.7 | 8.8 | 29.2 | 11.4 | 1.7 | 1.0 | 2.3 | 3.4 |
| 12 | ICSV 700 | Male | 81.0 | 5.0 | 2.0 | 13.1 | 189.3 | 55.5 | 7.6 | 23.9 | 7.4 | 0.3 | 3.0 | 2.3 | 3.4 |
| 13 | ICSB 11019 | Female | 76.0 | 6.4 | 3.0 | 9.6 | 117.4 | 70.4 | 8.0 | 25.8 | 6.2 | 0.8 | 1.0 | 2.7 | 3.2 |
| 14 | IESV 91104 DL | Male | 72.0 | 5.5 | 1.0 | 9.6 | 164.8 | 74.2 | 8.9 | 21.3 | 8.0 | 7.1 | 2.0 | 3.2 | 3.2 |
| 15 | ICSR 38 | Male | 72.0 | 5.1 | 1.0 | 5.4 | 127.5 | 67.7 | 7.3 | 28.0 | 7.9 | 5.1 | 8.0 | 1.7 | 3.2 |
| 16 | ICSB 11033 | Female | 73.0 | 6.1 | 4.0 | 3.7 | 136.5 | 71.0 | 8.2 | 30.1 | 11.0 | 0.0 | 4.0 | 2.3 | 3.2 |
| 17 | ICSB 11036 | Female | 81.0 | 6.4 | 3.0 | 9.7 | 117.3 | 67.4 | 8.0 | 22.1 | 9.8 | 1.3 | 0.0 | 2.3 | 3.1 |
| 18 | ICSB 11039 | Female | 73.0 | 5.5 | 1.0 | 5.6 | 112.2 | 70.8 | 7.8 | 26.5 | 8.1 | 5.8 | 4.0 | 2.2 | 3.1 |
| 19 | BTX 623 | Female | 71.0 | 5.6 | 3.0 | 7.2 | 110.7 | 70.6 | 8.0 | 28.4 | 6.5 | 6.2 | 2.0 | 2.3 | 3.1 |
| 20 | ICSB 29011 | Female | 80.0 | 5.5 | 4.0 | 9.0 | 145.2 | 67.9 | 8.9 | 26.3 | 9.2 | 11.7 | 2.0 | 2.0 | 3.1 |
| 21 | Macia | Male | 74.0 | 5.8 | 3.0 | 9.6 | 116.3 | 61.6 | 7.9 | 22.9 | 7.8 | 6.8 | 3.0 | 2.3 | 3.1 |
| 22 | ICSB 11016 | Female | 76.0 | 6.4 | 2.0 | 5.5 | 113.9 | 67.2 | 8.4 | 29.7 | 9.1 | 0.4 | 1.0 | 2.7 | 3.1 |
| 23 | ICSB 11004 | Female | 72.0 | 5.5 | 6.0 | 6.2 | 120.2 | 63.8 | 7.6 | 35.3 | 8.3 | 3.0 | 0.0 | 2.9 | 3.1 |
| 24 | ICSB 12 | Female | 72.0 | 6.0 | 2.0 | 6.0 | 111.7 | 69.9 | 7.3 | 30.3 | 7.9 | 3.9 | 2.0 | 1.9 | 3.0 |
| 25 | ICSB 232 | Female | 78.0 | 5.6 | 6.0 | 7.4 | 108.2 | 71.4 | 8.3 | 28.4 | 6.9 | 0.7 | 1.0 | 2.3 | 3.0 |

Appendix 1 Continued

| GYLD rank | Genotype | Status | DFL | SG | NTIL | BYLD | PHT | LL | LW | PL | PW | PE | LO | SD | GY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 26 | ICSB 75 | Female | 76.0 | 6.4 | 4.0 | 11.4 | 148.7 | 74.5 | 9.0 | 32.6 | 7.2 | 7.9 | 5.0 | 3.0 | 2.9 |
| 27 | KARI Mtama 1 | Male | 68.0 | 5.3 | 1.0 | 9.3 | 143.9 | 67.2 | 7.6 | 23.6 | 8.7 | 6.5 | 1.0 | 3.2 | 2.7 |
| 28 | ICSB 11007 | Female | 78.0 | 5.9 | 2.0 | 7.3 | 133.0 | 64.2 | 8.4 | 29.8 | 6.5 | 2.6 | 6.0 | 2.7 | 2.7 |
| 29 | ICSB 29003 | Female | 77.0 | 6.1 | 3.0 | 7.6 | 108.8 | 67.1 | 8.2 | 27.5 | 9.4 | 4.2 | 2.0 | 2.3 | 2.7 |
| 30 | ICSB 74 | Female | 83.0 | 6.3 | 3.0 | 14.6 | 161.6 | 68.7 | 8.4 | 32.3 | 9.0 | 4.6 | 1.0 | 2.6 | 2.7 |
| 31 | ICSB 29015 | Female | 78.0 | 5.2 | 4.0 | 8.1 | 128.3 | 69.0 | 8.4 | 28.2 | 8.5 | 5.5 | 0.0 | 2.4 | 2.7 |
| 32 | Wahi | Male | 71.0 | 5.9 | 2.0 | 6.9 | 104.0 | 66.7 | 7.6 | 27.3 | 6.7 | 5.1 | 1.0 | 2.6 | 2.6 |
| 33 | Hakika | Male | 71.0 | 5.5 | 2.0 | 7.7 | 112.7 | 70.5 | 7.2 | 26.8 | 7.2 | 2.7 | 1.0 | 3.0 | 2.6 |
| 34 | Seredo | Check | 66.0 | 5.1 | 5.0 | 8.0 | 146.4 | 59.4 | 6.7 | 30.4 | 7.9 | 6.5 | 3.0 | 2.4 | 2.6 |
| 35 | ICSB 29002 | Female | 83.0 | 5.8 | 3.0 | 7.9 | 118.9 | 67.4 | 8.2 | 27.2 | 8.7 | 0.9 | 1.0 | 2.1 | 2.6 |
| 36 | ICSB 29007 | Female | 85.0 | 5.9 | 5.0 | 10.2 | 147.6 | 79.3 | 8.5 | 29.8 | 7.1 | 7.0 | 1.0 | 2.0 | 2.5 |
| 37 | ICSB 11003 | Female | 73.0 | 5.7 | 6.0 | 5.0 | 113.8 | 66.4 | 7.2 | 28.7 | 9.0 | 1.5 | 0.0 | 2.9 | 2.5 |
| 38 | ICSB 11035 | Female | 73.0 | 6.3 | 3.0 | 7.6 | 88.3 | 61.2 | 7.9 | 21.8 | 6.9 | 1.1 | 2.0 | 2.0 | 2.4 |
| 39 | ICSB 228 | Female | 80.0 | 6.3 | 4.0 | 6.1 | 94.1 | 64.8 | 9.8 | 30.4 | 9.9 | 0.0 | 0.0 | 2.1 | 2.4 |
| 40 | ICSB 29005 | Female | 74.0 | 5.5 | 2.0 | 6.4 | 103.9 | 76.3 | 7.8 | 26.0 | 7.8 | 3.4 | 4.0 | 2.4 | 2.4 |
| 41 | ICSB 11013 | Female | 78.0 | 7.0 | 4.0 | 5.8 | 105.3 | 66.0 | 9.7 | 32.1 | 10.0 | 0.2 | 1.0 | 2.7 | 2.3 |
| 42 | ICSB 29001 | Female | 84.0 | 6.0 | 1.0 | 9.4 | 101.0 | 60.2 | 8.1 | 23.7 | 6.6 | 0.4 | 1.0 | 2.2 | 2.3 |
| 43 | ICSB 29017 | Female | 82.0 | 6.5 | 2.0 | 9.0 | 134.8 | 75.1 | 11.2 | 26.7 | 7.2 | 10.7 | 0.0 | 2.1 | 2.3 |
| 44 | ICSB 11034 | Female | 74.0 | 5.5 | 5.0 | 3.9 | 99.7 | 60.5 | 7.7 | 29.6 | 7.2 | 6.0 | 4.0 | 2.2 | 2.3 |
| 45 | ICSB 25002 | Female | 78.0 | 6.8 | 3.0 | 8.0 | 97.9 | 74.7 | 8.1 | 29.6 | 7.8 | 0.7 | 0.0 | 2.2 | 2.2 |
| 46 | ICSB 101 | Female | 75.0 | 5.3 | 2.0 | 7.8 | 115.1 | 72.1 | 8.2 | 25.8 | 7.2 | 7.4 | 0.0 | 2.2 | 2.1 |
| 47 | ICSB 206 | Female | 76.0 | 5.9 | 4.0 | 1.2 | 64.0 | 50.4 | 7.0 | 20.9 | 5.4 | 1.1 | 0.0 | 1.7 | 1.1 |
| | **Grand means** | | **76.0** | **5.9** | **3.0** | **7.9** | **123.8** | **67.7** | **8.1** | **27.6** | **8.0** | **3.8** | **2.0** | **2.3** | **2.9** |
| | Fpr | | <.001 | 0.002 | 0.209 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 |
| | lsd | | 8.463 | 2.253 | 9.336 | 7.517 | 37.19 | 15.585 | 3.1555 | 12.33 | 5.071 | 9.698 | 8.257 | 1.066 | 2.389 |
| | CV% | | 4.3 | 14.7 | 118.2 | 36.4 | 11.5 | 8.8 | 14.8 | 17.1 | 24.1 | 95.4 | 159 | 17.3 | 30.9 |

DFL=days to flowering, SG=stem girth (cm), NTIL=number of tillers, BYLD=biomass yield (tha-1), PHT=plant height (cm), LL=leaf length (cm), LW=leaf width (cm), PL=panicle length (cm), PW=panicle width (cm), PE=panicle exertion (cm), LO=number of plants lodged, SD=100 seed mass (g), GY=grain yield (tha-1), LSD=least significant difference, SE=standard error of differences, CV%=Coefficient of variation, ns=not significant.

Appendix 2: Mean performance of sorghum hybrid parents evaluated at Kampi ya Mawe 2014/15 Short rains

| GY rank | Genotype | Status | DFL | SG | BYLD | PHT | LL | LW | PL | PW | PE | LO | SD | GY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Seredo | Check | 66 | 5.3 | 6.0 | 143.0 | 71.7 | 6.7 | 23.0 | 5.3 | 3.7 | 4.0 | 2.0 | 2.6 |
| 2 | ICSB 29003 | Female | 74 | 6.0 | 4.3 | 97.7 | 62.7 | 6.7 | 21.3 | 6.0 | 4.7 | 0.0 | 2.0 | 1.8 |
| 3 | ICSB 75 | Female | 74 | 6.3 | 8.1 | 131.3 | 75.7 | 7.3 | 26.3 | 5.0 | 4.3 | 1.0 | 2.7 | 1.6 |
| 4 | ICSR 24010 | Male | 77 | 5.3 | 8.3 | 172.3 | 66.0 | 7.3 | 18.0 | 5.7 | 2.7 | 11.0 | 2.0 | 1.6 |
| 5 | ICSB 29002 | Female | 74 | 6.0 | 4.9 | 118.3 | 71.3 | 6.7 | 24.0 | 5.7 | 2.0 | 2.0 | 1.7 | 1.5 |
| 6 | IESV 91104 DL | Male | 74 | 5.7 | 9.6 | 182.0 | 84.0 | 8.0 | 19.0 | 6.5 | 2.5 | 10.0 | 2.0 | 1.5 |
| 7 | ICSR 24008 | Male | 77 | 5.7 | 6.1 | 121.7 | 65.7 | 7.0 | 18.7 | 5.3 | 0.0 | 0.0 | 2.0 | 1.4 |
| 8 | ICSB 11040 | Female | 76 | 5.7 | 5.3 | 106.3 | 69.3 | 6.3 | 23.7 | 5.0 | 3.0 | 0.0 | 1.3 | 1.4 |
| 9 | ICSB 29004 | Female | 72 | 6.3 | 5.9 | 98.7 | 67.0 | 7.3 | 18.7 | 4.3 | 1.0 | 4.0 | 2.0 | 1.3 |
| 10 | Macia | Male | 74 | 6.0 | 5.1 | 95.7 | 65.0 | 6.3 | 17.7 | 4.3 | 0.0 | 1.0 | 2.0 | 1.2 |
| 11 | ICSB 11003 | Female | 71 | 6.0 | 3.5 | 101.7 | 61.0 | 5.0 | 21.3 | 4.7 | 1.3 | 2.0 | 2.0 | 1.2 |
| 12 | ICSB 11036 | Female | 82 | 6.3 | 11.1 | 100.0 | 69.0 | 7.0 | 20.0 | 4.7 | 2.3 | 0.0 | 2.3 | 1.1 |
| 13 | ICSB 29016 | Female | 76 | 6.3 | 6.7 | 117.0 | 67.0 | 7.0 | 20.0 | 4.3 | 1.3 | 1.0 | 2.0 | 1.1 |
| 14 | ICSB 11037 | Female | 78 | 6.3 | 6.7 | 121.5 | 74.5 | 6.5 | 25.5 | 6.0 | 5.0 | 0.0 | 1.7 | 1.1 |
| 15 | ICSR 160 | Male | 72 | 5.3 | 2.3 | 110.0 | 70.0 | 6.3 | 19.0 | 4.7 | 0.0 | 18.0 | 2.3 | 1.1 |
| 16 | ICSB 11038 | Female | 74 | 5.7 | 4.3 | 110.3 | 70.3 | 6.3 | 22.7 | 5.0 | 0.0 | 4.0 | 2.0 | 1.1 |
| 17 | ICSB 11034 | Female | 73 | 6.0 | 3.7 | 94.7 | 66.0 | 7.0 | 25.7 | 4.7 | 2.3 | 1.0 | 1.7 | 1.1 |
| 18 | ICSB 74 | Female | 83 | 6.3 | 13.7 | 139.0 | 73.7 | 6.7 | 23.0 | 5.0 | 2.3 | 0.0 | 2.7 | 1.0 |
| 19 | BTX 623 | Female | 71 | 6.7 | 4.2 | 95.0 | 68.3 | 6.0 | 20.0 | 3.7 | 1.3 | 3.0 | 1.7 | 1.0 |
| 20 | Hakika | Male | 71 | 5.3 | 5.9 | 115.0 | 64.3 | 6.3 | 20.7 | 4.0 | 0.0 | 1.0 | 2.0 | 1.0 |
| 21 | KARI Mtama 1 | Male | 75 | 5.3 | 6.8 | 131.7 | 77.3 | 7.0 | 17.7 | 5.0 | 1.7 | 5.0 | 2.3 | 1.0 |
| 22 | ICSB 11004 | Female | 71 | 6.0 | 4.4 | 117.3 | 68.7 | 5.7 | 21.3 | 4.3 | 2.7 | 6.0 | 1.3 | 1.0 |
| 23 | ICSR 89058 | Male | 70 | 6.0 | 4.5 | 120.3 | 63.7 | 6.0 | 23.7 | 4.0 | 0.0 | 10.0 | 1.7 | 1.0 |
| 24 | Wahi | Male | 70 | 5.7 | 6.8 | 106.5 | 67.0 | 6.5 | 24.5 | 4.5 | 2.5 | 2.0 | 2.7 | 1.0 |
| 25 | ICSR 38 | Male | 75 | 5.0 | 4.4 | 105.7 | 65.0 | 6.3 | 20.0 | 4.3 | 3.7 | 6.0 | 2.0 | 0.9 |
| 26 | ICSB 29017 | Female | 78 | 6.0 | 6.8 | 117.0 | 66.0 | 6.3 | 20.3 | 4.3 | 8.3 | 1.0 | 2.0 | 0.9 |
| 27 | ICSB 11018 | Female | 79 | 6.3 | 6.2 | 104.3 | 65.0 | 7.0 | 18.7 | 4.7 | 0.0 | 0.0 | 1.7 | 0.9 |
| 28 | ICSB 11033 | Female | 76 | 5.0 | 4.4 | 107.0 | 62.3 | 6.3 | 20.7 | 5.0 | 0.0 | 2.0 | 2.7 | 0.9 |
| 29 | IESV 92172 DL | Male | 75 | 6.3 | 4.3 | 89.7 | 70.3 | 6.3 | 21.0 | 5.0 | 0.0 | 4.0 | 2.0 | 0.8 |

| GY rank | Genotype | Status | DFL | SG | BYLD | PHT | LL | LW | PL | PW | PE | LO | SD | GY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 30 | ICSB 11019 | Female | 77 | 6.0 | 5.9 | 101.7 | 73.3 | 7.0 | 19.0 | 4.0 | 1.3 | 0.0 | 1.7 | 0.8 |
| 31 | ICSB 101 | Female | 77 | 5.7 | 4.4 | 100.7 | 68.7 | 6.3 | 22.0 | 4.7 | 0.0 | 0.0 | 1.7 | 0.8 |
| 32 | ICSB 11016 | Female | 79 | 6.3 | 6.7 | 92.7 | 66.0 | 8.3 | 18.7 | 5.3 | 0.0 | 1.0 | 1.7 | 0.8 |
| 33 | ICSB 29005 | Female | 73 | 5.7 | 3.0 | 94.3 | 68.3 | 6.3 | 19.3 | 4.3 | 0.0 | 2.0 | 1.7 | 0.7 |
| 34 | ICSV 700 | Male | 82 | 5.0 | 11.8 | 202.5 | 68.0 |  | 14.0 | 5.0 | 0.0 | 3.0 | 1.7 | 0.7 |
| 35 | ICSB 11035 | Female | 76 | 6.7 | 4.4 | 79.0 | 63.3 | 6.7 | 18.3 | 4.3 | 0.0 | 2.0 | 2.0 | 0.7 |
| 36 | ICSB 29015 | Female | 80 | 5.7 | 7.3 | 110.0 | 67.7 | 7.0 | 19.3 | 4.3 | 3.0 | 0.0 | 2.0 | 0.7 |
| 37 | ICSB 25002 | Female | 80 | 6.3 | 3.9 | 91.3 | 75.0 | 6.0 | 22.0 | 4.7 | 0.0 | 1.0 | 1.7 | 0.6 |
| 38 | ICSB 11013 | Female | 79 | 6.7 | 5.9 | 93.0 | 65.5 | 8.0 | 20.5 | 5.0 | 0.0 | 7.0 | 1.3 | 0.6 |
| 39 | ICSB 206 | Female | 73 | 7.0 | 0.4 | 71.0 | 51.5 | 7.0 | 22.5 | 5.5 | 0.0 | 0.0 | 2.0 | 0.6 |
| 40 | ICSB 12 | Female | 74 | 5.7 | 2.6 | 89.7 | 64.7 | 4.7 | 21.3 | 4.0 | 0.0 | 5.0 | 2.0 | 0.5 |
| 41 | ICSB 29001 | Female | 83 | 6.0 | 4.4 | 92.5 | 63.5 | 6.0 | 20.5 | 5.0 | 0.0 | 0.0 | 2.0 | 0.5 |
| 42 | ICSB 11039 | Female | 78 | 5.7 | 5.3 | 103.3 | 70.7 | 6.0 | 20.7 | 3.7 | 0.0 | 2.0 | 1.3 | 0.5 |
| 43 | ICSB 11007 | Female | 81 | 6.3 | 6.3 | 113.5 | 67.0 | 6.5 | 19.0 | 3.5 | 0.0 | 1.0 | 2.0 | 0.5 |
| 44 | ICSB 29011 | Female | 81 | 5.7 | 7.3 | 107.3 | 65.0 | 7.7 | 20.0 | 4.7 | 6.7 | 1.0 | 3.0 | 0.5 |
| 45 | ICSB 232 | Female | 80 | 5.7 | 3.6 | 101.5 | 65.5 | 7.0 | 24.0 | 5.0 | 0.0 | 0.0 | 2.7 | 0.4 |
| 46 | ICSB 29007 | Female | 91 | 5.7 | 8.3 | 121.3 | 73.7 | 6.7 | 19.3 | 3.7 | 8.7 | 0.0 | 2.0 | 0.4 |
| 47 | ICSB 228 | Female | 83 | 6.3 | 6.5 | 80.5 | 66.5 | 7.5 | 18.0 | 4.0 | 0.0 | 0.0 | 1.7 | 0.3 |
|  | **G. Means** |  | **76** | **5.9** | **5.8** | **111.0** | **67.9** | **6.7** | **20.7** | **4.7** | **1.7** | **3.0** | **2.0** | **1.0** |
|  | Fpr |  | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | 0.013 | 0.017 | <.001 | 0.042 | 0.001 |
|  | lsd |  | 10.834 | 2.11 | 5.317 | 45.045 | 17.683 | 2.6026 | 9.814 | 3.1103 | 11.01 | 14.692 | 1.9788 | 1.954 |
|  | se |  | 2.813 | 0.55 | 1.381 | 11.696 | 4.591 | 0.6758 | 2.548 | 0.8076 | 2.858 | 3.815 | 0.5138 | 0.5073 |
|  | CV% |  | 3.7 | 9.3 | 24 | 10.6 | 6.8 | 10.2 | 12.4 | 17.2 | 190.8 | 133.1 | 26.2 | 50.2 |

DFL=days to flowering, SG=stem girth (cm), NTIL=number of tillers, BYLD=biomass yield (tha-1), PHT=plant height (cm), LL=leaf length (cm), LW=leaf width (cm), PL=panicle length (cm), PW=panicle width (cm), PE=panicle exertion (cm), LO=number of plants lodged, SD=100 seed mass (g), GY=grain yield (tha-1), LSD=least significant difference, SE=standard error of differences, CV%=Coefficient of variation, ns=not significant.

Appendix 3: Mean performance of sorghum hybrid parents evaluated across locations

| Rank | Genotype | Status | DFL | SG | WB | NTIL | BYLD | PHT | LL | LW | PL | PW | PE | SS | LO | SD | GY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | ICSR 24008 | Male | 76.9 | 5.6 | 3.9 | 1.6 | 7.1 | 132.3 | 63.8 | 7.6 | 24.2 | 7.2 | 1.0 | 95.2 | 4.9 | 2.1 | 3.2 |
| 2 | ICSB 29004 | Female | 73.9 | 6.2 | 3.4 | 2.3 | 7.3 | 117.8 | 66.7 | 7.9 | 23.6 | 7.2 | 2.8 | 95.2 | 2.9 | 2.1 | 3.1 |
| 3 | ICSR 24010 | Male | 74.6 | 5.2 | 3.1 | 1.3 | 10.9 | 186.6 | 64.6 | 7.8 | 21.3 | 7.9 | 3.1 | 95.0 | 5.0 | 1.8 | 3.0 |
| 4 | ICSB 11040 | Female | 76.7 | 5.9 | 4.2 | 2.6 | 8.0 | 109.7 | 70.0 | 7.0 | 27.7 | 6.7 | 2.8 | 95.1 | 0.9 | 2.0 | 3.0 |
| 5 | ICSR 160 | Male | 73.7 | 5.4 | 3.1 | 1.1 | 5.7 | 127.5 | 71.1 | 7.4 | 25.6 | 6.9 | 2.8 | 96.8 | 8.3 | 2.1 | 2.7 |
| 6 | ICSB 11038 | Female | 73.7 | 5.8 | 3.7 | 1.3 | 6.6 | 112.0 | 70.1 | 7.3 | 25.8 | 7.3 | 3.0 | 94.6 | 1.9 | 2.4 | 2.7 |
| 7 | ICSB 11018 | Female | 79.8 | 6.4 | 3.2 | 4.4 | 9.0 | 117.8 | 64.3 | 7.9 | 23.7 | 6.4 | 1.8 | 97.9 | 0.6 | 2.0 | 2.6 |
| 8 | ICSB 29016 | Female | 76.1 | 6.2 | 3.8 | 2.3 | 8.0 | 127.2 | 68.0 | 8.8 | 25.5 | 7.0 | 2.7 | 92.8 | 0.7 | 2.2 | 2.6 |
| 9 | IESV 91104 DL | Male | 72.4 | 5.5 | 3.8 | 0.9 | 9.6 | 169.1 | 76.7 | 8.7 | 20.7 | 7.6 | 6.0 | 96.1 | 4.3 | 2.8 | 2.6 |
| 10 | IESV 92172 DL | Male | 73.6 | 6.3 | 3.2 | 0.6 | 7.5 | 107.4 | 68.1 | 7.4 | 27.4 | 6.8 | 3.1 | 90.4 | 2.8 | 2.4 | 2.6 |
| 11 | ICSB 11037 | Female | 79.9 | 6.1 | 3.3 | 1.7 | 7.8 | 121.7 | 75.4 | 8.2 | 28.3 | 10.1 | 2.6 | 98.7 | 0.7 | 2.1 | 2.6 |
| 12 | ICSR 89058 | Male | 71.0 | 5.8 | 3.6 | 0.9 | 6.2 | 135.4 | 66.7 | 6.9 | 28.2 | 6.1 | 4.0 | 98.1 | 7.7 | 1.9 | 2.6 |
| 13 | Seredo | Check | 65.8 | 5.2 | 3.4 | 3.4 | 7.3 | 145.3 | 63.5 | 6.7 | 28.0 | 7.0 | 5.5 | 97.6 | 3.1 | 2.3 | 2.6 |
| 14 | ICSV 700 | Male | 81.0 | 5.0 | 3.1 | 1.2 | 12.7 | 192.6 | 58.7 | 7.5 | 21.4 | 6.8 | 0.2 | 98.6 | 2.7 | 2.1 | 2.5 |
| 15 | ICSB 75 | Female | 75.6 | 6.4 | 3.4 | 2.6 | 10.3 | 142.9 | 74.9 | 8.5 | 30.5 | 6.5 | 6.7 | 85.0 | 3.6 | 2.9 | 2.5 |
| 16 | ICSB 11036 | Female | 81.3 | 6.3 | 4.1 | 1.9 | 10.1 | 111.6 | 67.9 | 7.7 | 21.4 | 8.1 | 1.6 | 96.7 | 0.3 | 2.3 | 2.5 |
| 17 | Macia | Male | 73.7 | 5.8 | 3.8 | 1.9 | 8.1 | 109.4 | 62.8 | 7.4 | 21.2 | 6.7 | 4.5 | 93.2 | 2.5 | 2.2 | 2.4 |
| 18 | ICSR 38 | Male | 72.8 | 5.1 | 3.3 | 0.9 | 5.0 | 120.2 | 66.8 | 7.0 | 25.3 | 6.7 | 4.6 | 93.8 | 6.9 | 1.8 | 2.4 |
| 19 | BTX 623 | Female | 70.6 | 6.0 | 3.4 | 1.9 | 6.2 | 105.5 | 69.8 | 7.3 | 25.6 | 5.6 | 4.6 | 93.8 | 2.1 | 2.1 | 2.4 |
| 20 | ICSB 11019 | Female | 76.1 | 6.3 | 3.7 | 2.1 | 8.4 | 112.1 | 71.4 | 7.7 | 23.6 | 5.5 | 1.0 | 85.0 | 0.8 | 2.3 | 2.4 |
| 21 | ICSB 11033 | Female | 74.1 | 5.8 | 3.3 | 2.7 | 3.9 | 126.7 | 68.1 | 7.6 | 26.9 | 9.0 | 0.0 | 92.6 | 3.7 | 2.4 | 2.4 |
| 22 | ICSB 11004 | Female | 71.7 | 5.7 | 3.9 | 3.7 | 5.6 | 119.2 | 65.4 | 6.9 | 30.7 | 7.0 | 2.9 | 92.4 | 2.3 | 2.4 | 2.4 |
| 23 | ICSB 29003 | Female | 75.9 | 6.0 | 3.2 | 1.9 | 6.5 | 105.1 | 65.6 | 7.7 | 25.5 | 8.3 | 4.3 | 77.5 | 1.0 | 2.2 | 2.4 |
| 24 | ICSB 11016 | Female | 77.1 | 6.4 | 3.3 | 1.3 | 5.9 | 106.8 | 66.8 | 8.4 | 26.0 | 7.9 | 0.3 | 93.3 | 0.9 | 2.4 | 2.3 |
| 25 | ICSB 11039 | Female | 74.8 | 5.6 | 4.3 | 0.7 | 5.5 | 109.2 | 70.8 | 7.2 | 24.6 | 6.6 | 3.9 | 95.2 | 3.3 | 1.9 | 2.3 |
| 26 | ICSB 29011 | Female | 80.3 | 5.5 | 3.6 | 2.3 | 8.4 | 132.6 | 66.9 | 8.5 | 24.2 | 7.7 | 10.0 | 83.3 | 1.7 | 2.2 | 2.2 |
| 27 | ICSB 29002 | Female | 79.4 | 5.9 | 3.9 | 2.2 | 6.9 | 118.7 | 68.7 | 7.7 | 26.2 | 7.7 | 1.2 | 92.4 | 1.1 | 2.0 | 2.2 |
| 28 | ICSB 12 | Female | 72.9 | 5.9 | 3.4 | 1.2 | 4.9 | 104.3 | 68.2 | 6.4 | 27.3 | 6.6 | 2.6 | 97.6 | 3.2 | 1.9 | 2.2 |
| 29 | KARI Mtama 1 | Male | 70.3 | 5.3 | 3.1 | 0.9 | 8.5 | 139.8 | 70.6 | 7.4 | 21.6 | 7.4 | 4.9 | 98.5 | 2.6 | 2.9 | 2.2 |

Appendix 3 Continued

| Rank | Genotype | Status | DFL | SG | WB | NTIL | BYLD | PHT | LL | LW | PL | PW | PE | SS | LO | SD | GY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 30 | ICSB 74 | Female | 82.7 | 6.3 | 3.6 | 2.0 | 14.3 | 154.1 | 70.3 | 7.8 | 29.2 | 7.7 | 3.9 | 95.3 | 0.6 | 2.6 | 2.1 |
| 31 | ICSB 232 | Female | 78.4 | 5.6 | 3.8 | 4.1 | 6.1 | 106.5 | 69.9 | 8.0 | 27.3 | 6.4 | 0.5 | 97.7 | 0.3 | 2.4 | 2.1 |
| 32 | Hakika | Male | 70.9 | 5.5 | 3.4 | 1.2 | 7.1 | 113.5 | 68.4 | 6.9 | 24.8 | 6.1 | 1.8 | 96.7 | 0.6 | 2.6 | 2.1 |
| 33 | Wahi | Male | 71.0 | 5.8 | 3.7 | 1.1 | 6.9 | 104.6 | 66.8 | 7.4 | 26.6 | 6.2 | 4.5 | 89.5 | 1.4 | 2.6 | 2.1 |
| 34 | ICSB 11003 | Female | 72.1 | 5.8 | 2.9 | 4.3 | 4.5 | 109.8 | 64.6 | 6.4 | 26.2 | 7.6 | 1.4 | 95.2 | 0.9 | 2.6 | 2.1 |
| 35 | ICSB 29015 | Female | 78.4 | 5.4 | 3.3 | 2.4 | 7.8 | 122.2 | 68.6 | 7.9 | 25.2 | 7.1 | 4.7 | 93.1 | 0.0 | 2.3 | 2.0 |
| 36 | ICSB 11007 | Female | 78.6 | 6.0 | 3.6 | 1.2 | 7.0 | 128.1 | 64.9 | 7.9 | 27.1 | 5.8 | 2.0 | 95.5 | 4.0 | 2.5 | 2.0 |
| 37 | ICSB 11034 | Female | 73.6 | 5.7 | 3.2 | 3.0 | 3.8 | 98.0 | 62.4 | 7.4 | 28.3 | 6.4 | 4.7 | 94.3 | 2.7 | 2.0 | 1.9 |
| 38 | ICSB 29005 | Female | 73.8 | 5.6 | 3.8 | 1.6 | 5.3 | 100.7 | 73.6 | 7.3 | 23.8 | 6.6 | 2.3 | 77.3 | 3.6 | 2.2 | 1.9 |
| 39 | ICSB 11035 | Female | 74.2 | 6.4 | 3.8 | 1.8 | 6.5 | 85.2 | 61.9 | 7.5 | 20.6 | 6.0 | 0.7 | 97.5 | 1.7 | 2.0 | 1.9 |
| 40 | ICSB 29007 | Female | 87.1 | 5.8 | 3.8 | 3.0 | 9.6 | 137.7 | 77.4 | 7.9 | 25.9 | 5.8 | 7.7 | 97.0 | 0.3 | 2.0 | 1.8 |
| 41 | ICSB 29017 | Female | 80.1 | 6.3 | 3.7 | 1.0 | 8.3 | 128.9 | 72.1 | 9.6 | 24.6 | 6.2 | 9.9 | 83.7 | 0.4 | 2.0 | 1.8 |
| 42 | ICSB 11013 | Female | 77.8 | 6.9 | 3.2 | 2.9 | 5.8 | 102.2 | 65.9 | 9.3 | 29.2 | 8.7 | 0.2 | 96.0 | 2.7 | 2.3 | 1.8 |
| 43 | ICSB 29001 | Female | 83.4 | 6.0 | 4.1 | 0.6 | 7.7 | 98.8 | 61.0 | 7.6 | 22.9 | 6.2 | 0.3 | 97.4 | 0.6 | 2.1 | 1.7 |
| 44 | ICSB 228 | Female | 80.5 | 6.3 | 3.6 | 2.8 | 6.3 | 90.7 | 65.3 | 9.3 | 27.3 | 8.4 | 0.0 | 95.8 | 0.2 | 2.0 | 1.7 |
| 45 | ICSB 101 | Female | 75.2 | 5.4 | 3.6 | 1.0 | 6.7 | 110.3 | 70.9 | 7.6 | 24.5 | 6.4 | 5.0 | 89.8 | 0.2 | 2.0 | 1.7 |
| 46 | ICSB 25002 | Female | 78.9 | 6.7 | 3.7 | 1.9 | 6.6 | 95.7 | 74.8 | 7.4 | 27.1 | 6.7 | 0.4 | 92.4 | 0.6 | 2.0 | 1.6 |
| 47 | ICSB 206 | Female | 74.7 | 6.2 | 3.9 | 2.7 | 1.0 | 66.0 | 50.7 | 7.0 | 21.3 | 5.4 | 0.8 | 84.0 | 0.0 | 1.8 | 0.9 |
| | **G.means** | | **75.9** | **5.9** | **3.6** | **2.0** | **7.2** | **119.6** | **67.7** | **7.7** | **25.4** | **7.0** | **3.1** | **93.2** | **2.2** | **2.2** | **2.3** |
| | F pr. | | <.001 | <.001 | 0.733 | 0.002 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 |
| | LSD0.01 | | 4.01 | 0.96 | 1.67 | 4.40 | 3.50 | 17.53 | 7.35 | 1.01 | 5.82 | 2.38 | 4.55 | 13.19 | 3.90 | 0.50 | 1.12 |
| | SE± | | 3.27 | 0.78 | 1.37 | 3.59 | 2.86 | 14.31 | 6.00 | 0.82 | 4.75 | 1.95 | 3.71 | 10.77 | 3.19 | 0.41 | 0.91 |
| | cv% | | 4.3 | 13.4 | 37.8 | 116.9 | 36.3 | 11.5 | 8.9 | 10.2 | 17.1 | 24 | 94.4 | 11.5 | 160 | 17.4 | 30.7 |

DFL=days to flowering, SG=stem girth (cm), NTIL=number of tillers, BYLD=biomass yield (tha-1), PHT=plant height (cm), LL=leaf length (cm), LW=leaf width (cm), PL=panicle length (cm), PW=panicle width (cm), PE=panicle exertion (cm), LO=number of plants lodged, SD=100 seed mass (g), GY=grain yield (tha-1), LSD=least significant difference, SE=standard error of differences, CV%=Coefficient of variation, ns=not significant.

Appendix 4: Weather data for Kiboko and Kampi ya Mawe Year 2014 and 2015

| | | Kampi ya Mawe | | | Kiboko | | |
|---|---|---|---|---|---|---|---|
| Year | Month | Tmax°C | Tmin°C | Rainfall (mm) | Tmax°C | Tmin°C | Rainfall (mm) |
| 2014 | Jan-14 | 29 | 17.4 | 0 | 30.0 | 17.0 | 0.0 |
| 2014 | Feb-14 | 29.5 | 18.5 | 91.9 | 32.5 | 18.4 | 55.0 |
| 2014 | Mar-14 | 29.4 | 19.1 | 153.7 | 31.9 | 19.3 | 186.5 |
| 2014 | Apr-14 | 28 | 19 | 99.9 | 31.4 | 19.5 | 42.5 |
| 2014 | May-14 | 28 | 18 | 21.8 | 30.2 | 16.6 | 12.4 |
| 2014 | Jun-14 | 27 | 17 | 2.9 | 28.9 | 15.5 | 4.0 |
| 2014 | Jul-14 | 27 | 16 | 0 | 27.9 | 14.0 | 0.4 |
| 2014 | Aug-14 | 28 | 16 | 0 | 29.5 | 14.2 | 0.0 |
| 2014 | Sep-14 | 28 | 17 | 1.5 | 30.3 | 16.1 | 1.5 |
| 2014 | Oct-14 | 30 | 18 | 9 | 32.9 | 18.1 | 2.5 |
| 2014 | Nov-14 | 28 | 16 | 161.6 | 31.0 | 18.7 | 186.5 |
| 2014 | Dec-14 | 27 | 10.5 | 166.3 | 29.6 | 18.4 | 199.5 |
| 2015 | Jan-15 | 30 | 16 | 20.3 | 32.1 | 16.2 | 0.0 |
| 2015 | Feb-15 | 32 | - | 0 | 33.5 | 17.9 | 52.5 |
| 2015 | Mar-15 | 31.3 | - | 18.7 | 32.6 | 17.9 | 64.5 |
| 2015 | Apr-15 | 29 | - | 269.9 | 32.1 | 18.7 | 185.6 |
| 2015 | May-15 | 27.8 | - | 16.6 | 30.0 | 17.2 | 83.2 |
| 2015 | Jun-15 | 27 | - | 4.5 | 29.4 | 14.9 | 8.7 |
| 2015 | Jul-15 | 26 | - | 3.5 | 28.7 | 13.9 | 3.8 |
| 2015 | Aug-15 | 26 | - | 2.7 | 28.3 | 14.6 | 5.0 |
| 2015 | Sep-15 | 28.6 | - | 0 | 31.0 | 15.4 | 0.0 |
| 2015 | Oct-15 | 30 | - | 6 | 31.8 | 17.7 | 0.5 |
| 2015 | Nov-15 | 28.3 | - | 248.2 | 31.4 | 18.8 | 155.0 |
| 2015 | Dec-15 | 27.5 | - | 120.8 | 30.9 | 17.9 | 160.5 |

Appendix 5 List of sorghum hybrids and a check used in the study

| Entry no | Genotype | Status |
|---|---|---|
| 1 | ICSA 11019 x Hakika | Hybrid |
| 2 | ICSA 11013 x Hakika | Hybrid |
| 3 | ICSA 228 x Hakika | Hybrid |
| 4 | ICSA 11003 x ICSR 160 | Hybrid |
| 5 | ICSA 11033 x ICSR 160 | Hybrid |
| 6 | ICSA 11004 x ICSR 24008 | Hybrid |
| 7 | ICSA 232 x ICSR 24008 | Hybrid |
| 8 | ICSA 29007 x ICSR 24008 | Hybrid |
| 9 | ICSA 29004 x ICSR 24010 | Hybrid |
| 10 | ICSA 29005 x ICSR 24010 | Hybrid |
| 11 | ICSA 29017 x ICSR 24010 | Hybrid |
| 12 | ICSA 101 x ICSR 38 | Hybrid |
| 13 | ICSA 29016 x ICSR 38 | Hybrid |
| 14 | ICSA 75 x ICSR 38 | Hybrid |
| 15 | ICSA 29011 x ICSR 89058 | Hybrid |
| 16 | ICSA 29015 x ICSR 89058 | Hybrid |
| 17 | ICSA 29001 x ICSV 700 | Hybrid |
| 18 | ICSA 29002 x ICSV 700 | Hybrid |
| 19 | ICSA 29003 x ICSV 700 | Hybrid |
| 20 | ICSA 11040 x IESV 91104 DL | Hybrid |
| 21 | ICSA 206 x IESV 91104 DL | Hybrid |
| 22 | ICSA 25002 x IESV 91104 DL | Hybrid |
| 23 | ICSA 12 X IESV 92172 DL | Hybrid |
| 24 | ICSA 11036 x KARI Mtama 1 | Hybrid |
| 25 | ICSA 11038 x KARI Mtama 1 | Hybrid |
| 26 | ICSA 11039 x KARI Mtama 1 | Hybrid |
| 27 | ICSA 11034 x Macia | Hybrid |
| 28 | ICSA 11035 x Macia | Hybrid |
| 29 | ICSA 11037 x Macia | Hybrid |
| 30 | ICSA 74 x Macia | Hybrid |
| 31 | ATX 623 x Macia | Hybrid |
| 32 | ICSA 11007 x Wahi | Hybrid |
| 33 | ICSA 11016 x Wahi | Hybrid |
| 34 | ICSA 11018 x Wahi | Hybrid |
| 35 | Seredo | Check OPV |