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Original Paper

Genotype by Environment Interaction and Stability on Grain Yield of Sorghum Genotypes in North Western Ethiopia

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Abstract*—Sorghum grain yield is heavily constrained by genotype-by-environment interaction (GEI), which confounds the selection of stable, high-yielding cultivars across heterogeneous agro-ecologies. This study quantified the magnitude of GEI and evaluated the yield stability of released lowland sorghum varieties to identify broad and niche-specific adaptabilities within the Amhara region. Nine varieties were evaluated across six representative moisture-stressed locations during the 2019 main cropping season using a randomized complete block design with three replications. Combined analysis of variance (ANOVA) revealed highly significant main and interaction effects, with environment capturing the largest share of the total phenotypic variation. The variety Melkam achieved the highest mean grain yield, supported by an optimized grain-filling rate and a robust multi-trait resilience profile against anthracnose and Striga hermonthica. Parametric and multivariate stability frameworks including Wricke's ecovalence, AMMI Stability Value, and GGE biplot analyses demonstrated distinct adaptation patterns. Melkam and Girana-1 emerged as the most stable genotypes, with Melkam exhibiting dynamic, broad adaptation across the primary macro-environmental cluster. Conversely, Mesay displayed high environmental interactivity but superior niche-specific adaptation tailored exclusively to the high-moisture, heavy black soils of Belesa. Consequently, Melkam is recommended for widespread cultivation in equivalent lowland agro-ecological zones of North-Western Ethiopia and as an elite candidate for climate-smart breeding programs

Keywords*—Grain yield, sorghum variety, stability analysis

I. INTRODUCTION

Sorghum (*Sorghum bicolor* L. Moench), a member of the Poaceae family, is among the most important cereal crops globally and holds particular significance in Ethiopia, which is considered one of its centers of origin. The country harbors four of the five recognized sorghum races wild, weedy, intermediate, and cultivated reflecting substantial genetic diversity [1].

In Ethiopia, sorghum is a vital multipurpose crop, ranking among the leading cereals in terms of production and productivity. It plays a central role in ensuring food security, sustaining rural livelihoods, and enhancing resilience among smallholder farmers [2]. The crop is widely consumed in the form of traditional foods and beverages such as injera and porridge. Additionally, its biomass components, including stalks and leaves, are utilized as livestock feed, fuel, and construction materials, making it indispensable in mixed farming systems [3].

A large proportion of sorghum cultivation occurs in arid and semi-arid agro-ecologies characterized by erratic rainfall, recurrent drought, and poor soil moisture retention. These environmental constraints strongly influence both crop performance and productivity [4]. Consequently, genotype performance varies considerably across locations and seasons, complicating the identification of high-yielding and stable varieties.

Genotype-by-environment interaction (GEI) significantly weakens the relationship between genotype and phenotype, thereby reducing selection efficiency and slowing genetic progress. Stable yield performance requires not only high genetic potential but also consistent adaptability across diverse environments [5]. Therefore, multi-environment trials are essential for evaluating genotype performance and identifying broadly or specifically adapted cultivars.

Various statistical approaches have been developed to analyze GEI, ranging from traditional univariate methods such as analysis of variance (ANOVA) and regression techniques to advanced multivariate models including Additive Main Effects and Multiplicative Interaction (AMMI) and Genotype plus Genotype-by-Environment (GGE) biplot analyses. These models are widely applied in plant breeding to assess genotype stability and adaptability [6].

Accordingly, this study aimed to (i) quantify the magnitude of GEI, (ii) evaluate yield stability of released sorghum genotypes, and (iii) identify genotypes with broad or specific adaptation across diverse agro-ecological zones of the Amhara region, Ethiopia.

TABLE I. EXPERIMENTAL MATERIALS USED IN THE STUDY

Entry Code	Genotype	Pedigree	Seed Source
G1	Dekeba	IESV92186-DL	MARC
G2	Mesay	IESV92152-DL	MARC
G3	Melkam	IESV92040-DL	SARC
G4	Meskir	MISKER (PGRC/E# 69441 × P-9401)	SARC
G5	Girana one	GIRANA-1 (Cr:35 × DJ1195 × N-13)	SARC
G6	Teshale	IESV92168-DL	MARC
G7	Gobeye	IESV92199-DL	MARC
G8	Gambela	IESV92057-DL	MARC
G9	Local	Local	—

Note: MARC = Melkasa Agricultural Research Center; SARC = Sirinka Agricultural Research Center.

II. MATERIALS AND METHODS

A. Plant Materials

Eight lowland improved sorghum varieties released by the Ethiopian Sorghum Improvement Program, along with a local check, were evaluated in this study (Table 1). The genotypes were selected based on their yield potential, adaptability, and year of release.

B. Description of the Study Area

The experiment was conducted during the 2019 main cropping season across six representative lowland environments of the Amhara region, Ethiopia (Table 2). These areas are characterized by moisture stress conditions and are major sorghum-producing zones.

C. Experimental Design and Field Management

The experiment was laid out in a randomized complete block design (RCBD) with three replications. Each plot consisted of five rows of 5 m length, with 0.75 m spacing between rows and 0.15 m between plants, giving a total plot area of 22.5 m².

Sowing was carried out manually using a seed rate of 10 kg ha^{-1}. Thinning was performed two weeks after emergence to maintain optimal plant density. Fertilizer was applied at the recommended rate of 100 kg ha^{-1} DAP at planting and 50 kg ha^{-1} urea at the knee-height stage. Standard agronomic practices, including weed and pest management, were applied uniformly across all plots.

D. Data Collection

Data were collected from the central rows and five randomly selected plants per plot following standard sorghum descriptors [7]. The measured traits included:.

Phenological traits: days to 50% heading, days to maturity, and grain filling period

Growth parameters: plant height (cm) and panicle length (cm)

Yield components: grain yield (t ha^{-1}), stand count at harvest, and grain filling rate (t ha^{-1} day^{-1})

Disease incidence: anthracnose severity scored on a 1–9 scale

Parasitic weed infestation: number of Striga plants per plot

E. Statistical Analysis

Prior to analysis, the assumptions underlying analysis of variance were verified. The normality of residuals and homogeneity of variance were evaluated using the Shapiro Wilk and Bartlett's tests, respectively. Following validation of these assumptions, a combined analysis of variance across environments was conducted using R software (version 4.4.2). Mean comparisons were performed at significance levels of $P < 0.05$ and $P < 0.01$.

Genotype-
by-environment interaction was further partitioned into its components genotype, environment, and interaction effects sing pooled ANOVA. Stability and adaptability of genotypes were assessed using multiple complementary approaches.

Wricke's ecovalence (Wi) was employed to quantify the contribution of each genotype to GEI, where lower values indicate greater stability [8]. Kang's yield stability index (YSI) was used to integrate yield performance with stability ranking, favoring genotypes with lower index values [9].

The AMMI model was applied to partition GEI into additive and multiplicative components, providing a robust framework for interpreting genotype responses across environments [10]. The model is expressed as:

$$Y_{ij} = \mu + G_i + E_j + \Sigma\lambda_k\alpha_{ik}\gamma_{jk} + \varepsilon_{ij} \quad (1)$$

where μ is the grand mean, G_i and E_j represent genotype and environment effects, λ_k denotes the eigenvalue of the k-th principal component, α_{ik} and γ_{jk} are genotype and environment scores, and ε_{ij} is the residual error term.

The AMMI Stability Value (ASV) was computed to provide a quantitative measure of genotype stability, with lower values indicating higher stability [11].

In addition, GGE biplot analysis was employed to visualize genotype performance and identify patterns such as "which-won-where" and mean versus stability relationships [12]. This integrated analytical approach enabled comprehensive assessment of both yield performance and stability across heterogeneous environments.

III. RESULTS AND DISCUSSION

A. Combined Analysis of Variance Across Locations

The combined ANOVA revealed highly significant ($P < 0.001$) effects of genotype, environment, and genotype-by-environment interaction for grain yield and related traits (Table 3). This indicates substantial genetic variability among genotypes and pronounced environmental heterogeneity across testing locations. Similar findings have been reported in sorghum by [13].

B. Mean Performance of Genotypes

Mean performance analysis (Table 4) revealed that 'Melkam' achieved the highest grain yield (4.34 t ha^{-1}), followed by 'Mesay' and 'Girana-1', while the local check and 'Gobeye' recorded the lowest yields. This superior

TABLE II. AGRO-ECOLOGICAL FEATURES OF THE EXPERIMENTAL LOCATIONS

Location	Zone	Wereda	Altitude (m a.s.l.)	Rainfall (mm)	Soil Type	Latitude	Longitude	Temp. Max (°C)	Temp. Min (°C)
Metema	N. Gondar	Gendwa	745	791.2	Red loam	10°8′21″ N	34°18′21″ E	35.2	19.6
Kokit	N. Gondar	Kokit	750	760.4	Red loam	13°35′00″ N	35°56′ 00″E	39.5	21.0
Belesa	N. Gondar	Arbaya	1000	920.9	Black soil	12°35′00″ N	37°37′00″ E	33.2	12.0
Shewa Robit	N. Shewa	Ataye	1500	830.7	Black soil	09°59′50″N	39°59′50″E	32.2	10.5
Sanja	N. Gondar	Sanja	800	730.7	Black soil	14°8′21″ N	10°15′21″ E	35.0	13.0
Kobo	N. Wollo	Kobo	1470	873.4	Black soil	12°8′21″ N	39°14′21″ E	34.0	13.0

Note: m a.s.l. = meters above sea level.

TABLE III. COMBINED ANALYSIS OF VARIANCE (ANOVA) FOR GRAIN YIELD AND RELATED TRAITS

Trait	Genotype (Df=8)	Location (Df=5)	GEI (Df=40)	Replication (Df=12)	Error (Df=96)	CV (%)
GY (t ha^{-1})	4.130**	25.825**	0.602**	0.913*	0.268	16.0
DH	252.3***	650.4***	56.8***	5.1 ns	5.5	3.1
DM	3395.9***	2141.4***	3125.5***	15.1 ns	2.6	1.3
HL	279.5***	83.3***	5.1***	1.9*	2.6	7.5
HHA	485.3**	16,796.5***	499.3***	337.3*	131.5	9.5
PLH	26,908.5***	12,443.3***	2711.2***	459.6**	131	5.7
GFP	49.1***	819.4***	66.2***	6.3 ns	7.5	6.4
GFR	3071.7***	18,589.0***	527.1***	388.3*	187.7	17.3
Anthracnose	1.4***	0.2 ns	0.4**	0.2 ns	0.2	124.9
Striga	303,911.4**	4,386,337.7**	136,700.7*	620,779.5**	85,304.6	74.7

Note: GY = Grain yield; DH = Days to heading; DM = Days to maturity; HL = Head length; HHA = Heads harvested; PLH = Plant height; GFP = Grain filling period; GFR = Grain filling rate.

***, **, * indicate significance at $P \leq 0.001$, $P \leq 0.01$, $P \leq 0.05$; ns = not significant.

yield architecture in high-performing genotypes was strongly associated with longer panicles and extended grain-filling periods (45.1 days). These findings suggest a robust source sink efficiency and a positive relationship between reproductive phenology and final yield, consistent with [14]. Melkam's high productivity was further driven by an optimized grain-filling rate (104.2 kg ha^{-1} day-1), which ensured efficient carbohydrate translocation despite localized environmental heat loads.

Because genotype selection cannot rely on yield potential alone, candidate varieties must demonstrate resilience against regional biotic stresses. A multi-trait evaluation protects 'Melkam' against typical agronomic trade-offs, as it paired its yield advantage with exceptional resistance to Anthracnose (severity score of 0.2) and intermediate tolerance to the parasitic weed Striga hermonthica (322.5 plants/plot).

While the local check and 'Gobeye' exhibited lower Striga infestations (224.0 and 193.8 plants/plot, respectively), their severely suppressed grain yields (3.01 and 2.66 t ha^{-1}) render them economically non-viable. Conversely, highly susceptible varieties like 'Dekeba' (514.1 plants/plot) and 'Gambela' (541.0 plants/plot) suffered from intense weed pressure. Consequently, 'Melkam' represents the most balanced ideotype for regional food security, justified by both its multi-index stability profile and its superior multi-trait resilience.

C. Genotype Stability Analysis

a) Wricke's Ecovalence and YSI: To prevent the biased selection of low-yielding yet highly stable varieties, multiple stability indices were cross evaluated. Wricke's ecovalence ((Wi)) and the AMMI Stability Value (ASV) were utilized to quantify static (agronomic) stability, identifying genotypes with minimal performance variance across environments. Conversely, Kang's Yield Stability Index (YSI) provided a holistic, non-arbitrary approach by simultaneously integrating mean yield ranks with ASV-derived stability ranks (Tables 5 and 7). Genotypes exhibiting concurrently low values across all three parameters were prioritized as possessing true agronomic utility. In this study, the indices exhibit high structural agreement. Girana-1 (G5) achieved the lowest Wi (87, 868) and lowest ASV, confirming it as the most statically stable genotype; however, its mean yield (3.50 t ha^{-1}) was moderate. Melkam (G3) showed an excellent low-range Wi (267,719) and an optimized YSI score of 4, successfully bridging the gap between yield potential (4.34 t ha^{-1}) and spatial adaptability.

b) AMMI Analysis: The combined Additive Main Effects and Multiplicative Interaction (AMMI) analysis of variance (ANOVA) revealed that environmental main effects accounted for the overwhelming majority of the total variation (69.34%), substantially exceeding genetic (17.74%) and genotype-by-environment interaction (GEI; 12.93%) effects. The first two interaction principal component axes (IPCA1 and IPCA2) captured 74.7% of the GEI sum of squares, confirming the adequacy of a two-dimensional AMMI model for stable interpretation (Table 6). This pronounced environmental dominance underscores severe spatial and

TABLE IV. MEAN PERFORMANCE OF SORGHUM GENOTYPES ACROSS LOCATIONS

Genotype	DH	DM	HL	HHA	PLH	GY	GFP	GFR	Anth	Striga
Dekeba	74c	116d	20.4cd	120.0abc	151.1f	3.38bc	41.7d	85.3bc	0.5b	514.1a
Mesay	70d	114e	21.3b	120.5abc	216.1c	3.65b	46.7a	86.8b	0.4bcd	372.4abc
Melkam	74c	117d	26.6a	123.8abc	159.9e	4.34a	45.1ab	104.2a	0.2cde	322.5bc
Meskir	76b	121b	19.9de	116.3cd	205.2d	3.0de	43.2cd	67.4d	0.1e	438.3ab
Girana -1	75bc	118c	19.7de	118.4c	229.3b	3.50bc	42.7cd	84.0bc	0.1e	317.7cb
Teshale	71d	114e	19.0ef	124.2ab	235.8b	3.21cd	43.6cb	76.4c	0.16de	373.6abc
Gobeye	71d	113f	20.9c	126.8a	147.7f	2.66e	42.4cd	63.3d	1.0a	193.8c
Gambela	77b	118c	18.6f	123.9abc	209.8cd	3.18cd	41.6d	77.7c	0.5bc	541.0a
Local	83a	129a	18.2f	109.7d	252.0a	3.01de	43.7bc	64.3d	0.2bcde	224.0c

climatic heterogeneity across the evaluated lowlands of the Amhara region.

c) Agronomically, this macro-environmental variance is driven by sharp microclimatic divergence among the testing sites. The evaluation network spans a wide altitudinal and thermal gradient (Table 2), ranging from ultra-low altitude, hyperthermic, and moisture-stressed environments like Kokit (750 m a.s.l., 39.5°C maximum temperature) to milder, higher-altitude plain environments such as Shewa Robit (1500 m a.s.l.). The substantial environmental mean squares are further explained by edaphic and hydrological variations. Soil profiles shift from highly porous Red Loams in Metema to highly moisture-retentive Vertisols (Black Soils) in Belesa and Kobo, while annual precipitation varies erratically from 730.7 mm in Sanja to 920.9 mm in Belesa. These contrasting abiotic factors exert distinct, localized pressures on early vegetative growth and subsequent grain-filling stages.

d) Consequently, environmental constraints act as the primary determinants of phenotypic expression, dictating grain yield potential before genetic variance can fully manifest. The AMMI1 biplot (Figure 1) revealed that genotypes Girana-1 (G5), Melkam (G3), Teshale (G6), and Gobeye (G7) were positioned near the origin, indicating low interaction effects and high stability. In contrast, genotypes such as Mesay (G2), Meskir (G4), and Gambela (G8) were more interactive and hence less stable across environments in agreement with earlier studies on sorghum [15].

e) AMMI Stability Value: ASV further confirmed the stability rankings of the genotypes (Table 7) and Girana-1, Gobeye, and Melkam identified as the most stable genotypes, conversely Mesay and Meskir exhibited higher instability [16].

f) GGE Biplot Analysis: The GGE biplot analysis (Figure 2) provides an accurate, visually precise synthesis of mean yield versus stability via the Average Environment Coordination (AEC) view. The analysis confirms that Melkam (G3) achieved the highest mean yield performance across testing environments, as indicated by its advanced positive position along the Average Environment Abscissa (AEA) direction. Conversely, Girana-1 (G5) exhibited exceptional stability due to its minimal projection distance relative to the AEC ordinate axis. Examining this AEC framework reveals critical agronomic trade-offs between yield capacity and stability. Girana-1 is positioned perfectly on the Average Environment Abscissa line, exhibiting nearly zero interaction variance (high static stability), but sacrifices yield

TABLE V. STABILITY PARAMETERS BASED ON WRICKE'S ECOVALENCE AND YSI

Genotype	Wi	Rank	Mean	YSI
Dekeba	1,146,036	-6	3.38	11
Mesay	1,820,317	-9	3.65	11
Melkam	267,719	-2	4.34	4
Meskir	1,223,867	-7	3.00	16
Girana one	87,868	-1	3.50	4
Teshale	493,837	-3	3.21	9
Gobeye	700,001	-4	2.66	11
Gambela	1,329,207	-8	3.18	12
Local	955,312	-5	3.01	12

TABLE VI. AMMI ANALYSIS OF VARIANCE FOR GRAIN YIELD (T HA-1)

Source	DF	SS	MS	% Total	% GEI	Cumulative
Treatments	53	186,239,256	3.5**	83.6	—	—
Genotypes	8	33,036,900	4.1**	17.7	—	—
Locations	5	129,126,863	25.8**	69.3	—	—
GEI	40	24,075,493	0.6**	12.9	—	—
IPCA1	12	12,188,128	1.0**	—	50.6	50.6
IPCA2	10	5,797,208	0.5*	—	24.1	74.7
Residuals	18	6,090,157	0.3 ^{ns}	—	25.3	100

capacity. Melkam deviates slightly from the AEC stability axis, illustrating dynamic stability meaning its yield shifts positively in response to optimal environmental conditions (such as the favorable rainfall profile in Kobo or Belesa). For resource constrained farmers, Girana-1 represents a low-risk, predictable option, whereas Melkam offers optimal productivity under variable moisture availability.

The "which-won-where" polygon configuration (Figure 3) separates the testing sites into definitive environmental sectors. Most low-moisture locations clustered into a singular major environmental sector where 'Melkam' (G3) sits as the vertex genotype, validating its recommendation for wide adaptation. Despite geographical divergence, this clustering into a single apparent macro-environmental sector indicates that severe terminal moisture stress and high ambient temperatures (exceeding 35 °C in Kokit and Sanja) function as the dominant selective pressures across these zones, unifying genotype responses.

Grand Mean = 3331, CV (%) = 15.6

Conversely, 'Mesay' (G2) is positioned at the vertex of the sector targeting Belesa (E3), reinforcing its highly specialized, specific adaptation profile to that niche. Belesa features high moisture retention due to its heavy black soils combined with the highest recorded localized rainfall (920.9 mm). 'Mesay' capitalized on this unique pocket via rapid early vegetative development matching the shortest days to heading (70 days) enabling it to excel in that specific niche.

TABLE VII. AMMI STABILITY VALUES (ASV), IPCA SCORES, AND FINAL STABILITY RANKINGS

Entry Code	Genotype	IPCA1 Score	IPCA2 Score	ASV	Stability Rank	Mean Yield (t ha^{-1})
G5	Girana one	-0.012	-0.015	0.029	1	3.50
G7	Gobeye	-0.221	0.410	0.621	2	2.66
G3	Melkam	0.314	-0.215	0.702	3	4.34
G6	Teshale	0.280	-0.320	0.672	4	3.21
G9	Local	-0.340	0.280	0.768	5	3.01
G1	Dekeba	0.420	-0.680	1.140	6	3.38
G4	Meskir	-0.890	1.150	2.210	7	3.00
G8	Gambela	-0.760	0.980	1.940	8	3.18
G2	Mesay	1.120	-1.450	2.840	9	3.65

While these findings align with earlier GGE biplot assessments of sorghum adaptability [17], a true "mega-environment" definition requires long-term environmental consistency. Given the single-season nature of this dataset, this clustering must be cautiously interpreted as a seasonal macro-grouping heavily influenced by the 2019 rainfall distribution rather than a permanent agro-ecological boundary.

IV. CONCLUSION

This study successfully evaluated the grain yield performance, spatial stability, and multi-trait resilience of nine lowland sorghum genotypes across six diverse macro-environments in North-Western Ethiopia using AMMI and GGE biplot models. Combined analysis of variance revealed that environmental differences dominated phenotypic expression, accounting for the vast majority (69.34%) of total variation, followed by highly significant genotype-by-environment interactions (GEI). Despite geographical differences among the testing locations, severe terminal moisture stress and high ambient temperatures functioned as overriding selective pressures, unifying genotypic responses and clustering the majority of testing sites into a single apparent seasonal macro-environment.

By integrating parametric stability indices including Wricke's ecovalence (Wi), AMMI Stability Value (ASV), and the Yield Selection Index (YSI) with critical agro-physiological and biotic stress traits, distinct genotypic profiles emerged:

'Melkam' (G3): Identified as the premier, dynamically stable variety. It combined the highest mean yield potential with robust source-sink efficiencies and a multi-trait defense architecture. While 'Gobeye' (G7) and local checks exhibited lower Striga counts, their heavily compromised yields render them economically non-viable compared to 'Melkam', 'Girana-1' (G5): Demonstrated the highest level of static stability (positioning closest to the AEC ordinate axis), proving highly reliable as a low-risk, predictable option for consistent performance across fluctuating microclimates, and 'Mesay' (G2): Positioned at the vertex of the "which-won-where" polygon for the Belesa (E3) sector, confirming highly specialized, specific adaptation driven by rapid early phenological development that capitalized on the high moisture retention of Belesa's heavy black soils.

Due to the inherent limitations of a single-season dataset (2019 cropping cycle), these findings primarily reflect spatial adaptability and cannot definitively forecast long-term temporal stability across years. Consequently, 'Melkam' is temporarily recommended for large-scale production across pilot zones matching these specific lowland agro-ecologies in the Amhara region. Furthermore, both 'Melkam' and 'Girana-1' are highly recommended as premium, climate-smart parental lines in future sorghum breeding programs aimed at breaking the yield-stability trade-off. Future multi-year validation trials across expanded temporal scales remain a critical prerequisite to fully validate long-term resilience and confirm permanent mega-environment delineations before launching massive regional seed system rollouts.

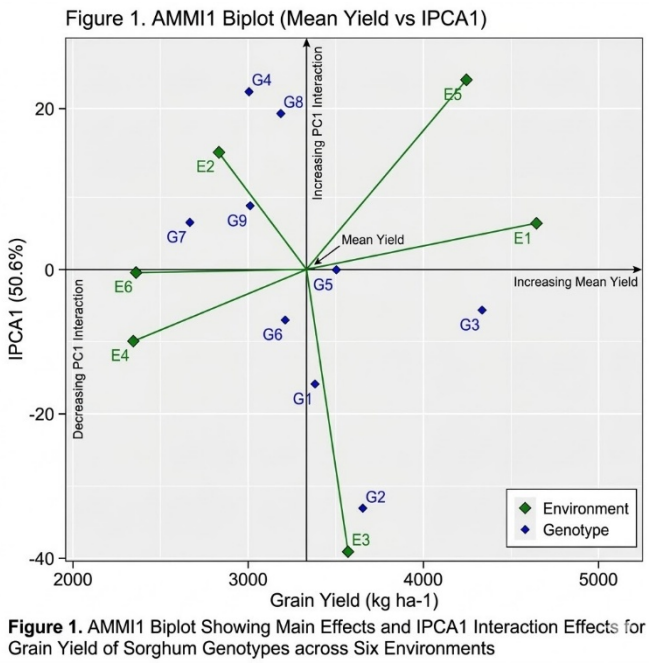


Fig. 1. AMMI1 Biplot Showing Main Effects and IPCA1 Interaction Effects for Grain Yield of Sorghum Genotypes across Six Environment

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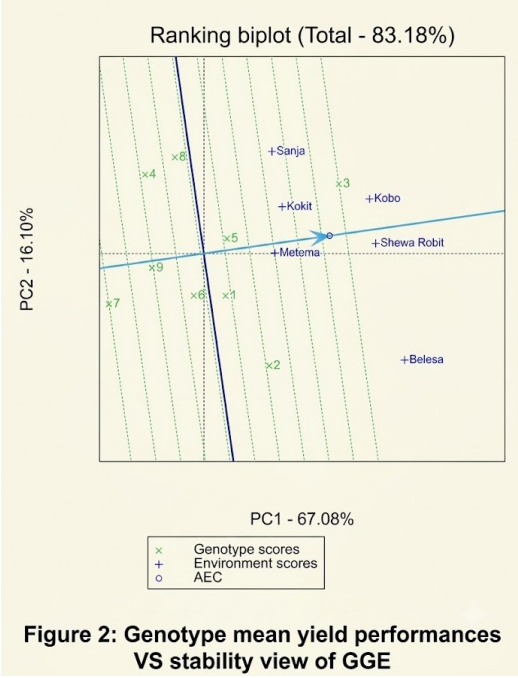


Figure 2: Genotype mean yield performances VS stability view of GGE

Fig. 2. GGE Biplot (Mean Yield vs. Stability): Average Environment Coordination (AEC) View

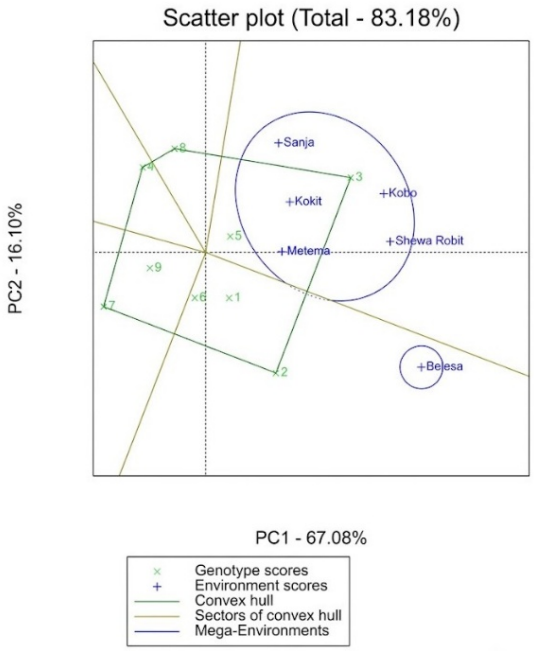


Figure 3 GGE biplot of which-won-where-biplot for yield

Fig. 3. GGE Biplot (”Which-Won-Where”) Showing Genotype Adaptation across Six Environments

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