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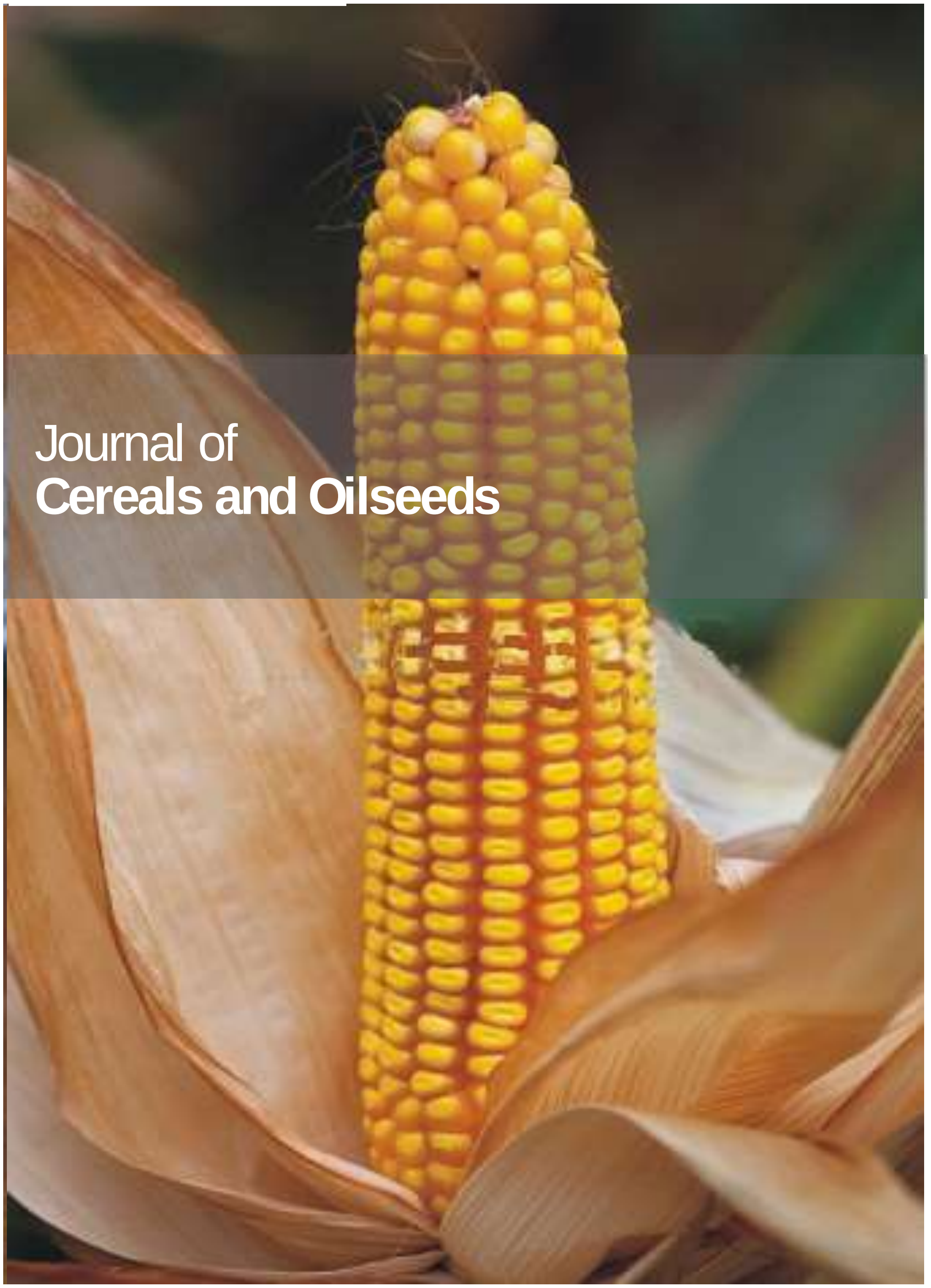

July-December 2020
ISSN 2141-6591
DOI: 10.5897/JCO
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Vol. 11(2), pp. 37-43, July-December 2020
DOI: 10.5897/JCO2020.0217
Article Number: DDDEC8C64707
ISSN 2141-6591

http://www.academicjournals.org/JCO

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Journal of Cereals and Oilseeds

Review

Understanding biodiversity in sorghums to support the development of high value bio-based products in sub-Saharan Africa

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Received 7 July, 2020; Accepted 25 August, 2020

Sorghum [*Sorghum bicolor* (L.) Moench] is one of the most important cereals worldwide with great genetic diversity. Like most small grains it has good adaptation to drought prone and marginal areas were other cereals are not productive. Globally, sorghum has been underutilized compared to other cereal staple crops however, there is growing interest in sorghum and its related products due to its unique nutritional traits, crop physiology and phenology. Given the genetic variability of sorghum there is great scope to use the crop to produce an array of commodities in the food, feed, industrial and bioenergy sector. This review paper presents sorghum genetic diversity and with special reference to bio-based and value added products such as gluten free, high protein, aromatic, syrup, popping, weaning, pet food, baked products and alcohol free malt beverages that can be explored in Africa to popularize it and improve livelihoods.

Key words: Small grain, sorghum bicolor, value addition.

INTRODUCTION

Sorghum [*Sorghum bicolor* (L.) Moench] is an important cereal that ranks fifth after rice, wheat, maize, and barley. In sub-Saharan Africa (SSA), it ranks second in importance after maize (Prajapati et al., 2018). Sorghum comprises the main food source from which over half a billion people in developing countries who derive their energy requirements from it (Oluwafemi, 2020). Sorghum is inherently adapted to hot and dry areas which give it an edge over other crops in such hostile environments. Consequently, the importance of the crop is now being released in most African countries given the unprecedented changes due to climate change (Boyles et

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al., 2019). Strengthening sorghum production is therefore essential for improving food security and livelihoods in SSA. Globally the utility of sorghum varies with geographical location and technological advances. Accordingly, this review sought to understand the sorghum germplasm resource base in SSA, its characteristics and potential for value addition based on specialty attributes. This is in recognition that the diversification of sorghum products could play a role in transforming livelihoods of people in marginal areas and beyond.

BIODIVERSITY OF SORGHUM

Sorghum belongs to the genus Sorghum, tribe Andropogoneae, Poaceae family which is made up three main species namely *S. bicolor*, *S. halepense* and *S. propinquum* (Kunth) Hitchc. (Verma et al., 2017). *Sorghum bicolor* includes all the cultivated sorghums which are Bicolor, Kafir, Caudatum, Durra and Guinea races. These races further have various sorghum use types that include; grain, forage, sweet/syrup, biomass and broom sorghum. These differ in their morphological features of the stem, inflorescence, grain and glumes (Buschmann, 2018).

The center of origin of cultivated sorghum is Ethiopia, from where it was disseminated to other regions of the world (Tesfaye, 2017). Cultivated sorghum is a genetically diverse diploid (2n = 20). It is sexually compatible with some of its wild or weedy relatives such as Johnson grass (*Sorghum halepense*) (OECD, 2017). Wide sorghum biodiversity has been reported within and among cultivars at morphological and genotypic level. Plant breeders exploit this biodiversity for crop improvement that meets specific requirements crucial for food and nutrition security and livelihoods (Tesfaye, 2017). Increased loss of crop biodiversity can be attributed among other factors to the promotion of large scale monocultures and the use of a limited number of introduced commercially available sorghum varieties. Crop biodiversity present in sorghum provides the opportunity for development of specialty sorghum types targeting niche markets and end uses. Various natural mutants of sorghums with altered starch, protein and phenolic properties offer benefits for nutrition and/or processing (González, 2005; Weerasooriya et al., 2018). Sorghum kernels vary in size, shape, colour, density, hardness, composition, texture, processing properties, taste and nutritive value (Rooney and Awika, 2005; Rhodes, 2014). This makes them amenable to a wide range of uses, some unique for a cereal which span the food, feed, fuel and various types of novel products.

COMPARATIVE PERFORMANCE OF SORGHUM

The adaptation of sorghum is due to its unique crop physiology, phenology and phenotypic plasticity (Boyles et al., 2019). Being a unique C4 plant, sorghum has high photosynthetic efficiency in drier and hotter areas compared to other cereals (Kanbar et al., 2019). Morphologically sorghum has several characteristics that enable it to adapt to drought stressed environments such as a deep extensive root system, thick waxy cuticles, narrow leaf sizes and leaf rolling (Hasanuzzaman et al., 2013; Takele and Farrant, 2013; Schittenhelm and Schroetter, 2014; Hadebe et al., 2017). Various physiological traits and responses such as stay green traits, pronounced osmotic adjustment and stomatal regulation give sorghum greater adaptive ability to drought prone environments than other cereals (Thomas and Howarth, 2014; Hadebe et al., 2019). Furthermore, sorghum is adapted to marginal environments such as saline, infertile, alkaline and waterlogged soils (Muui, 2014). Sorghum is easier and less expensive to cultivate, requires fewer pesticides and fertilizers and has lower greenhouse gas emissions on a life-cycle basis than maize (Kanbar et al., 2019). Accordingly, sorghum is a suitable alternative in many places where most cereal crops are not adapted.

CHEMICAL COMPOSITION OF SORGHUM

The nutrient composition of sorghum is comparable to that of other cereals (Table 1) making it a suitable crop choice to complement dietary and energy needs for populations in areas where other cereals are not well adapted.

Sorghum contains approximately 4.4 to 21.1% protein, 55 to 75% starch, 0.5 to 7.6% lipids, 0.7 to 4.2% soluble sugars and 1 to 6% crude fiber on a dry weight basis. Approximately 80, 16 and 3% of the protein is contained in the endosperm, embryo, and pericarp, respectively. The endosperm is made up of 80 to 82% starch, which is comprised of 70 to 80% branched amylopectin and 20 to 30% amylase (Ratnavathi and Patil, 2014). The starch for waxy, glutinous sorghum is almost 100% amylopectin with no amylose. Sorghum grain also contains some anti-nutritional factors such as tannins and phytins. These bind to proteins and other nutrients present in grain making them unavailable for the intestinal absorption, thus inhibiting their digestibility (Queiroz et al., 2015).

COMMON AND PROSPECTIVE USES OF SORGHUM

More than 35% of world sorghum production is dedicated to human consumption, while the rest is for animal feed, brewery and other industrial products (Kangama, 2017). Besides the traditional use of sorghum at household level there are several raw materials derived from the crop such as starch, fiber, dextrose syrup, biofuels, edible oils

Table 1. Comparative analysis of nutrient composition of sorghum versus other staple cereals.

Cereal type	Protein (g)	Fat(g)	Crude fibre (g)	Carbohydrate (g)	Energy (kcal)	Calcium (mg)	Iron(mg)
Rice (brown)	7.9	2.7	1.0	76.0	363	33	1.8
Wheat	11.6	2.0	2.0	71.0	348	30	3.5
Maize	9.2	4.6	2.8	73.0	358	26	2.7
Sorghum	10.4	3.1	2.0	70.7	329	25	5.4
Pearl millet	11.8	4.8	2.3	67.0	363	42	11.0
Finger millet	7.7	1.5	3.6	72.6	336	35	3.9

Source: Muui (2014).

and gluten free feed (Muui, 2014). Furthermore, crop residues provide sources of building materials, and fuel, particularly in the semi -arid tropics (SAT). In Africa, white and red sorghum have been traditionally used to produce opaque low-alcohol beers such as lager and stout on a large industrial scale. The darker sorghums are usually avoided because of high levels of tannins; however some farmers prefer them because it is believed that the tannins play a defensive role against fungi, insects and birds (Ramatoulaye et al., 2016). Farmers doing field work mostly prefer tannin sorghum porridge because they remain full for longer periods. The slower digestibility of tannin sorghums is most likely related to the binding that occurs between the tannins, proteins and other components of the grain (Rooney and Awika, 2005). Worldwide for consumption purposes, sorghum is used to make various boiled, steamed, baked, fermented and deep fried products (Arendt and Zannini, 2013).

SPECIALTY SORGHUM AND NOVEL PRODUCTS

A specialty crop is a plant that can be cultivated and used by people for food, medicinal or aesthetic purposes and to produce some novel products. A wide range of uses and sorghum types exist worldwide that can be adopted by farmers and communities in Africa to improve their livelihoods and nutrition. Sorghum is a gluten-free cereal that can serve as an alternative to wheat for people with celiac disease (Schaffert et al., 2012). In the developed countries sorghum was primarily used a feed crop but now there is growing demand for gluten free food products (Mofokeng et al., 2017). The lack in Vitamin A in diets causes blindness especially in children. There are some sorghum types with yellow grain and they are referred to as yellow sorghums which can be used to solve this problem especially in poor communities. Yellow sorghums derive their colour from carotenes and xanthophylls that are vitamin-A precursors (Rooney and Awika, 2005). This special type of sorghum is more popular in Nigeria. In Ethiopia there is an elite type of sorghum which is highly nutritious and very palatable. Its taste has been described as that of roasted chestnuts. Analysis of this type of sorghum showed that it contained thirty percent more protein than other sorghums and the protein had twice the normal level of lysine (Afify et al., 2012). Other types of sorghums with small white seeds can be boiled like rice. These sorghum type belongs to the guinea race and very little is known about this interesting type of sorghum (Young et al., 1993). In some parts of Sri Lanka and India there is some sorghum which have an aroma of basmati rice. Basmati rice is Asian rice with a fragrance and is sold worldwide as a highly priced specialty. The discovery and breeding of such aromatic sorghums might open up opportunities as they can become specialty foods of high value. This will in turn help to improve markets and boost the acceptance and consumption of sorghum (National Research Council, 1996).

Some sorghum type pop like popcorn is found in parts of Africa and Asia. Popping in its nature enhances flavour, is nutritionally desirable and saves a lot of energy as it is rapid and hydrolyses the vitamins and proteins slightly as compared to boiling (Golubinova et al., 2017). In India and even in certain parts of Binga in Zimbabwe, sorghum is eaten like green mealies. The panicle is harvested at soft dough stage (milky stage) when the grains are still sweet. This is either boiled or roasted and the sweet grains make a very pleasant meal (National Research Council, 1996). Sweet sorghums have high soluble sugar content and dry matter yields; these are normally referred to as sorghos. In the United States, these sorghums are used to produce sorghum syrup, similar to molasses. In Southern Africa, sweet sorghum is popular but commercial seed are rarely available and farmers resort to the informal seed sector to access planting material at subsistence level. These, however, have a great potential for the production of renewable fuels. Syrup and sugar can be readily produced from these sweet sorghums. Sweet sorghum types which contain enough fructose which prevents crystallization are selected to make syrup while those that contain sucrose and can readily crystalize are used for sugar production (Dahlberg et al ., 2011).

OPPORTUNITIES FOR SPECIALTY SORGHUMS

Strengthening sorghum production is considered essential for improving food, nutrition security and livelihoods in developing countries and Africa in particular. In most African countries, the current product portfolio of sorghum is milled flour for food and beer brewing. New niche markets for bio based sorghum products may have ripple effects, reorient plant breeding programmes and stimulate more demand by various stakeholders for the crop (Suad and Maarouf, 2015).

Ethanol production

The negative impacts of fossil fuels on the environment have revived the drive for alternative sources of energy such as ethanol. Plant based sources of energy have the advantages of providing cleaner fuels which are renewable and their production can be integrated with food production. Compared to sugarcane and maize, sorghum is able to thrive with less water. Yan et al. (2011) reported that about four percent of US ethanol was being produced from sorghum grain while ninety five percent of ethanol was produced from maize. More fuel ethanol can be produced from sorghum given the advantages it has over maize and sugarcane. It is however noteworthy that production of plant based sources of energy should not compete with food crops given the challenges of food security particularly in Africa. A study done by Kim et al. (2012) revealed that even the panicle, bagasse and leaves of sweet sorghum varieties can be fermented and as well be used to produce ethanol. This was supported by Wright et al. (2016) who concluded that sweet sorghum bagasse had favourable fuel value compared to sugarcane bagasse. Furthermore, bagasse can be used to reinforce wood composites, as a fertilizer, hay and paper production (Ashori, 2008; Bluemmel et al., 2009; Ghanbari et al., 2014). Besides the use for ethanol production, sorghum juice can be used to produce bio-plastics and beverages (Pabendon et al., 2017). Sorghum producing countries can also adopt the technologies used by other countries and use this crop to produce fuel which is currently very scarce and expensive (Tang et al., 2018).

Waxy and heterowaxy sorghums

The starch of waxy and heterowaxy sorghums is composed of 0 and 17% amylose respectively and almost 100% amylopectin. This is attributed to the absence or inactivation of granule-bound starch synthase (GBSS) (Pedersen et al., 2005). In sorghum, the waxy trait is recessive controlled by alleleswxalleles. In waxy wx^a the GBSS is absent and in waxy wx^b there is reduced activity of the GBSS (Funnell-Harris et al., 2015). Waxy sorghums are superior to non-waxy ones dry matter, feed efficiency and gross energy digestibility (Ezegou et al., 2005). Since amylopectin has low viscosity, it can therefore be easily digested by amylases due to a lower gelatinization temperature. This natural waxy mutation renders the starch with low amylase more amenable for use for feed, food, and grain-based ethanol (González, 2005).

Functional foods production

Products such as gluten-free foods, flakes, weaning foods and noodles can be produced from sorghum using various technologies. Most of these uses take into cognizance the nutrient properties of sorghum like comparatively high levels of niacin, vitamin B and fibre (Edia, 2018). There is high sensory acceptance, antioxidant activity and dietary fibre in sorghum derived breakfast cereals compared to wheat based ones (Anunciação et al., 2017; Lopes et al., 2018). A good example of a ready to eat cereal made from sorghum is Morvite, a pre-cooked sorghum with added vitamins, citric acid, and sweeteners. This is an instant porridge formulation taken after the addition of warm or cold water (Taylor, 2004).

Weaning foods

Weaning is a transition where the infant diet changes from liquid milk to semi-solid food. Such semi-solid food is called ‘weaning food’. The weaning food is expected to be easily digestible, high in energy density and low in bulk. A study done by Aloysius and Ajawubu (2013) revealed that sorghum can be blended very well with Bambara nuts (*Voandzeia subterraneal* (L.) Vigna) to produce a weaning food which is rich in proteins. This was observed to prevent protein energy malnutrition which is prevalent especially in children living in rural communities of developing nations. Blending sorghum based weaning foods with legumes and oil seeds supplements make them a complete diet for infants (Usman et al., 2016).

Baked products

In Germany and other parts of Eastern Europe, tannin containing varieties are used to make confectionary products like chocolate cakes, cookies and muffins, or molasses cookies as they are believed to be more healthy (Taylor et al., 2006). In wheat flour blends, sorghum can improve nutrition, food quality and health functions for example in pasta. Moreover, sorghum is slowly digested as compared to other cereals and this is advantageous for diabetics as it helps in reducing obesity (Rooney and Awika, 2005; Teferra and Awika, 2019).

Malt beverages

The use of sorghum in tea beverages has not been fully successful and therefore improvements can be made to make grain tea beverages from sorghum. Other novel products which can be produced from sorghum are low calorie and nutritive drinks made from sorghum powders. The powders should be able to infuse with water or milk. Since sorghum is naturally low in fat the drinks may have the potential of being fully accepted by the society given the fact that more people nowadays are more concerned about their health and want to avoid fatty foods. Non-alcoholic beverages such as “Milo” are made from sorghum malt and cocoa. Sorghum mealie meal can also be fermented to produce a non-alcoholic drink known as *Mahewu*. This can also be blended with Bambara groundnut to improve its nutritional quality (Qaku et al., 2020).

Sweet sorghum syrup

Sorghum syrup from the juicy stem can be used as a natural alternative sweetener in breakfast, confectionery and diary industries. The syrup unlike sugarcane sweeteners has a better mineral nutrient profile rich in iron, calcium and zinc (Ratnavathi and Patil, 2014). Furthermore, biomass of sweet sorghum can also be an alternative livestock feed (Yucel, 2020).

Health benefits

Compared to other cereals, sorghum has “good” carbohydrates that are made up of slowly digestible starch and resistant starch which contributes to a low glycemic index (Teferra and Awika, 2019). Furthermore, some sorghum varieties especially the pigmented ones, contain health-beneficial phenolic compounds. Documented health benefits attributed to phenolic extracts include prevention and treatment of colon cancer, anti-inflammatory activity and antioxidant properties (Vanamala et al., 2018).

Pet food from sorghum

Given the similarity in starch properties with other cereals, sorghum can be used in pet food formulations as an alternative (Di Donfrancesco and Koppel, 2017). Furthermore, by-products from ethanol production can be used in pig and rabbit as an additive. However, care is needs to be exercised when using red sorghum due to polyphenolic anti-nutritional that require additional ingredients to enhance palatability and digestibility (Yang et al., 2019).

CHALLENGES ASSOCIATED WITH SORGHUM

Lack of sorghum processing technologies to address niche markets is a limiting factor in their utilisation for biobased products (Ratnavathi and Patil, 2014). Pigmented sorghums are particularly rich in phenolic compounds which cannot be digested readily by the human body. Furthermore, preparation of food items from such sorghum is very laborious and time-consuming, for example, to make them palatable, the tannins must be firstly removed by either milling or pounding. The seeds are pounded using heavy poles and this make life difficult especially for the rural communities depending on sorghum as their staple food. This is a barrier to the wider use of this crop and thus it is considered as a poor man’s crops (Rao et al., 2010; Musara et al., 2019). These factors are the reason why other cereals like maize, wheat and rice are favoured because they are can be easily processed and cooked (Ratnavathi and Patil, 2014). Breeding of specialty sorghums such as dual purpose sorghums is a challenge as only a few sorghum genotypes have good combining ability for both high grain yield and high biomass (Chikuta, 2017).

PROPOSED PERSPECTIVES AND DIRECTIONS

Given that water is becoming more and more limiting for agricultural production, sorghum will play a major role in agricultural production systems throughout the world. The potential for sorghum in semi-arid drought prone and marginal areas of Africa is vast. Several bio-based products and downstream industries can develop from the crop. However, cost reductions in the production of this novel value added products and pro-active government policies that promote the use of sorghum are the prerequisites for commercialization of sorghum to take place. In future breeding sorghum, varieties for increased grain yield without regard to quality will be a major mistake. Poor quality grain cannot be made into acceptable value added products. Therefore major stakeholders in crop breeding, that is, Consultative Group for International Agricultural Research (CGIAR**)** and the National Agricultural Research System (NARS) should not only focus on grain sorghum but also on these specialty types of sorghum. This continued, focused, fundamental and applied research will stimulate demand by various stakeholders in the sorghum production chain. There is also need for promotional campaigns to increase public awareness of alternative products and processing technologies for the diverse sorghum germplasm. Furthermore, smallholder farmers should be included in the sorghum value chain by empowering them with appropriate planting material, production skills and market linkages. These steps will strengthen the sorghum value chain in Africa and contribute in eradicating hunger and poverty in the continent and even the world at large.

CONFLICT OF INTERESTS

The authors received financial support of the Benefit-Sharing Fund of the International Treaty on Plant Genetic Resources for Food and Agriculture (Reference Number LoA/TF/PR-316-Uganda/2019/CBDT).

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Vol. 11(2), pp. 44-51, July-December 2020
DOI: 10.5897/JCO2020.0209
Article Number: 5D8196B65448
ISSN 2141-6591

http://www.academicjournals.org/JCO

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Journal of Cereals and Oilseeds

Full Length Research Paper

Multi-locations evaluation of sorghum (*Sorghum bicolor* L.) genotypes for grain yield and yield related traits at western Oromia, Ethiopia

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Received 24 March, 2020; Accepted 13 October, 2020

A field experiment was conducted on twelve sorghum genotypes against one local and two standard checks at Haro Sabu Agricultural Research Center (HSARC) sub sites for three consecutive years (2016-2018) using randomized completely block design (RCBD) to evaluate and select high yielding sorghum genotypes and to assess the impact of genotype by environmental interaction on grain yield and yield components across diverse growing environments of western Oromia. Eight agronomic traits and three economically important disease reaction were collected depending on the crop descriptor. Pooled over locations analysis of variance detected significance difference among tested genotypes for all collected traits. Genotype by environment interactions (G×E) significantly affected all recorded traits excluding days to heading and thousand seed weight. Genotype and genotype by environment interaction (GGE) bi-plot analysis revealed that G3, G11 and G12 as ideal genotypes in terms of yielding ability and stability and were promoted as candidates for possible release and use as genetic resource in future breeding programs.

Key words: Sorghum bicolor L., Genotype by environment interactions (G×E), Genotype and genotype by environment interaction (GGE) bi-plot, stability.

INTRODUCTION

Among grain crops cereals are the major food crops in Ethiopia, both in terms of the land coverage and volume of production (CSA, 2016). Sorghum is the most widely grown food crop in Ethiopia. It thrives in a range of agro-climatic zones including high and low altitudes. High altitude sorghums grow satisfactorily at altitudes as high as 2,300 m where mean temperatures range from a minimum of 14 to 26°C. Sorghum (*Sorghum bicolor* L.) is an important drought tolerant rain fed cereal largely cultivated for food, feed and fodder by subsistence farmers in Ethiopia (Ayana et al., 2000). The national average production of sorghum is 2.5 $tonha^{-1}$ (CSA,

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Table 1. Passport description of the test genotypes.

S/N	Landrace code	Code	Region	Zone	Woreda	Village	Altitude	Soil type
1	SLRC-010	G1	Oromia	K/Wollega	D/sadi	Laku	1514	Sandy
2	SLRC-06	G8	Oromia	W/Wollega	Guliso	D/guda	1708	Sandy clay
3	SLRC-027	G7	Oromia	W/Wollega	Begi	Shelxa	1433	Clay loam
4	SLRC-028	G5	Oromia	W/Wollega	Begi	Meganteya	1584	Sandy loam
5	SLRC-037	G4	Oromia	K/Wollega	Gidami	Alchayajilo	1698	Sandy loam
6	SLRC-043	G3	Oromia	K/Wollega	Seyo	Minko	1690	Sandy loam
7	SLRC-046	G12	Oromia	K/Wollega	H/Galan	Mesareta	1482	Sandy loam
8	SLRC-048	G6	Oromia	K/Wollega	Y/Walel	Odamoti	1369	Clay loam
9	SLRC-058	G11	Oromia	K/Wollega	Y/Walel	Horamelka	1429	Clay loam
10	Local check	G9	Oromia	K/Wollega				
11	Gemadi	G2	Oromia	K/Wollega				
12	Lalo	G10	Oromia	K/Wollega				

2016).Of the total national sorghum production (432,3299.8 ton), Oromia region shares production (1,884,630.1 ton) of sorghum which is almost about half of the total annual production of the country (CSA, 2016). In sub Saharan Africa and south Asia sorghum is consumed as staple food and is also used in the production of a variety of by-products like alcohol, edible oil, and sugar (Wang et al., 2008). It is used as food, feed, beverage, and its stalk was used for construction of fences in Western Ethiopia and surrounding vicinities. It has a dense and deep root, has ability to reduce transpiration through leaf rolling and stomatal closure among others which in turn makes the crop to survive dry spelling periods. Hence sorghum has become a strategic crop in the face of climate unpredictability across different sorghum growing environments. In spite of all these advantages, sorghum has been a neglected crop, both at national as well as global level and the sorghum crop production is still very low (Stemler et al, 1977).

Among figurative problems, a biotic and biotic factor, the effect of genotype by environment interaction and stability of released varieties across the growing environments are the major one (Tesso et al., 2004; Girma et al., 2010). It is recalled that genotype and genotype by environment interaction (GGE) bi-plot is the most recent approach for analysis of G×E and ever more being used in G×E studies in plant breeding research (Yang et al., 2007). The GGE bi-plot model was used extensively in quantitative genetics and plant breeding (Yang et al., 2007). Additionally, the additive main effects and multiplicative interactions (AMMI) model are also defined as powerful tools for effective analysis and interpretation of multi environment data structure in breeding programs. In most cases plant breeders faces instability of yield when genotypes were grown in different environments due to G×E. Therefore, multi -environment trials (MET) are required to identify specific and the general adaptability pattern of genotypes. The aim of the present study was**,** therefore, to examine the stability and yielding performance of sorghum genotypes s and to identify stable and high yielding cultivar for wider cultivation.

MATERIALS AND METHODS

Twelve sorghum genotypes were tested against one local and two standard checks (Table 1) were evaluated for three (2016-2018) cropping seasons at Haro Sabu agricultural research center on station, Hawa-Galan Farmers Training Center (FTC), Kombo FTC, and Guliso FTC of Western Oromia, Ethiopia (Table 2). The trial was planted in randomized completed block design (RCBD) with three replications. Each plot consists of six rows (with four harvestable rows) having 3 m plot length with inter-row and intra-row spacing of 0.75 and 0.15 m, respectively and 2 m spacing was used between each block. A seed rate of 25 $kgha^{-1}$ and recommended fertilizer was applied. All other agronomic practices were performed as per the recommendation for the crop.

Data collection method

Five plants were selected randomly before heading from each row (four harvestable rows) and tagged with thread and all the necessary plant based data were collected from these sampled plants.

Plant-based: Plant height, head height and head weight.
Plot based: Days to heading, days to physiological maturity, lodging percentage, thousand seed weight, grain yield and three economically important insect pest and disease reaction like stalk borer (*Chilo Partellus*), anthracnose (*Colletotrichum sublineolum*) and leaf blight (*Exserhilum turcicum*) were scored.

Statistical analysis

AMMI method as described in Zobel et al. (1988) was used to analyze adaptability and phenotypic stability using the following

Table 2. Description of the test locations for geographical position and soil type.

Locations	Code	Geographical position		Altitude (m.a.s.l) (m)	Average rain fall(mm)	Soil type
		Latitude	Longitude			
Haro Sabu	HS	8° 19'N	35° 30'E	1550	1100	Sandy clay
Kombo	KB	8° 92 'N	35° 09'E	1440	1200	Sandy loam
Guliso	GL	NI	NI	1600	1400	Sandy clay
Hawa Galan	HG	8° 38' N	35° 50'E	1905	1600	Sandy loam

NI=not identified.

statistical model:

$$y_{ij} = \mu + gi + e_j + \sum_{k=n}^{n} \lambda_k \alpha_{ik} y_{ij} + r_{ij} + \varepsilon_{i_j}$$

Where, Y_{ij} is the yield of the i^{th} genotype in the j^{th} environment; μ is the grand mean; g_i and e_j are the genotype and environment deviations from the grand mean, respectively; λ_k is the eigen value of the PCA analysis axis k; α_{ik} and γ_{ij} are the genotype and environment principal component scores for axis k; n is the number of principal components retained in the model and ε_{ij} is the error term.

AMMI stability value of the i^{th} genotype (ASV) was calculated for each genotype according to the relative contribution of IPCA1 to IPCA2 to the interaction SS as follows (Purchase et al., 2000):

$$ASV = \sqrt{[(SS_{IPCA1} \div SS_{IPCA2})(IPCA1score)]^2 + (IPCA2score)^2}$$

Where, SSIPCA1/SSIPCA2 is the weight given to the IPCA1 value by dividing the IPCA1 sum of squares by the IPCA2 sum of squares. Based on the rank of mean grain yield of genotypes (RYi) across environments and rank of AMMI stability value (RASVi) a selection index called Genotype Selection Index (GSI) was calculated for each genotype, which incorporates both mean grain yield (RYi) and stability index in single criteria (GSIi) as suggested by Farshadfar (2008):

GSIi = RASVi + RYi

The analysis of GGE Bi-plot method was carried out for grain yield, according to the following model (Yan and Tinker, 2006).

$\ddot{Y}_{ij} = \lambda 1\ \gamma_{i}1\ \delta_{j}1 + \lambda 2\ \gamma_{i}2\ \delta_{j}2 + \rho_{ij}$

where $\lambda_1$and λ_2 are singular values of the first and second Principal Components (PC) associated with the matrix of the effects of genotypes added to effects of genotype × environment interactions; γ_{i1} and γ_{i2} are eigenvectors of the first and second PC associated with the effect of the genotype i; $\delta_{j1}$and δ_{j2} are eigenvectors of the first and second PC associated with the effect of the environment j; ρ_{ij} is the residual of the model associated with the genotype i in the environment j.

Bi-plots of the scores associated with two first PC were generated to better understanding the interrelationship among genotypes and/or environments, as proposed by Yan and Tinker (2006). Analysis of variance was carried using statistical analysis system (SAS) version 9.2 software (SAS Inst., 2008). AMMI analysis and GGE bi-plot analysis were performed using GenStat 15th edition statistical package (GenStat, 2012).

RESULTS AND DISCUSSION

Combined analysis of variance

All agronomic and yield component parameters were affected by environmental effect whereas all except grain yield were affected by cropping seasons. Days to maturity and head weight of genotypes were not affected across a cropping seasons and it agrees with the findings of Worede et al. (2020). Except days to heading and thousand seed weight all agronomic and yield components among tested genotypes were statistically affected across an environmental set. Statistically significant ($P < 0.01$) difference were documented for grain yield among genotypes, environments and G×E and it's in concordance with the finding of Filho et al. (2014) and Worede et al. (2020)(Table 3).

Yield performance of sorghum genotypes across environments

The mean performance of the tested sorghum genotypes for grain yield showed fluctuation over growing seasons and environments (Table 4). It's also noted that some genotypes consistently performed in a set of tested environments whereas some of them are irregular across locations. The highest grain yield was recorded from G11 (5.56-ton ha^{-1}) genotype at Haro Sabu (2018) whereas the lowest was from G8 (1.27-ton ha^{-1}) at Haro Sabu (2016). The combined over locations showed G12 as the highest yielder. In contrary, the local check included in this study was the low yielder among all tested genotypes that might be stem due to the genetic potential of the genotype (Mengistu et al., 2013). The disparity in yield rank of genotypes across the growing environments displays the prevalence of G×E interactions (Purchase et al., 2000; Yang et al., 2007).

Agronomic performance

Delayed days to heading and days to physiological maturity were recorded from genotypes G11 (132.5) and

Table 3. Analysis of variance (ANOVA) for grain yield and yield related traits of sorghum genotypes evaluated in 2016-2018 main cropping seasons.

Sov	DF	DH	DM	PH	HH	HW	LGD	TSW	YLD
Year	2	653.0**	22.5**	627.9**	55.6*	1158.1**	3274.8**	413.7**	0.56ns
Env	3	3472.5**	4859.5**	620.5**	157.0**	191.4**	431.2**	136.6**	61.2**
Rep	2	27.6**	10.3ns	3.58ns	18.2ns	6.7*	2.3ns	61.8**	17.1*
Gen	11	484.7**	1005.8**	223.6**	180.0**	5.1**	4.06**	29.4**	203.87**
Year×Env	2	60.4**	226.6**	493.9**	100.7**	0.04ns	15.4*	99.0**	0.89ns
Year×Gen	22	125.6**	3.4ns	66.3**	20.1*	0.91ns	4.22ns	27.3**	0.97*
Gen×Env	33	4.3ns	9.6**	35.71**	20.8*	2.41**	7.46**	13.4ns	33.43**

Key: ns=-non –significant, *-significant at (P ≤ 0.05), **-significant at (P ≤ 0.01), DH- Days to heading; DM- Days to maturity; PH- Plant height in cm; HH- Head height in cm; HW-Head weight in gm, LGD- Lodging percentage, TSW- Thousand seed weight in gm, YLD – Yield in ton.

Table 4. Mean grain yield (tonha^{-1}) of sorghum genotypes evaluated at four environments.

Genotype	Grain yield in tonha^{-1}								
	2016		2017				2018		
	Kombo	Haro Sabu	Haro Sabu	Guliso	Hawa Galan	Haro Sabu	Guliso	Hawa Galan	Comb. mean
G1	2.23^{fg}	3.39^{cd}	3.99^{c}	3.56^{ef}	3.96^{de}	3.76^{d}	3.83^{e}	4.01^{bc}	3.59^{d}
G2	2.89^{d}	4.36^{a}-^{c}	4.29^{b}	3.82^{d}	4.12^{cd}	4.40^{c}	4.12^{d}	4.29^{bc}	4.04^{c}
G3	4.52^{a}	4.92^{a}	5.18^{a}	4.82^{b}	5.28^{a}	5.33^{a}	4.89^{b}	4.88^{ab}	4.98^{a}
G4	2.58^{e}	2.83^{de}	4.34^{b}	4.39^{c}	4.35^{bc}	4.77^{b}	4.69^{bc}	4.46^{bc}	4.05^{c}
G5	3.39^{c}	3.13^{d}	3.62^{d}	3.67^{ed}	3.86^{de}	3.83^{d}	3.86^{e}	3.81^{c}	3.65^{d}
G6	4.49^{a}	3.17^{d}	4.50^{b}	4.34^{c}	4.61^{b}	4.63^{bc}	4.53^{c}	4.81^{ab}	4.39^{b}
G7	3.11^{cd}	3.66^{b}-^{d}	3.55^{d}	3.36^{f}	3.69^{e}	3.36^{e}	3.46^{f}	2.36^{d}	3.32^{e}
G8	2.08^{g}	1.28^{f}	2.89^{e}	2.62^{g}	2.48^{g}	2.78^{f}	2.58^{g}	2.86^{d}	2.45^{f}
G9	1.75h	1.69^{f}	2.58^{f}	2.64^{g}	2.82^{f}	2.59^{f}	2.54^{g}	2.73^{d}	2.42^{f}
G10	2.38^{ef}	1.79^{ef}	2.50^{f}	2.39^{g}	2.50^{g}	2.64^{f}	2.60^{g}	2.78^{d}	2.45^{f}
G11	3.86^{b}	3.81^{b}-^{d}	5.33^{a}	5.01^{b}	5.33^{a}	5.56^{a}	4.92^{b}	5.48^{a}	4.91^{a}
G12	3.26^{c}	4.46^{ab}	5.46^{a}	5.48^{a}	5.34^{a}	5.39^{a}	5.25^{a}	5.46^{a}	5.02^{a}
Mean	3.05	3.21	4.03	3.84	4.03	4.09	3.94	3.99	3.77
CV%	5.75	19.54	4.3	3.86	4.21	4.13	3.72	13.05	8.52
LSD(5%)	2.95	1.06	2.92	2.49	2.86	2.85	2.47	8.78	1.83
F test	**	**	**	**	**	**	**	**	**

G12 (131.04) whereas G5 (169.17) and G6 (169.17) were early to days to heading and days to physiological maturity suggesting a great flexibility for developing improved varieties suitable for various agro-ecologies with variable length of growing period. G1, G4, G8, G9 and G10 were high in terms of plant height indicating that these genotypes might be susceptible to root and/or stem lodging (Mengistu et al., 2019). Contrariwise, G3, G11 and G12 genotypes were medium in terms of plant height indicating that the possibility to develop resistant variety against lodging problems. Moreover, G3, G11and G12 were recorded the highest grain yield and they had 23.33, 21.72 and 24.3% yield advantage over the best standard check G2 (Table 5). Those genotypes that had better grain yield among tested genotypes had correspondingly low scores to economically important insect pest and disease reactions. Maximum anthracnose disease reaction score was recorded from G2 and G6. Likewise, maximum leaf blight disease reaction was recorded from G2 and G10. Conversely, G3, G11 and G12 genotypes were better tolerant to stalk borer, anthracnose and leaf blight (Table 6).

Table 5. Combined mean grain yield and other agronomic traits of sorghum genotypes.

Genotypes	DH	DM	LDG	PH	HH	HW	TSW	YAD (%)
G1	127.67^{d}	172.83^{d}	2.5^{b}	420.70	32.87	99.82^{c}	24.76^{e}	-11.09
G2	122.60^{f}	172.92^{d}	2.25^{cd}	327.12^{ef}	26.28^{de}	101.50^{c}	32.79^{b}	0
G3	130.37^{bc}	174.00^{d}	1.04^{h}	349.80^{d}	33.07	114.75^{b}	32.58^{b}	23.33
G4	124.02^{e}	165.62^{f}	2.08^{d}	407.95^{b}	31.66	106.35^{bc}	26.56^{c-e}	0.37
G5	124.42^{e}	169.17^{e}	2.62^{b}	388.83^{c}	31.83	118.88	25.36^{e}	-9.47
G6	122.71^{f}	169.17^{e}	1.7^{ef}	353.3^{d}	29.60^{b}	99.32^{c}	25.69^{de}	8.64
G7	129.83^{c}	175.83^{c}	1.83^{e}	344.05^{de}	28.81^{bc}	103.96^{bc}	27.47^{c-e}	-17.77
G8	120.02^{g}	163.08^{g}	2.29^{c}	407.08^{b}	27.24^{cd}	114.03^{b}	25.36^{e}	-39.43
G9	127.75^{d}	166.17^{f}	1.60^{f}	394.66^{bc}	33.52	110.00-^{c}	29.80-^{c}	-40.18
G10	116.44^{h}	163.08^{g}	2.88	403.34^{bc}	27.09^{c-e}	110.22^{c}	29.40^{b-d}	-39.33
G11	132.58	181.88^{b}	1.29^{g}	326.33^{f}	25.24^{e}	106.56-^{c}	33.45	21.72
G12	131.04^{b}	183.42	1.10^{h}	344.03^{de}	29.39^{b}	105.36^{bc}	32.48^{b}	24.3
Mean	125.78	171.44	1.93	372.26	29.71	106.81	28.83	
CV%	1.68	1.2	15.83	8.1	11.1	20.5	22.85	
LSD (5%)	120	1.17	0.17	17.19	1.89	12.47	3.75	

Key: DH-Days to heading, DM-Days to maturity, PH- Plant height in cm, HH-Head height in cm, LDG- Lodging percentage, HW-head weight in gm, TSW- Thousand seed weight in gm, YAD- yield advantage of genotypes over G2.

Table 6. Combined mean of disease and insect pest reactions of sorghum genotypes evaluated in 2016-2018 main cropping seasons.

Genotypes	Stalk borer	Anthracnose	Leaf blight
G1	1.00^{e}	1.36^{d}	2.04^{e}
G2	1.169^{a}	2.5^{a}	2.88^{a}
G3	1.027^{de}	1.4^{d}	2.04^{e}
G4	1.022^{de}	2.29^{b}	2.04^{e}
G5	1.00^{e}	2.29^{b}	2.54^{b}
G6	1.078^{bc}	2.417^{a}	2.38^{c}
G7	1.00^{e}	1.44^{d}	1.88f
G8	1.11^{b}	1.56^{c}	2.21^{d}
G9	1.056^{cd}	1.08^{e}	2.04^{e}
G10	1.167^{a}	2.33^{b}	2.88^{a}
G11	1.00^{e}	1.63^{c}	1.57g
G12	1.083^{bc}	1.37^{d}	1.29^{h}
CV%	4.79	8.61	1.37
LSD (5%)	0.03	0.09	0.02

Additive main effects and multiple interaction (AMMI) model

AMMI analysis of variance (ANOVA) with the appropriate AMMI model was indicated in Table 7. The analysis of variance (ANOVA) indicated highly significant differences (P ≤ 0.01) for environments, genotypes and importantly G×E.

The genotype, environment and genotype by environment interaction explained 23.1, 69.5 and 7% of the total variation indicating the prevalence of considerable environmental variation. The interactive principal component axis (IPCA-1) and IPCA-2 axis of the G×E were highly significant (P ≤ 0.01). The first principal component managed over 68.6% of the G×E sum squares while the second principal component revealed 18.6% of the interaction, and the remaining 12.8% is due to residual (noise) and it is difficult to interpret and thus

Table 7. Partitioning of the explained sum of square (SS) and mean of square (MS) from AMMI analysis for grain yield of sorghum genotypes evaluated at four environments.

Source of variation	D.F	S.S	EX.SS%	M.S
Total	287	31574	100	110
Treatments	95	30462	96.5	320.7**
Genotypes	11	7061	23.1	641.9**
Environments	7	21181	69.5	3025.8**
Block	16	120	0.4	7.5^{ns}
Interactions	77	2220	7	28.8**
IPCA 1	17	1528	68.6	89.9**
IPCA 2	15	407	18.6	27.1**
Residuals	45	285	12.8	6.3 ^{ns}
Error	176	992		5.6

Table 8. AMMI stability value, AMMI rank, yield, yield rank and genotype selection index.

Genotype	ASV	ASV rank	YLDtonha^{-1}-	YLD rank	GSI
G12	28.26	10.00	5.02	1.00	11.00
G3	18.38	6.00	4.98	2.00	8.00
G11	20.20	7.00	4.91	3.00	10.00
G6	24.18	9.00	4.39	4.00	13.00
G4	30.03	11.00	4.05	5.00	16.00
G2	20.43	8.00	4.04	6.00	14.00
G5	13.11	2.00	3.66	7.00	9.00
G1	16.78	4.00	3.59	8.00	12.00
G7	40.22	12.00	3.32	9.00	21.00
G10	16.80	5.00	2.45	10.00	15.00
G8	16.66	3.00	2.45	11.00	14.00
G9	4.29	1.00	2.42	12.00	13.00

need to be discarded. Considerable percentage of G×E was explained by the first two IPCA axes. Different authors suggest the importance of apprehending most of the G×E sum squares in the first axis, to attain accurate information (Purchase et al., 2000; Kaya et al., 2002).

AMMI stability value (ASV) and genotype selection index (GSI)

G3, G11 and G12 were the highest yielder genotypes with relatively moderate ASV (Table 8). G9 and G5 showed the lowest ASV accompanied with the lowest grain yield. However, stability alone cannot be considered in production agriculture and hence identifying genotypes with high grain yield coupled with consistent stability across growing environments has paramount importance (Farshadfar, 2008). In this regard, GSI was utilized to further identify stable genotypes with better yield performance. Accordingly, G3, G11, G12, and G5 were considered as most stable genotypeswhereas; G7 was the least stable genotypes.

Genotype and genotype by environment interaction (GGE) biplot analysis

The polygon is drawn by joining the cultivars (G3, G4, G8, G10, G7 and G12) that are located farthest from the biplot origin so that all other cultivars are contained in the polygon. These vertex cultivars are the highest-yielding cultivar in all environments that share the sector with it. Vertex cultivars in which any environments fell in their sectors were the poor performing genotypes. Genotypes such as G1, G5 and G6 located at the origin would rank the same in all environments and is not responsive to the change in environments. G3, G11 and G12 genotypes were the best yielder among tested genotypes and relatively stable genotypes across various environments (Figure 1). G1, G5, G8 and G9 genotypes were inferior in

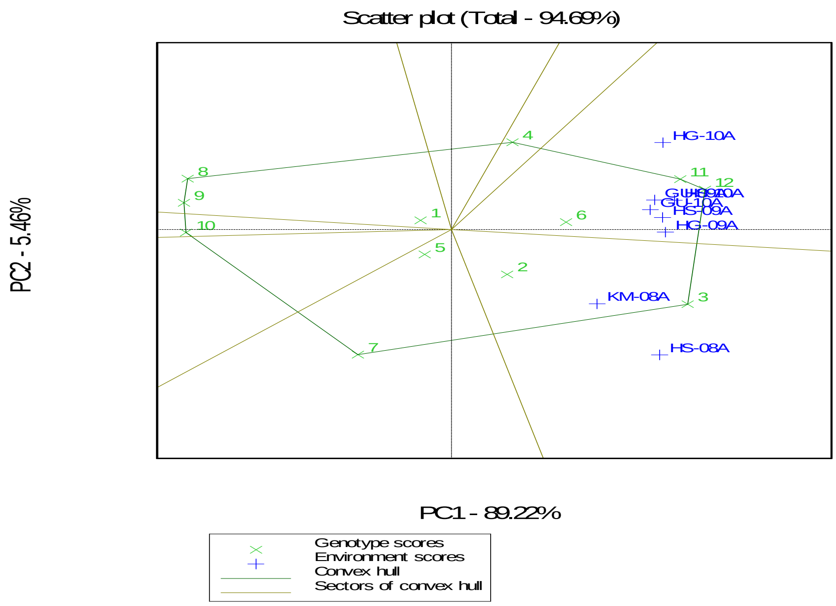

Figure 1. The scatter plots showing the which-won-where pattern of the GGE biplot. Hs= Haro Sabu, GU= Guliso, KM= Kombo, HG= Hawa Galan.

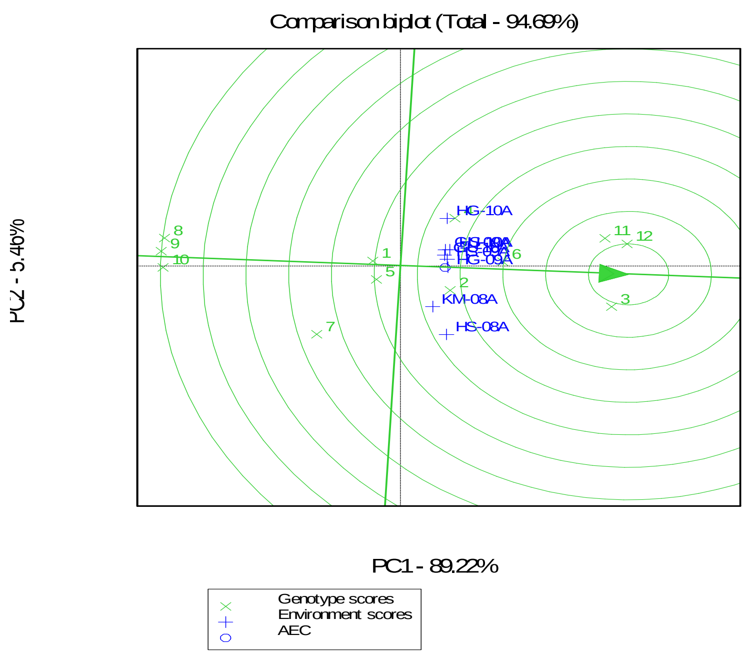

Figure 2. GGE bi-plot based on genotype-focused scaling for comparison of genotypes for their yield potential and stability.

yield performance and stable genotypes and G7 was the most unstable genotypes.

Genotype-focused scaling considers stability and mean grain yield concurrently and environments as well as genotypes that fall in the central (concentric) circle of genotype-focused scaling are considered as an ideal environments and stable genotypes, respectively (Gauch and Zobel, 1997). Genotype G3, G11 and G12 fell in and around the center of concentric circle and therefore, idealgenotypes (Figure 2). Contrariwise, G8, G9 and G10 are located far from ideal genotypes and thus they are undesirable genotypes.

CONCLUSION AND RECOMMENDATIONS

The genotypes were significantly influenced by environment, genotype and their interaction. GGE biplot and GSI index incorporating with the ASV and the yield capacity of the different genotypes in a single non-parametric index were found to be useful for discriminating genotypes with superior and stable grain yield. Depending on yield performance and reasonable stability G3, G11 and G12 genotypes were the best in the test environments and they can be used as candidates for possible release and for use as parents in future breeding programmes.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

ACKNOWLEDGMENTS

The authors greatly appreciate Oromia Agricultural Research Institute for financial support. Haro Sabu Agricultural Research Center staff members are warmly appreciated for technical and administrative support.

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