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Research Article

Multivariate analysis and multitrait genotype-ideotype distance index (MGIDI) for selection of promising genotypes under drought stress in post rainy sorghum (*Sorghum bicolor* L. Moench)

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Abstract
The primary impediment to sorghum productivity in *rabi* conditions worldwide is drought. This study aimed to identify drought-tolerant lines from a germplasm set of 156 accessions which includes the elite breeding lines from institutes all over India using drought tolerance indices. Study was conducted during the *rabi* 2022-23 season at AICRP on Sorghum, University of Agricultural Sciences, Dharwad. Results indicated a significant reduction in mean yield under moisture stress conditions. Principal component analysis (PCA) and correlation analysis revealed a significant positive correlation between yield under stress (Y_S) and indices such as the stress tolerance index (STI), geometric mean productivity (GMP), mean productivity (MP), mean relative performance (MRP), harmonic mean (HM), and yield index (YI), validating their effectiveness in selecting drought-tolerant genotypes. Cluster analysis sorted the germplasms into five clusters, differentiating tolerant and susceptible lines. Additionally, MGIDI analysis pinpointed lines G72, G78, G4, G100, and G135 as the most drought-tolerant based on multiple indices and yield under stress, suggesting their potential as valuable pre-breeding material for future breeding programs aimed at improving drought resilience in sorghum.

Keywords: *Rabi* Sorghum, Drought tolerance indices, Principal component, MGIDI

INTRODUCTION

Sorghum (*Sorghum bicolor* (L). Moench) is an annual tropical C_4 grass belonging to Poaceae family. It is having diploid chromosome number of 2n = 2x = 20 with a haploid genome size of approximately 730 Mbp. Sorghum is one of the earliest domesticated and most versatile crop, used for food, fodder, fiber, fuel, and raw materials. "Sorghum continues to be a crucial component of food security for over 300 million people in Africa and serves as a staple crop for more than 500 million people across 30 sub-Saharan African and Asian countries" (Wagaw, 2019; Mindaye *et al*., 2016). In India, Sorghum is grown during the *kharif* season (southwest monsoon) and the *rabi* season (post-monsoon). *Rabi* sorghum is a key food and fodder crop in areas with limited water availability and serves as an important dryland crop. According to reports during 2022-23 seasons, India recorded a production of 38.14 lakh tons over an area of 35.35 lakh hectares, with a productivity of 1,079 kg per hectare (Anonymous, 2023). During 2023-24, global sorghum production is estimated to reach 63.64 million tonnes with a productivity of 1.52 tonnes per hectare (USDA, 2023-24).

Rabi sorghum is often cultivated under conditions of diminishing soil moisture, making it vulnerable to both soil and atmospheric drought. This dual exposure to drought is a major factor that disrupts its productivity. Since *rabi* sorghum is typically grown in environments where moisture is stored and gradually depleting, and with rising temperatures post-flowering, it frequently encounters water shortages. This scarcity of water leads to moisture stress, which affects several metabolic processes within the plant.

Drought occurs when soil moisture levels are too low to sustain plant growth, primarily due to below-average rainfall. This lack of sufficient precipitation leads to reduced soil moisture and groundwater, ultimately causing crop damage and lower yields (Panagoulia and Dimou, 1998). Sorghum thrives across diverse geographic regions with different altitudes, day lengths, rainfall, and temperature conditions. It is more resilient to various abiotic stresses, including drought, waterlogging, salinity, extreme heat, and cold, compared to other cereals. These properties make sorghum a widely grown crop in semi-arid tropical regions and a vital fundamental food for millions of rural households (Paterson *et al*., 2009). Despite its drought tolerance, sorghum can still suffer yield losses of 60–90% due to drought, depending on the severity. Drought impacts sorghum plants unique at various physiological growth stages, such as the seedling, pre-flowering, and post-flowering stages, all of which influence the final produce. Pre-flowering and post-flowering drought curtail grain yield (Borrell *et al*., 2014). Drought stress during the green stage in sorghum can result in yield losses of 50–60%. On the other hand, water stress during the post-flowering stage leads to even greater yield losses of 87–100%, as this stage requires substantial water for grain filling (Craufurd and Peacock, 1993). This highlights the need for ongoing breeding efforts to enhance drought tolerance and productivity in sorghum (Wagaw, 2019).

Identifying drought-tolerant lines for improved sorghum yield is crucial. Relative yield performance under both stressed and control environments helps pinpoint genotypes suited to variable rainfall (Mohammadi, 2016). Drought susceptibility is assessed by yield reduction under stress (Blum, 1989) and morpho-physiological traits serve as indicators for selecting tolerant genotypes. Various stress tolerance indices incorporating yield, morphology and physiology enhance selection efficiency (Drikvand *et al*., 2012). Productivity remains the primary selection index and its correlation with tolerance indices aids in identifying superior genotypes (Farshadfar *et al*., 2012). Screening drought-tolerant crops at flowering and post-flowering stages is cost-effective, especially when coupled with moisture conservation techniques (Ali *et al*., 2011). Understanding plant responses to drought is essential for selecting resilient genotypes (Farshadfar *et al*., 2012). Based on yield performance genotypes are classified into four groups: consistently high-yielding (Group A), high-yielding in non-stressed conditions (Group B), high yielding under stress (Group C) and low-yielding in both conditions (Group D) (Fernandez, 1992). Thus, Various drought indices have been suggested which compare yields under stress and optimal conditions to assess tolerance. Selecting high-yielding drought-tolerant genotypes is crucial for improving crop performance in drought-prone areas. However, relying solely on yield is challenging due to its complex heritability (Anwaar *et al*., 2020). Instead, drought indices, which quantify yield performance under stressed and non-stressed conditions offer a more reliable selection method (Anwaar *et al*., 2020). Numerous researchers have explored the effectiveness of various indices in evaluating genotype performance under both drought and irrigated conditions. These indices include the stress tolerance index (STI) and geometric mean productivity (GMP) (Fernandez, 1992), stress susceptibility index (SSI) (Fischer and Maurer, 1978), tolerance index (TOL) (Hossain *et al.,* 1990), mean productivity (MP) (Rosielle and Hamblin, 1981), yield index (YI) (Gavuzzi *et al*., 1997), yield stability index (YSI) (Bouslama and Schapaugh, 1984), harmonic mean (HM) (Schneider *et al*., 1997), and mean relative performance (MRP) (Osmanzai, 1994). Each of these indices varies in accuracy, making direct comparisons between genotypes complex. Typically, genotypes that perform well in both favorable and drought conditions exhibit higher or positive values of STI, MP, HM, MRP, GMP, YSI, and YI, while TOL and SSI tend to be lower. To enhance sorghum productivity and stability in drought-prone environments, it is essential to identify selection indices capable of effectively distinguishing high-yielding genotypes under such conditions.

The Smith-Hazel Selection Index is one of the widely used method for multi-trait selection in plant breeding. However, it has several limitations including multicollinearity, subjective economic weighting, computational complexity, limited flexibility and the potential neglect of important traits (Olivoto *et al*., 2017). These challenges led to the development of an alternative approach, the Multi-Trait Genotype-Ideotype Distance Index (MGIDI). Unlike traditional selection methods, MGIDI integrates all traits into a single index, accounting for their correlations. This approach addresses limitations of poorly conditioned matrices and biased index coefficients seen in other indices. MGIDI simplifies multivariate data, improves selection accuracy and facilitates balanced genetic gains across traits (Olivoto & Nardino, 2020). It is particularly useful in METs enabling the selection of stable and adaptable genotypes vital for managing climate variability (Nardino *et al*., 2022). Genetic improvement is a key approach for enhancing tolerance, particularly in resource-limited areas (Keneni, 2007). This study aims to identify drought-tolerant germplasm of sorghum for use in breeding programs aimed at improving drought tolerance in sorghum.

MATERIALS AND METHODS

Plant materials and location: The experiment was performed during *rabi* 2022-23 season at AICRP on sorghum, Main Agricultural Research Station (MARS), University of Agricultural Sciences, Dharwad which is located 15° 29′ N latitude, 74°59′ E longitudes at an altitude of 689m above mean sea level. A set of 156 germplasm accessions which included elite breeding lines from Institutes all over India, received from Indian Institute of Millet Research, Hyderabad and AICRP on Sorghum, MARS, UAS Dharwad were used in the study.

Experimental design, Data collection and statistical analysis: The study employed an Alpha Lattice Design with two replications. Germplasm accessions were sown under two conditions *i.e.*, stress (S) and non-stress (NS) conditions. Under stress condition, drought was imposed by avoiding irrigation except for the irrigation given during sowing for better crop establishment under stress condition. Under non-stress condition, three additional irrigations were given one each at booting stage (55 DAS), 50% flowering stage (75 DAS) and grain filling stage (95 DAS). Care was taken to avoid the seepage of water from irrigated to stress plots by maintaining buffer zone of 20m in between. Yield was recorded for five random plants from each plot in stress (Y_S) and non-stress (Y_P) condition, average was calculated and employed for estimating different drought indices based on equations given in **Table 1**. The individual ANOVA was performed under stress and nonstress conditions separately to see the significant difference between the genotypes based on the replicated data. The correlation between Y_S, Y_P and other drought indices were estimated. Multivariate analyses such as cluster analysis and principal component analysis (PCA) were carried out using R statistical software version 4.3.1.

Computing MGIDI index: To identify superior performing individuals based on multiple indices, the multi-trait genotype-ideotype distance index (MGIDI) was computed. The preliminary step to compute the MGIDI index was to rescale the matrix X so that all the values have a 0-100 range (Olivoto and Lúcio, 2020). The rescaled value for the j^{th} trait of the i^{th} genotype (rX_{ij}) was obtained as described

$$r\mathbf{X}_{ij} = \frac{\eta_{nj} - \varphi_{nj}}{\eta_{oj} - \varphi_{oj}} \times (\theta_{ij} - \eta_{oj}) + \eta_{nj}$$

Where, η_{nj} and ϕ_{nj} are the new maximum and minimum values for the trait j after rescaling, respectively; η^{oj} and ϕ_{oj} are the original maximum and minimum values for the trait j, respectively, and θ_{ij} is the original value for the j^{th} trait of the i^{th} genotype.

Furthermore, an exploratory factor analysis was conducted to group correlated traits into distinct factors and determine factorial scores for each genotype. This analysis was based on following equation

$$X=\mu+Lf+\varepsilon$$

Where, X is a p×1 vector of observations; μ is a p×1 vector of standardized means; L is a p×f matrix of factorial loadings; f is a p×1 vector of common factors; and ε is a p×1 vector of residuals, being p and f, the number of traits and common factors retained, respectively.

Factors with eigenvalues greater than one were considered to obtain the initial loadings. Final loadings were then estimated using the varimax rotation criterion. Genotype scores were calculated based on

$$F=Z(A^TR^{-1})^T$$

Where, F is a g×f matrix with the factorial scores; Z is a g ×p matrix with the standardized means (rX); A is a p×f matrix of canonical loadings, and R is a p×p correlation matrix between the traits. g, f, and p represents the number of genotypes, factors retained, and analyzed traits, respectively.

The MGIDI index was computed as suggested by Olivoto and Nardino (2020) (https://github.com/TiagoOlivoto/metan) as follows:

$$MGIDI_i = \sqrt{\sum_{j=1}^{f}(F_{ij} - F_j)^2}$$

Where, $MGIDI_i$ is the multi-trait genotype-ideotype distance index for the *i*th genotype; F_{ij} is the score of the *i*th genotype in the *j*th factor (*i = 1, 2, ..., g; j = 1, 2, ..., f*), being *g* and *f* the number of genotypes and factors, respectively, and F_j is the *j*th score of the ideotype. The genotype with the lowest MGIDI is then closer to the ideotype and therefore should presents desired values for all the analyzed traits.

RESULTS AND DISCUSSION

Drought tolerance indices and yield response of germplasm lines: The analysis of variance results for grain yield revealed significant genotypic variation under both non-stressed and stressed conditions (**Table 2**). This suggests that there is potential to select genotypes that perform better in both stressed and non-stressed environments. The average seed yield under non-stressed conditions was 53.57 grams per plant compared to 40.17 grams in the stressed conditions. The results indicated that drought stress led to a significant decrease in grain yield of 25%. Yield reduction under drought conditions has also been documented by several authors, including a 30% reduction in wheat by Aktas (2016), a 42% reduction in wheat by Bennani *et al*. (2016), an average 27% reduction in rice by Kandel *et al*. (2022), 48% reduction in sorghum by Abebe *et al*. (2020) and 30 to 40% in different small millets by Ashok *et al.* (2018). The lines G72 (61.1g), G13 (55.5g), G25 (54.4g), G78 (54.4g) and G16 (53.9g) produced higher yield under stress condition with average of more than 55g per plant and lines G65 (73g), G72 (71.9g), G59 (70.40g), G135 (67.7g) and G56 (67.6g) showed highest yield under non-stress condition with average of more than 70g per plant.

Among the different drought indices, according to previous reports (Aktas *et al*., 2016; Abebe et al., 2020;

Table 1. Drought tolerant indices, Formula and references

Index Name	Formula	Reference
Relative yield (RY)	RY = $\frac{Y_S}{Y_P} \times 100$	Lewis (1954)
Stress susceptibility index (SSI)	SSI = $\frac{1-\frac{Y_S}{Y_P}}{1-\frac{\bar{Y}_S}{\bar{Y}_P}}$	Fisher and Maurer (1978)
Stress tolerance index (STI)	STI = $\frac{Y_S \times Y_P}{(\bar{Y}_P)^2}$	Fernandez (1992)
Tolerance index (ToL)	ToL = $Y_P - Y_S$	Rosielle and Hamblin (1981)
Yield stability index (YSI)	YSI = $\frac{Y_S}{Y_P}$	Bouslama and Schapaugh (1984)
Geometric mean productivity (GMP)	GMP = $\sqrt{Y_S \times Y_P}$	Fernandez (1992), (Schneider *et al.*, 1997)
Harmonic mean (HM)	HM = $\frac{2(Y_S \times Y_P)}{Y_S + Y_P}$	Jafari et al. (2009)
Mean productivity (MP)	MP = $\frac{Y_S + Y_P}{2}$	Rosielle and Hamblin (1981)
Drought resistance index (DI)	DI = $\frac{Y_S \times (\frac{Y_S}{Y_P})}{Y_P}$	Lan (1998)
Yield index (YI)	YI = $\frac{Y_S}{\bar{Y}_S}$	Gavuzzi *et al.* (1997)
Mean relative performance (MRP)	MRP = $\frac{Y_S}{\bar{Y}_S} + \frac{Y_P}{\bar{Y}_P}$	Osmanzai (1994)
Stress susceptibility percentage index (SSPI)	SSPI = $\frac{(Y_P - Y_S)}{2 \times \bar{Y}_P} \times 100$	Mousavi *et al.* (2008)
Relative drought index (RDI)	RDI = $\frac{\frac{Y_S}{Y_P}}{\frac{\bar{Y}_S}{\bar{Y}_P}}$	Fisher and Maurer (1978)

Where,

Y_S and Y_P represents yield under stress and nonstress environments respectively

$\bar{Y}_S$ and $\bar{Y}_P$ represents mean yield across the genotypes under stress and nonstress environments respectively

Table 2. Analysis of variance for productivity under stress and non-stressed environments

source of variation	Stress (S) condition		Non-Stress (NS) condition	
	df	MSS	df	MSS
Replication	1	246.10*	1	79.81
Blocks within replication	12	351.36***	12	161.13**
genotypes (adjusted for blocks)	155	131.11***	155	122.16*
Error	143	60.3	143	85.01
Mean		40.17		53.57
CV		19.3		17.2

Kandel *et al*., 2022), the positive value of the indices STI, MP, HM, MRP, GMP, YSI and YI, while negative value of the indices TOL and SSI indicate the drought tolerance in genotypes. Among these, STI is especially effective for selecting cultivars that perform well in both stressed and non-stressed conditions (Nouraein *et al*., 2013). Based on the indices STI, GMP, and MP, the lines G72, G135, G78, G100, and G59 were identified as drought tolerant, while lines G89, G71, G39, G36, and G3 were more sensitive to drought. This suggests that these three indices are reliable for selecting drought-tolerant lines. Lines G60, G69, G13, G23, and G155 exhibited low SSI values, indicating minimal susceptibility to drought. In contrast, lines G95, G89, and G45 had the highest SSI values, classifying them as highly drought-susceptible genotypes with unstable yields across both stressed and non-stressed conditions. Additionally, lines G60, G69, and G13 displayed the highest RY values, signifying their ability to maintain stable yields under varying environmental conditions. Regarding HM, lines G72, G135, and G78 were identified as the most drought-tolerant, whereas lines G89, G71, and G39 showed the least tolerance. The lowest ToL value was observed for lines G60, G69 and G23, indicating that these genotypes had a lesser reduction of productivity in moisture deficit state. Based on YSI, lines G60, G69, G13, and G23 demonstrated the highest consistency across both stress and optimal conditions, whereas lines G95, G89, G45, and G84 were identified as the least stable genotypes. Similarly, according to YI, lines G72, G13, G25, and G78 exhibited the highest tolerance, while lines G89, G95, and G3 were found to be susceptible to moisture stress. The lines G72, G135, G78 and G100 had higher values of MRP which highlights these lines were having stable relative performance under stress and nonstress condition while lines G71, G89, G39 and G36 were least stable and fail to show stable performance across the conditions. The indices DI and RDI proved to be comparable in genotype selection, as both identified lines G60, G69, and G13 as the most drought-tolerant, while lines G95, G89, and G45 were classified as drought-susceptible. The lines G45, G95 and G94 were having high values of SSPI which suggest these lines were more susceptible to drought and show relatively high yield reduction under stress condition. Several researchers have used yield-based indices to screen the tolerant genotypes. For example, in Rice (Garg and Bhattacharya, 2017; Kandel *et al*., 2022), Sorghum (Abraha *et al*., 2015; Abebe *et al*., 2020), Chickpea (Sabaghnia and janmohammadi,2014; Jha *et al*., 2016), Maize (Khayatnezhad *et al.,* 2010), Common bean (Sánchez-Reinoso *et al*., 2020), Oats (Akcura and Ceri, 2011), Bread wheat (Aktas *et al*., 2016; Mousavi *et al*., 2008; Amare *et al*., 2019), Safflower (Bahrami *et al*., 2014; Khalili *et al*., 2014) and Cotton (Sun *et al*., 2023).

Association among drought tolerance indices and selection of germplasm lines based on MGIDI: Association analysis among drought indices and grain yield has proven to be an effective method for identifying which indices are suitable for selecting cultivars under water stress conditions (Farshadfar *et al.,* 2012). In this context, a suitable index should show a positive correlation with grain yield. Yield under stress and nonstress environment showed significant positive correlation (r = 0.57). Positive significant association between yield under stress and nonstress conditions were also reported by Abraha *et al*. (2015), Jha *et al*. (2016), Aktas *et al*. (2016) and Amare *et al*. (2019). Y_S and Y_P were positively correlated to indices MRP (r = 0.92, r = 0.84), GMP (r = 0.93, r = 0.83), MP (r = 0.89, r = 0.88), STI (r = 0.92, r = 0.83) and HM (r = 0.95, r = 0.78) respectively (**Fig. 1**). This indicates that these five indices were highly effective in selecting high yielding genotypes under both moisture-stressed and well-irrigated conditions. These findings align with previous studies by Akcura and Ceri (2011), Khayatnezhad *et al.* (2010), and Sánchez-Reinoso *et al*. (2020).The correlation among the indices STI, MP, GMP, MRP and YI were positively highly significant, exhibiting high resemblance among these indices for electing the best genotype (Mousavi *et al*., 2008; Abraha *et al*., 2015). There was also a highly positive and significant association among the indices SSI, ToL and SSPI (Jha *et al*., 2016; Abraha *et al*., 2015). The peak correlation (r = 1.00) was witnessed between productivity under stress (Y_S) and yield index (YI). Yield under stress (Y_S) showed significant negative correlation with indices SSI, SSPI and ToL which suggest lower values of these indices should be considered as desirable while selecting the genotypes for drought tolerance (Mohammed and Kadhem, 2017). In summary, the indices STI, MP, GMP, MRP and YI are among the best indicators of yield under both moisture stress and irrigated conditions. They can be effectively used to identify genotypes that are tolerant to moisture deficit conditions.

MGIDI analysis was carried out to identify the promising tolerant candidates based on yield under stress and multiple drought indices with a selection intensity of 15% (**Fig. 2**). MGIDI analysis allocate a rank to all the cultivars based on the preferred value of the selected traits. The selected lines were highlighted as red dots. The top ten selected lines were G72, G78, G4, G100, G135, G25, G13, G92, G57 and G16. These can be considered as best candidates for planning breeding programmes for drought tolerance. This method is very effective for the selection of genotypes based on multiple traits in plant breeding programmes. For instance, Pallavi *et al*. (2024) identified six high-performing rice accessions using MGIDI after evaluating 42 rice genotypes under field conditions. Similarly, Mamun *et al*. (2022) applied a 10% selection intensity to assess 100 rice mutants and selected the top 10 based on 16 quantitative traits. Mullangie *et al*. (2024) also utilized MGIDI to evaluate advanced rice breeding lines, enhancing selection for yield and lodging resistance by identifying genotypes with well-balanced agronomic traits. Their study reported a selection gain of 2% in yield for the F_5 generation and 5.80% in the BC_1F_4 generation. In our study, as shown in

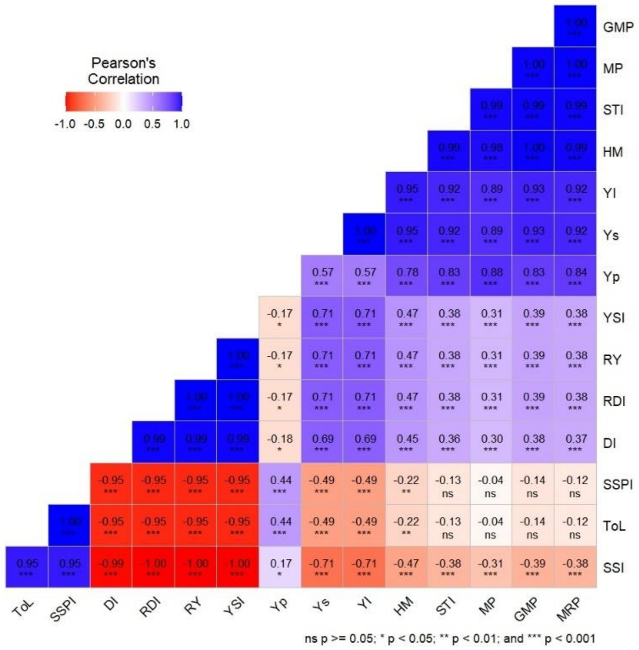

Fig. 1. **Heatmap showing correlation among yield under stress (Y_S), yield under nonstress (Y_P) and other drought indices**

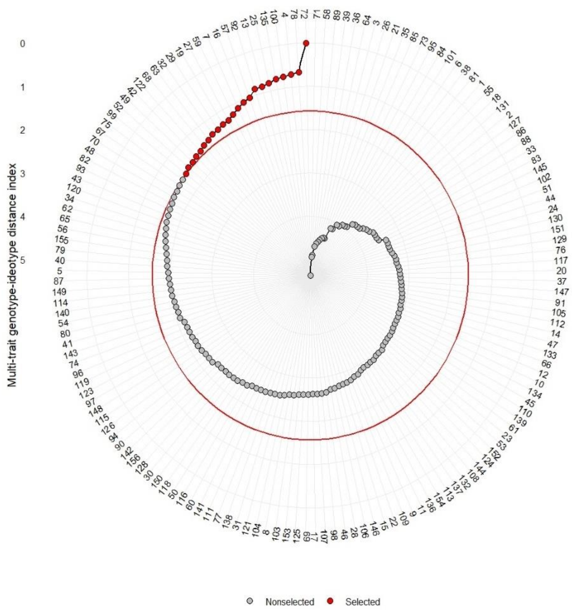

Fig. 2. **The rankings of sorghum germplasm lines illustrate the selected accessions based on the multi-trait genotype–ideotype index (MGIDI). Selected lines are indicated by red dots, while unselected accessions are represented by grey dots. The red circle denotes the cutoff point determined by the selection pressure**

Table 3, the mean values for the traits have increased for the selected genotypes compared to the original population, resulting in a positive selection differential and selection gains across all traits. Like this study, Pour-Aboughadareh *et al*. (2021) evaluated 146 wheat accessions using MGIDI, focusing on shoot dry matter under both stress (Ys) and control (Yp) conditions instead of yield. They also incorporated nine different tolerance indices to identify the top-performing genotypes.

Table 3. **Selection differential and selection gains of the traits in selected genotypes based on MGIDI.**

Trait	Xo	Xs	SD	SD %	SG	SG %
GMP	45.9	52.4	6.4	13.9	3.83	8.35
MP	46.8	52.7	5.91	12.6	3.41	7.29
HM	45.1	51.8	6.72	14.9	4.07	9.01
MRP	2	2.27	0.27	13.5	0.16	7.98
STI	0.765	0.974	0.209	27.3	0.117	15.4
YI	1	1.14	0.144	14.4	0.0693	6.93
Y_S	40.2	46	5.8	14.4	2.78	6.93

Where,
GMP: Geometric mean productivity, MP: Mean productivity, HM: Harmonic mean, MRP: Mean relative performance, STI: Stress tolerance index, YI: Yield index, Y_S: Yield under stress
Xo is mean of original population, Xs is mean of selected genotypes, SD is selection differential, SD% is % selection differential, SG is selection gain, SG% is % selection gain

Table 4. **Eigenvalue, variances and eigenvectors of the first five principal components for germplasm lines to different drought tolerant selection indices**

Parameter	Principal components				
	PC1	PC2	PC3	PC4	PC5
Eigenvalue	9.835	5.100	0.048	0.011	0.005
% variance	65.569	33.998	0.321	0.076	0.035
Cumulative % variance	65.569	99.568	99.889	99.964	99.999
Characters			Eigenvector		
Y_S	0.968	0.247	-0.031	0.010	-0.016
Y_P	0.350	0.935	0.062	0.002	-0.006
SSI	-0.859	0.509	-0.045	0.023	-0.011
STI	0.797	0.597	-0.063	0.037	0.059
GMP	0.808	0.589	-0.009	-0.021	-0.007
MP	0.751	0.660	0.017	0.007	-0.012
HM	0.852	0.520	-0.030	-0.043	-0.003
TOL	-0.690	0.717	0.099	-0.009	0.012
YI	0.968	0.247	-0.031	0.010	-0.016
YSI	0.859	-0.509	0.045	-0.023	0.011
MRP	0.797	0.603	0.009	0.007	-0.013
DI	0.847	-0.517	0.098	0.071	-0.010
SSPI	-0.690	0.717	0.099	-0.009	0.012
RDI	0.859	-0.509	0.045	-0.023	0.011
RY	0.859	-0.509	0.045	-0.023	0.011

Principal component analysis (PCA): PCA reduces a large dataset into a smaller number of components by identifying groups of variables with strong inter-correlations. Each component accounts for a certain percentage of the total variation. Principal components of the tolerance indices and productivity under drought and non-stressed environments of the germplasm lines are presented in (**Table 4**). Principal component analysis was conducted to evaluate the relationships among all attributes in order to identify the best genotypes for both water-stressed and non-stressed conditions. The analysis unveiled that the two first PCs accounted for 99.56% of total variation. Jha *et al*. (2016), Aktas *et al*. (2016), Amare *et al*. (2019) and Abebe *et al.* (2020) also reported more than 95% variance for the first two PCs. PC1 explained 65.6% of the variation with the larger contribution by the characters Y_S, YI, YSI, RDI, RY and SSI. PC2 explained 34% of the variation with a higher contribution of the traits Y_P, ToL and SSPI. In the PCA plot (**Fig. 3 and 4**), a cluster was formed, including YS, GMP, HM, MP, YI, MRP, and STI, further supporting

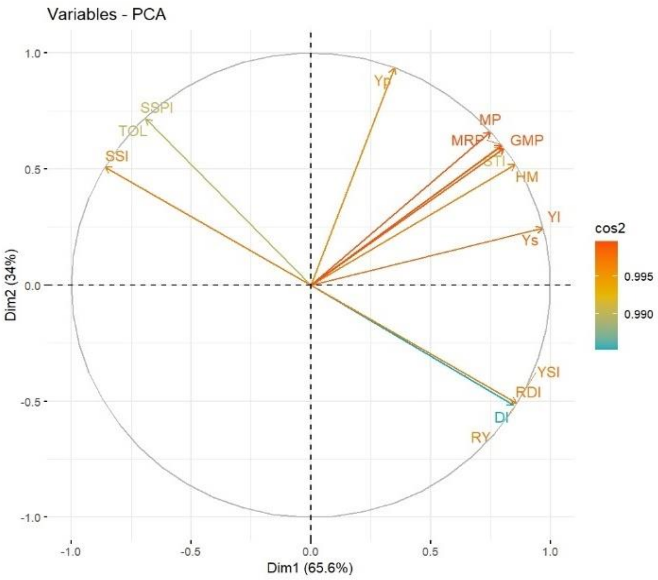

Fig. 3. Biplot showing proportion of contribution of the traits and their association in the principal components under drought condition

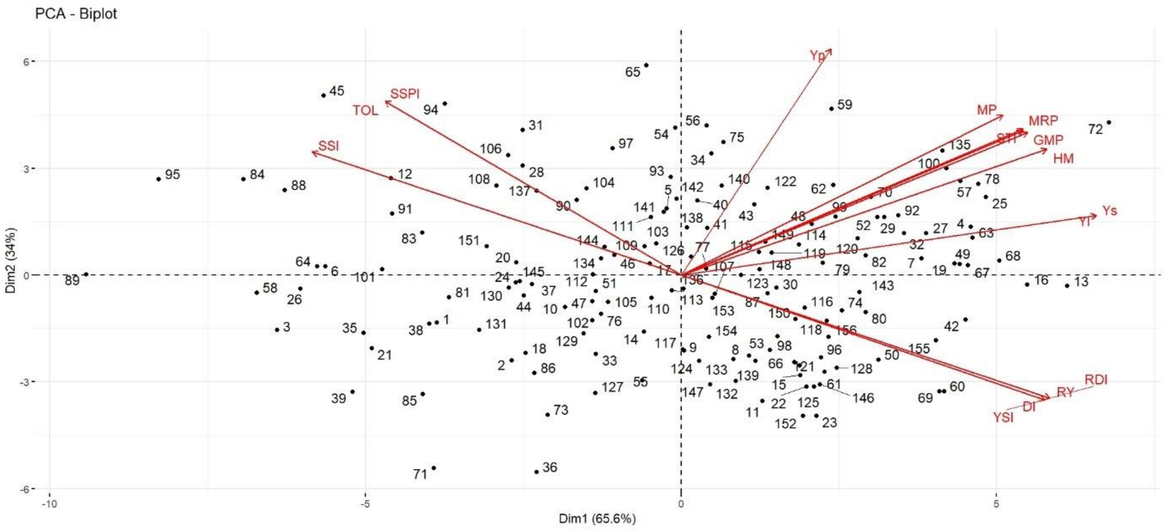

Fig. 4. PCA Biplot between PC1 and PC2 derived from PCA analysis showing distribution of sorghum germplasm lines

the correlation among them. Large obtuse angle between vectors of indices SSI, ToL and SSPI with Y_S, YI and HM in biplot graph indicate negative association between them. Negative association of SSI with RDI, DI, YSI and RY was indicated by straight angle between their vectors (**Fig. 3**). Based on correlation and PCA analysis, the indices STI, MRP, and MP emerge as the most effective for selection programs under both stress and irrigated conditions, outperforming other indices in their reliability and selection accuracy. These drought indices can be called as drought stress tolerance components. Similar findings showing a positive correlation with Y_S, Y_P, STI, and MP have been reported (Aktas, 2015; Abraha *et al*., 2015; Hooshmandi, 2019). Genotypes with a high value for the first component (PC1) are anticipated to yield well in both stressed and non-stressed conditions. Those with higher PC1 and lower PC2 values exhibited high grain yields (indicating stability), while genotypes with lower PC1 and higher PC2 scores showed low grain yields (indicating instability). Likewise, Sánchez-Reinoso *et al*. (2020) also reported that genotypes with higher PC1 and lower PC2 values exhibited high grain yields, indicating stability, whereas those with low PC1 and high PC2 values showed lower yields, suggesting instability.

The genotypes were clustered in PCA plot as per their drought-tolerant ability. Selecting for high PC1 loading results in genotypes with high grain yield in both stressed and non-stressed environments. In contrast, selecting for low PC2 loading favors genotypes that experience less reduction in productivity due to drought. The preference for low PC2 loading is due to its strong relation with ToL and SSPI, where lower values indicate reduced sensitivity to moisture stress. The lines G60, G69, G23 and G155 had higher values for PC1 and low values for PC2 (low sensitivity and high yield) thus, these genotypes identified as drought tolerance. These entries showed higher values of STI, MP, MRP, YI, MP, GMP and HM coupled with low values of SSI and ToL. Lines G89, G3, G58, G39, and G71 were susceptible to drought and exhibited low productivity because these genotypes had lower levels of both PC1 and PC2 compared to other entries. Similarly, Abraha *et al*. (2015) employed PCA and classified 25 sorghum accessions into different groups based on yield performance under both stress and non-stress conditions and drought indices.

Grouping of germplasm lines based on drought indices using cluster analysis: Cluster analysis was performed on the drought indices by Ward's method using squared Euclidean distance as a measure of similarity. Cluster analysis using drought tolerance indices and grain yield data from both stressed and non-stressed conditions grouped the genotypes into five clusters (**Table 5 & Fig. 5**). Clusters I, II, III, IV, and V contained 18.6%, 10.9%, 18%, 28.2%, and 24.35% of the genotypes, respectively. The average of the indices and productivity of the cluster groups obtained from cluster analysis are illustrated in **Table 6**. Cluster I exhibited high productivity in both stressed and non-stressed conditions. It also had higher values for STI, GMP, MP, HM, YI, YSI, and MRP, along with lower values for ToL, SSI, and SSPI. This indicates that Cluster I contained desirable genotypes based on yield from both environments and selection indices. Cluster II comprised genotypes with low yield under stress, characterized by higher SSI, ToL, and SSPI values and lower STI, GMP, HM, YI, YSI, MRP, and RY values. This suggests that these genotypes are susceptible to drought and perform poorly under moisture deficit conditions. Cluster III displayed low yield under stress but optimal yield under non-stress conditions. Cluster IV was noted for higher grain yield under non-stress and optimal yield under stress, with intermediate values for STI, GMP, and MRP, indicating moderate drought tolerance. Cluster V exhibited optimal yield in both stress and non-stress conditions. El-Mohsen *et al*. (2015) successfully classified wheat genotypes into three different groups *viz*., tolerant, semi tolerant and sensitive based on drought tolerance indices and grain yield under stressed and non-stressed conditions. Similarly, based on yield under stress and non stressed condition and different drought indices 256 bread wheat genotypes grouped into nine clusters (Amare *et al*., 2019), seventy sorghum genotypes into three clusters (Abebe *et al*., 2020), 34 chickpea genotypes into four clusters (Jha *et al*., 2016) and 64 safflower genotypes into three clusters (Bahrami *et al*., 2014).

In conclusion, to select the genotypes with stable and high yielding under stress as well as nonstress condition the indices STI, GMP, MP and MRP can be employed as they showed highly positive significant association with yield under both conditions. The Multi-Trait Genotype–Ideotype Distance Index (MGIDI) analysis identified G72, G78, G4 and G100 as the superior lines having desirable values for multiple indices including yield under stress as well as nonstress conditions. MGIDI proved highly effective in identifying superior sorghum lines, achieving significant improvements across multiple traits. Multivariate techniques like principal component analysis and cluster analysis can be effectively utilized to distinguish between tolerant and susceptible genotypes, as well as to analyze interactions across multiple traits.

Table 5. Clustering of germplasm lines using drought tolerant indices

Cluster	No. of Genotypes	Genotypes
I	29	G36, G71, G86, G2, G18, G73, G55, G127, G81, G131, G1, G38, G44, G37, G130, G24, G145, G21, G151, G21, G35, G39, G85, G101, G6, G64, G3, G26, G58
II	17	G89, G95, G84, G88, G90, G104, G108, G137, G97, G31, G28, G106, G12, G83, G91, G45, G94
III	28	G92, G29, G52, G82, G120, G7, G27, G32, G43, G122, G48, G99, G62, G70, G13, G16, G4, G63, G68, G67, G19, G49, G72, G100, G135, G25, G57, G78
IV	44	G143, G74, G80, G116, G150, G118, G156, G39, G87, G123, G148, G149, G115, G119, G79, G114, G154, G124, G9, G117, G11, G132, G147, G133, G8, G139, G53, G98, G23, G152, G50, G22, G125, G146, G15, G66, G121, G96, G61, G128, G60, G69, G42, G155
V	38	G10, G51, G47, G105, G129, G76, G102, G14, G33, G107, G153, G110, G113, G136, G112, G144, G46, G134, G77, G126, G17, G103, G109, G93, G140, G40, G142, G41, G138, G111, G5, G141, G65, G59, G34, G75, G54, G56

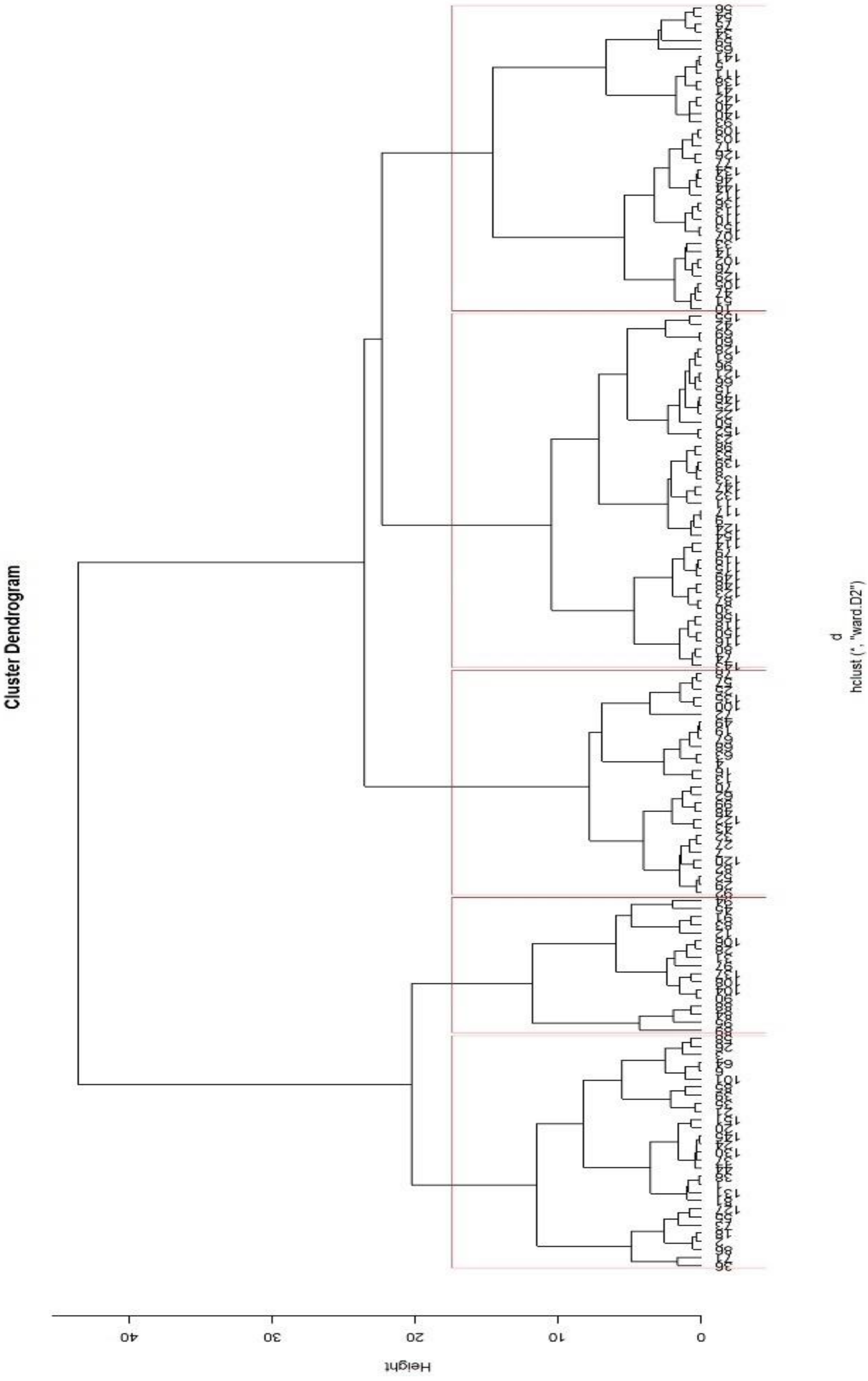

Fig. 5. Dendrogram of cluster analysis of sorghum germplasm lines derived from yield under stress condition (Y_S), yield under non-stress condition (Y_P) and other 13 drought indices using Ward's method.

Table 6. **Mean comparison of five cluster groups for yield and drought indices obtained from cluster analysis**

Traits	Clusters				
	I	II	III	IV	V
Y_S	51.230	26.793	32.622	40.886	42.476
Y_P	61.127	53.173	45.841	59.997	48.938
SSI	0.642	1.984	1.149	1.270	0.523
STI	1.097	0.505	0.528	0.859	0.728
GMP	55.930	37.676	38.640	49.481	45.569
MP	56.178	39.983	39.232	50.441	45.707
HM	55.683	35.518	38.060	48.542	45.431
TOL	9.897	26.380	13.219	19.111	6.462
YI	1.275	0.667	0.812	1.018	1.057
YSI	0.840	0.506	0.714	0.684	0.870
MRP	2.418	1.661	1.669	2.140	1.973
DI	0.709	0.260	0.514	0.471	0.760
SSPI	9.254	24.666	12.360	17.870	6.042
RDI	1.118	0.674	0.951	0.911	1.158
RY	84.015	50.640	71.422	68.404	86.996

The germplasm lines identified as tolerant in our study can serve as pre-breeding material for future breeding programs focused on enhancing drought tolerance.

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