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Research Article

Exploring the usefulness of drought tolerance indices in screening of maize inter-racial derivatives

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Abstract

Among all the abiotic factors affecting maize yield, drought stress is the most destructive one. Since drought tolerance is a complicated trait that is difficult to quantify, screening for stress involves measuring the effects of stress on several traits, most notably plant yield. Selection using the drought tolerance indices is an easy way to identify the stable and tolerant genotypes based on yield performances alone. The current study aims to identify suitable maize hybrids with high drought tolerance. A total of 30 maize-teosinte hybrids and 3 checks were raised under optimal and water-stressed environments and were screened using twelve different drought tolerance indices. It was observed that the inter-racial hybrids viz., G24, G27, and G29 were better than the drought tolerant *Zea mays* ssp. *mays* check C3 for yield and most of the indices. The indices STI, TOL, GMP, MP, YI, DI, SSPI, K_1STI, and K_2STI were observed to be significantly correlated with yield under stress and optimal environments. Based on the yield both environments, the genotypes were classified under four groups, with Group A consisting of genotypes with high yields under both environments. The indices Stress Tolerance Index (STI), Geometric Mean Productivity (GMP), Yield Index (YI), and Modified Stress Tolerance Index (K_2STI)were identified for their ability to discriminate Group A from the other genotypes and these indices could be utilized to screen for drought tolerance with high yield.Component Analysis revealed two principal components contributing up to 98.15 percent of the cumulative variation. The PCA biplot identified the hybrids viz., G24, G27, G14, G19, and G25 as tolerant ones. Based on the index scores, the hybrids viz., G27, G29, G17, G20,and G24were identified as the top-ranking genotypes, with high and more stable yields under both stress and optimal environments.

Keywords: Drought index, maize, 3D plot, inter-racial hybrids, teosinte

INTRODUCTION

Maize is an important cereal crop, cultivated globally. Due to the increasing unpredictability of the climate and extended periods of drought, water has become a scarce resource, greatly hindering crop production. Drought stress is more devastating and severe among all the abiotic stresses affecting maize production (Kunjammal and Sukumar, 2019). In maize, drought stress at flowering is found to be more critical and affects kernel yield, leading to yield loss between 30 – 90 % depending on the intensity (Sah *et al*., 2020). Therefore, it is of great importance to improve maize yields under drought conditions. Teosinte refers to primitive wild grass species native to Mexico and Central America. *Zeamays* subsp. *parviglumis* is considered the progenitor for the modern races of *Zeamays* subsp. *mays.* (Adhikari *et al*., 2021).Significant variations for drought tolerance were reported in the teosinte species *Zea mays* ssp. *mexicana*(Bondok *et al*., 2022), and parviglumis-derived maize lines (Kumar *et al*., 2020). Maize being a drought-sensitive crop,wide hybridization between maize and teosinte lines could introgress the wild alleles in the maize background resulting in significant variations in drought tolerance(Kumar *et al*., 2020).

Drought tolerance is a complex trait influenced by several mechanisms in different growth phases and parts of the crop. Drought tolerance could not be quantified as such, and screening for drought tolerance involves measuring the confounding effect of the stress on the studied traits, majorly plant yield. G × E interaction effects greatly affect the relative yield performances of genotypes, which warrants applying grain-yield-based stress indices for discriminating the genotypes based on their yield potential under stress and optimal conditions. Blum (2005) noted the significance of selecting genotypes based on high yield firstly under optimal conditions and secondly under stress conditions and implied that a genotype with high yield potential will perform well under both environments. Selection based on the stress indices is easy and does not requirean understanding ofthe various mechanisms underlying drought tolerance (Bonea, 2020). Most stress breeding programs generally focus on enhancing grain yield under stress, although genotypes with high yield may not always be tolerant to stress. Using stress tolerance indices that measure drought based on the yield under stress compared with optimal conditions could be a more efficient strategy for identifying potential drought-tolerant genotypes.

An attempt was made to identify suitable maize hybrids with drought tolerance using twelve different drought tolerance indices. The current investigation compares the different drought resistance or tolerance indices and finds the association of these indices with grain yield to identify potential genotypes suitable for optimal and stress conditions.

MATERIALS AND METHODS

Wide hybridization was carried out between maize and teosinte species with *Zeamays* ssp. *mays* inbreds as female parents. The maize inbreds were crossed with three wild relatives, teosinte *Zea mays* ssp. *mexicana*, *Zeamays* ssp. *parviglumis*, and *Zealuxurians* as tester. The crossing was carried out in the summer and *kharif* seasons of 2022 and the newly synthesized F$_1$s (30) and parents were separately evaluated for drought tolerance along with three checks, in the summer of 2023 at Department of Millets, Tamil Nadu Agricultural University, Coimbatore. The hybrids and three checks (**Table 1**) replicated twice, were raised in randomized block design under well-watered (WW) and water-stressed (WS) conditions. The checks include popular commercial hybrids CO H(M) 6, CO H(M) 8, and CO H(M) 11. Each genotype consists of a plot with two rows of 4 m each and adapted with a spacing of 60 × 25 cm. Water stress in the stress environment was given by withholding irrigation before anthesis and extended until the grain filling stage, after which rewatering was done. The rest of the operations were carried out according to the recommendations. The weather data for the evaluation period is presented in **Fig 1**.

Table 1. List of hybrids and checks

Code	Hybrid	Code	Hybrid
G1	VL1018299 ×*Zea luxurians*	G18	UMI 1230 B^{+} × Z. m. ssp. parviglumis
G2	VL1018300 ×*Zea luxurians*	G19	UMI 1201 ×*Z. m. ssp. parviglumis*
G3	DMRE63 ×*Zea luxurians*	G20	UMI 1205 ×*Z. m. ssp. parviglumis*
G4	UMI 1223 ×*Zea luxurians*	G21	VL1018299 ×*Z. m. spp.mexicana*
G5	UMI 1200 ×*Zea luxurians*	G22	VL1018300 ×*Z. m. spp. mexicana*
G6	UMI 1230 ×*Zea luxurians*	G23	DMRE63 ×*Z. m. spp. mexicana*
G7	UMI 1200 B^{+} ×*Zea luxurians*	G24	UMI 1223 ×*Z. m. spp. mexicana*
G8	UMI 1230 B^{+} ×*Zea luxurians*	G25	UMI 1200 ×*Z. m. spp. mexicana*
G9	UMI 1201 × *Zea luxurians*	G26	UMI 1230 ×*Z. m. spp. mexicana*
G10	UMI 1205 × *Zea luxurians*	G27	UMI 1200 B^{+} ×*Z. m. spp. mexicana*
G11	VL1018299 ×*Z. m. ssp. parviglumis*	G28	UMI 1230 B^{+} ×*Z. m. spp. mexicana*
G12	VL1018300 ×*Z. m. ssp. parviglumis*	G29	UMI 1201 × *Z. m. spp. mexicana*
G13	DMRE63 ×*Z. m. ssp. parviglumis*	G30	UMI 1205 × *Z. m. spp. mexicana*
G14	UMI 1223 ×*Z. m. ssp. parviglumis*		**Checks**
G15	UMI 1200 ×*Z. m. ssp. parviglumis*	C1	CO H(M) 6
G16	UMI 1230 ×*Z. m. ssp. parviglumis*	C2	CO H(M) 8
G17	UMI 1200 B^{+} ×*Z. m. ssp. parviglumis*	C3	CO H(M) 11

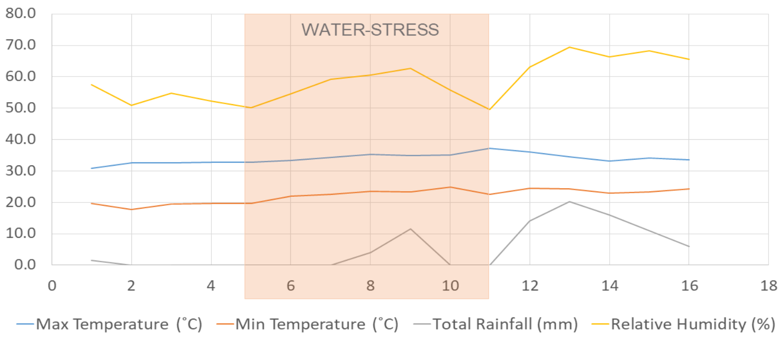

Fig. 1. Weekly weather data during evaluation (Summer'23)

The cobs of randomly selected plants per plot were harvested individually and post-harvest observations were recorded. The mean of individual grain weights per plant recorded in grams was corrected to the standard moisture percent of 15.5%, as described by Mulvaney and Devkota (2020) and observed as yield under optimal environment (Yp) and yield under water-stress environment (Ys). The mean yields under optimal and water-stress environments were observed as $\bar{Y}p$ and $\bar{Y}s$ respectively. The drought indices were derived from the yield parameters.

Fischer and Maurer (1978) applied the Stress Susceptibility Index (SSI) in wheat genotypes, which is based on the ratio of yield of a specific genotype under stress and optimal conditions to the ratio of mean yield of all genotypes under stress and optimal conditions. They also described the Relative Drought Index (RDI), which compared the yield ratios of genotypes to that of the population under stress and optimal conditions.

The tolerance index (TOL) as defined by Rosielle and Hamblin (1981) is the difference in the yield between stress and optimal environments. They also described and used the Mean Productivity index (MP), which denotes the average yield of genotypes under both stress and optimal conditions. The Geometric Mean Productivity (GMP) suggested by Fernandez (1992) depicts the relative performance of genotypes in stress and optimal environments.

The Yield Index (YI) described by Gavuzzi *et al.* (1997) and the Yield Stability Index (YSI) described by Bouslama and Schapaugh (1984) are used in studying the stability of genotypes under stress and optimal conditions. The Drought resistance Index (DI), proposed by Blum (1988) identifies genotypes with high yield under both stress and optimal environments. The Stress Tolerance Index (STI) described by Fernandez (1992) couldbe used to identify high-yielding genotypes with a high potential for stress tolerance. They have also pointed out that the best method for selection in drought stress should have the ability to discern the genotypes with desirable yield under stress and optimal conditions and have divided the genotypes into four groups (Group A) high yield under both environments, (Group B) higher yield only under optimal conditions, (Group C) higher yield only under stress conditions, and (Group D) poor performance under both environments.

A modified approach to STI was introduced by Farshadfar and Sutka (2002) as K_1STI and K_2STI, which applies weightage to yield under optimal conditions and yield under stress conditions to identify genotypes for optimal conditions and stress conditions respectively. The Stress Susceptibility Percentage Index (SSPI) proposed by Mousavi *et al.* (2008) is useful in screening drought-tolerant genotypes under stress and optimal conditions and selecting genotypes based on yield stability. Twelve drought tolerance indices were calculated using the following relationships:

i	Stress Susceptibility Index	$SSI = (1-(Ys/Yp)) / (1-(\bar{Y}s/\bar{Y}p))$	Fischer and Maurer (1978)
ii	Relative Drought Index	$RDI = (Ys/Yp)/(\bar{Y}s/\bar{Y}p)$	Fischer and Maurer (1978)
iii	Tolerance Index	$TOL = Yp - Ys$	Rosielle and Hamblin (1981)
iv	Mean Productivity	$MP = (Ys + Yp)/2$	Rosielle and Hamblin (1981)
V	Geometric Mean Productivity	$GMP = \sqrt{} (Ys \times Yp)$	Fernandez (1992)
vi	Stress Tolerance Index	$STI = (Ys \times Yp) / (\bar{Y}p^2)$	Fernandez (1992)
vii	Yield Index	$YI = (Ys) / (\bar{Y}s)$	Gavuzzi *et al.* (1997)
viii	Yield Stability Index	$YSI = Ys / Yp$	Bouslama and Schapaugh (1984)
ix	Drought Resistance Index	$DI = (Ys \times (Ys/Yp)) / \bar{Y}s$	Blum (1988)
x	Stress Susceptibility Percentage Index	$SSPI = (Yp - Ys/2(\bar{Y}p)) \times 100$	Mousavi *et al.* (2008)
xi	Modified Stress Tolerance Index, K_iSTI	$K_1STI = Yp^2/\bar{Y}p^2$	Farshadfar and Sutka (2002)
xii		$K_2STI = Ys^2/\bar{Y}s^2$	Farshadfar and Sutka (2002)

In the above formulas, Ys, Yp, $\bar{Y}s$, and $\bar{Y}p$ represent genotype yield under water stress, genotype yield under optimal conditions, and mean yield in water stress and optimal conditions, respectively.

The Pearson's correlation coefficients were calculated and correlation plots were derived using GRAPES version 1.1.0. The Principal Component Analysis was performed genotype–variable biplot was also derived using GRAPES version 1.1.0. The three-dimensional plots were worked out in R studio using the scatterplot3d function.

RESULTS AND DISCUSSION

In the investigation, 12 drought tolerance indices were studied, to screen for genotypes with high and stable yields. In order to identify the appropriate indices, it is essential to understand how the indices are associated with one another and with the yields. Correlation analysis can be used to determine the suitability of the indices based on their association with the yield. Principal component analysis was done to reduce the dimensionality of the data.

Correlation between the stress indices and grain yield:Farshadfar *et al.*(2001) implied that the most suitable indices for the selection of drought-tolerant cultivars are indicators that show a relatively high correlation with grain yield in both stress and non-stress environments. Correlation analysis revealed that a significant and positive correlation (r = 0.84***) was observed between the yield under stress (Ys) and optimal environment (Yp) (**Table 2**), implying that a genotype with high yield under optimal conditions could also possess the potential for high yield under stress conditions.This is consistent with the conclusions of Blum (2005). All the indices, except SSI, showed a significant positive correlation with the yield under water stress, while SSI expressed a significant negative correlation with yield under stress. Under water stress, a perfect positive correlation with grain yield was observed with YI (r = 1.00***). However, for grain yield under optimal conditions,the indices except SSI, RDI, and YSI showed a significant and positive correlation, and no significant correlation was observed between SSI, RDI, and YSI with Yp. Therefore, the indices TOL, STI, GMP, MP, YI, DI, SSPI, K_1STI, and K_2STI, which showed a significant correlation with both Yp and Ys can be noted as the best-suited indicators for screening drought tolerance in maize.

The intercorrelations among the different indices and yield also depict the relationship between the indices. SSI is negatively related to all indices except TOL. A significant and positive correlation were observed between the indices STI, GMP, MP, DI, YI, YSI, K_1STI, and K_2STI (**Fig. 2**). Jafari *et al.* (2009) and Ngugi *et al.* (2013), observed similar interrelationships between STI, GMP, and MP in maize. A complete and positive correlation was observed between the stability indices RDI and YSI, consistent with the findings of Naghavi *et al.* (2013).

Table 2. Genotypic correlations between the yield and stress indices

	Yp	TOL	SSI	RDI	STI	GMP	MP	YI	DI	YSI	SSPI	K_1STI	K_2STI
Ys	0.839**	0.504**	-0.519**	0.52**	0.964**	0.969**	0.929**	1.00**	0.940**	0.516**	0.504**	0.834**	0.976**
	Yp	0.893**	-0.004	0.006	0.920**	0.945**	0.981**	0.839**	0.623**	-0.001	0.893**	0.984*	0.789**

** Correlation is significant at 0.01 level (two-tailed)

* Correlation is significant at 0.05 level (two-tailed)

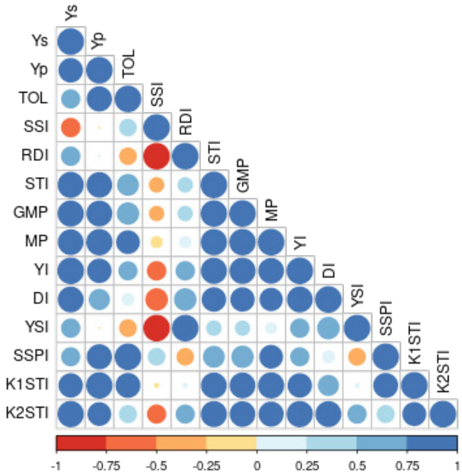

Fig. 2. Correlogram depicting the inter-correlations between the different stress indices and yield

Component Analysis: The principal component analysis was worked out between the indices and mean yields, and the results revealed that eight components, out of which only two principal components were significant by contributing 98.15 per cent of the variations (**Table 3**), while the remaining components together were responsible for a meagre 1.75 per cent of variations. The component PC1, contributed 67.74 per cent variation with a high correlation to Ys, Yp, STI, GMP, MP, YI, DI, K_1STI, and K_2STI and could be considered the performance component. The second component PC2, contributed 30.40 per cent variation and is correlated to TOL, SSI, RDI, YSI, and SSPI, and considered as the stress sensitivity component. Therefore selecting genotypes with higher values for both components will perform better in the predicted environments. The genotype-variable biplot (**Fig. 3**) couldbe used to identify the genotypes that are stable under both stress and non-stress conditions. El-Azeem *et al*. (2023) have used PCA biplot to identify the stable and tolerant genotypes. The genotypes predicting

Table 3. Eigenvalues, Percent variance, cumulative variance, and factor loadings of different stress indices to the PCs

	PC1	PC2
Eigenvalue	9.49	4.26
Percentage of variance	67.74	30.40
Cumulative %	67.74	98.15
Variables		
Ys	0.319	0.085
Yp	0.300	-0.184
TOL	0.212	-0.362
SSI	-0.121	-0.445
RDI	0.121	0.444
STI	0.321	-0.020
GMP	0.323	-0.030
MP	0.318	-0.095
YI	0.319	0.085
DI	0.282	0.218
YSI	0.120	0.446
SSPI	0.212	-0.362
K_1STI	0.299	-0.173
K_2STI	0.310	0.096

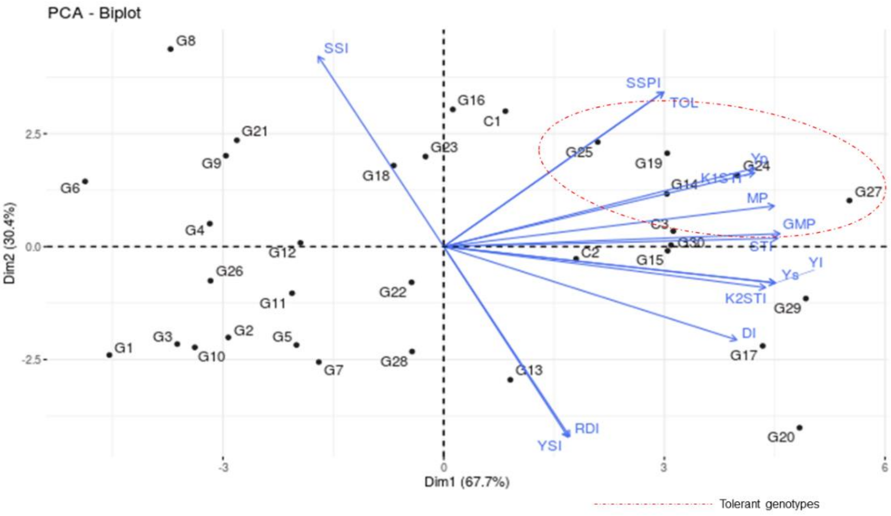

Fig. 3. Genotype by variable biplot of the first two PCs of 34 maize genotypes

high values for both PC1 and PC2 couldbe considered as high-yielding and stable ones. In the biplot, the genotypes plotted in the first quadrant are more likely to be stable owing to the higher values of both PC1 and PC2. Based on the biplot the genotypes viz., G24, G27, G14, G19, and G25couldbe noted as the high-yielding andtolerant genotypes, which also fall under Group A and observed from the three-dimensional plots (**Fig. 5**).

Relationship between mean yield and stress indices:The yield of genotypes under water stress (Ys) ranges between 8.61 g (G8) and 79.46g (G20) with a mean yield ($\bar{Y}$s) of 40.21 gwhile under optimal conditions the yield of genotypes ranged between 21.93 g (G1) and 162.55 g (G27) with a mean yield ($\bar{Y}$p) of 95.2 g. It is observed that the genotypes viz., G14, G15, G17, G19, G20, G24, G25, G27, G29, G30, C2, and C3 recorded grain yields higher than the average yield under the respective environments (**Table 4**). Further, the genotypes viz., G20, G29, G17, G27, G24, G30, and G15 are observed to have higher Ys than the drought-tolerant check C3.The twelve stress indices were determined based on the mean yields Ys and Yp for the hybrids and checks (**Table 4**). **Fig. 4a and 4b** compare the indices and mean yields of the genotypes and point out the correlation among different indices.

Table 4. Mean yield and estimates of stress indices for the hybrids

G	Ys	Yp	TOL	SSI	RDI	STI	GMP	MP	YI	DI	YSI	SSPI	K_1STI	K_2STI
G1	10.93	21.93	11.00	0.87	1.18	0.03	15.48	16.43	0.27	0.14	0.50	5.78	0.05	0.07
G2	23.72	47.59	23.87	0.87	1.18	0.12	33.60	35.66	0.59	0.29	0.50	12.54	0.25	0.35
G3	18.35	36.99	18.64	0.87	1.17	0.07	26.05	27.67	0.46	0.23	0.50	9.79	0.15	0.21
G4	20.09	59.95	39.86	1.15	0.79	0.13	34.70	40.02	0.50	0.17	0.34	20.93	0.40	0.25
G5	30.63	58.62	27.99	0.83	1.24	0.20	42.38	44.63	0.76	0.40	0.52	14.70	0.38	0.58
G6	8.92	39.47	30.55	1.34	0.53	0.04	18.76	24.19	0.22	0.05	0.23	16.05	0.17	0.05
G7	32.97	60.27	27.30	0.78	1.30	0.22	44.57	46.62	0.82	0.45	0.55	14.34	0.40	0.67
G8	8.61	80.03	71.42	1.54	0.25	0.08	26.25	44.32	0.21	0.02	0.11	37.51	0.71	0.05
G9	18.86	73.63	54.77	1.29	0.61	0.15	37.26	46.24	0.47	0.12	0.26	28.77	0.60	0.22
G10	20.22	40.00	19.78	0.86	1.20	0.09	28.44	30.11	0.50	0.25	0.51	10.39	0.18	0.25
G11	29.34	65.21	35.87	0.95	1.07	0.21	43.74	47.27	0.73	0.33	0.45	18.84	0.47	0.53
G12	28.70	74.19	45.49	1.06	0.92	0.23	46.14	51.44	0.71	0.28	0.39	23.89	0.61	0.51
G13	52.14	87.65	35.51	0.70	1.41	0.50	67.60	69.89	1.30	0.77	0.59	18.65	0.85	1.68
G14	57.56	139.46	81.90	1.02	0.98	0.89	89.60	98.51	1.43	0.59	0.41	43.01	2.15	2.05
G15	60.81	130.23	69.42	0.92	1.11	0.87	88.99	95.52	1.51	0.71	0.47	36.46	1.87	2.29
G16	34.51	122.06	87.55	1.24	0.67	0.46	64.90	78.29	0.86	0.24	0.28	45.98	1.64	0.74
G17	73.34	127.34	54.00	0.73	1.36	1.03	96.64	100.34	1.82	1.05	0.58	28.36	1.79	3.33
G18	33.28	102.51	69.24	1.17	0.77	0.38	58.41	67.90	0.83	0.27	0.32	36.36	1.16	0.68
G19	54.85	146.69	91.84	1.08	0.89	0.89	89.70	100.77	1.36	0.51	0.37	48.23	2.37	1.86
G20	79.46	119.18	39.71	0.58	1.58	1.04	97.31	99.32	1.98	1.32	0.67	20.86	1.57	3.91
G21	19.05	78.22	59.17	1.31	0.58	0.16	38.60	48.64	0.47	0.12	0.24	31.08	0.68	0.22
G22	40.18	86.95	46.77	0.93	1.09	0.39	59.11	63.56	1.00	0.46	0.46	24.57	0.83	1.00
G23	35.38	109.46	74.08	1.17	0.77	0.43	62.23	72.42	0.88	0.28	0.32	38.91	1.32	0.77
G24	61.90	152.28	90.38	1.03	0.96	1.04	97.09	107.09	1.54	0.63	0.41	47.47	2.56	2.37
G25	48.53	138.65	90.12	1.13	0.83	0.74	82.02	93.59	1.21	0.42	0.35	47.33	2.12	1.46
G26	21.48	51.87	30.39	1.01	0.98	0.12	33.38	36.68	0.53	0.22	0.41	15.96	0.30	0.29
G27	72.37	162.55	90.18	0.96	1.05	1.30	108.46	117.46	1.80	0.80	0.45	47.36	2.92	3.24
G28	42.04	76.89	34.85	0.78	1.29	0.36	56.86	59.47	1.05	0.57	0.55	18.30	0.65	1.09
G29	74.89	140.29	65.40	0.81	1.26	1.16	102.50	107.59	1.86	0.99	0.53	34.35	2.17	3.47
G30	61.01	131.41	70.41	0.93	1.10	0.88	89.54	96.21	1.52	0.70	0.46	36.98	1.91	2.30
C1	38.78	130.09	91.31	1.22	0.71	0.56	71.03	84.43	0.96	0.29	0.30	47.96	1.87	0.93
C2	53.66	115.78	62.12	0.93	1.10	0.69	78.82	84.72	1.33	0.62	0.46	32.63	1.48	1.78
C3	60.33	134.17	73.84	0.95	1.06	0.89	89.97	97.25	1.50	0.67	0.45	38.78	1.99	2.25

Ys – grain yield (g) of genotype under water stress, Yp - grain yield (g) of genotype under optimal conditions

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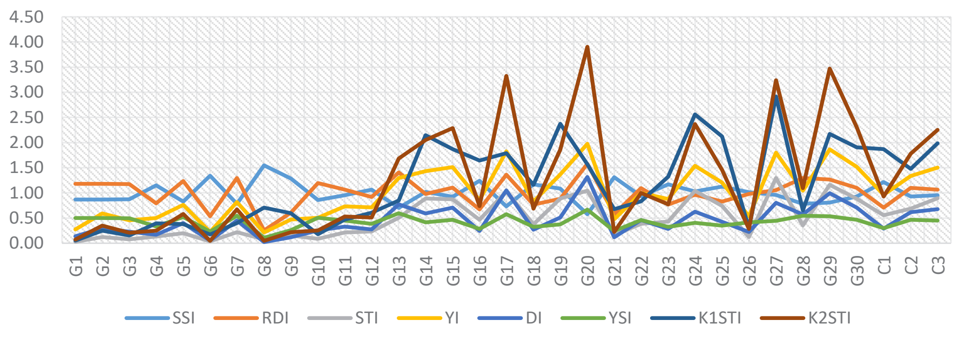

Fig. 4a. Comparison of indices SSI, RDI, STI, YI, DI, YSI, K_1STI & K_2STI

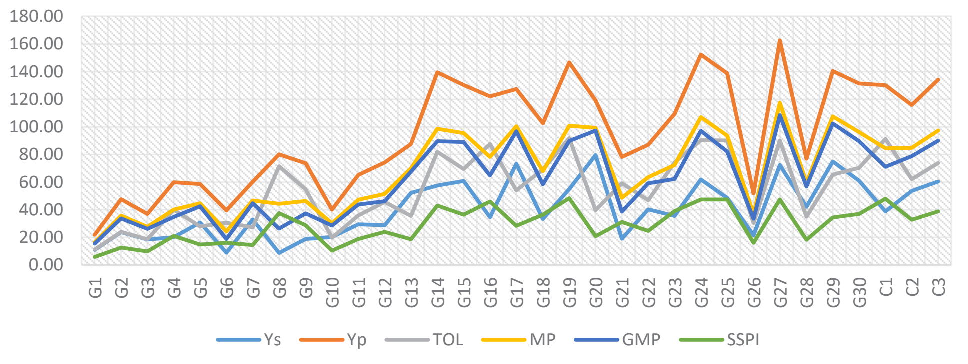

Fig. 4b. Comparison of Ys (g), Yp (g), TOL, MP, GMP & SSPI

Fig 4.(a) Comparison of SSI, RDI, STI, YI, DI, YSI, K_1STI & K_2STI
(b) Comparison of Ys (g), Yp (g), TOL, MP, GMP & SSPI

The lower values for the indices TOL and SSI were preferred for tolerant genotypes. The lower the difference between the mean yield under stress and optimal conditions for the genotypes, as indicated that the lower the TOL for the genotypes, and the lesser will be their SSI. The genotype G1 (11.00) showed the least difference between the yield under the two environments, however, it falls under Group D with poor yield under both environments, while G19 (91.84) is identified as the most sensitive genotype, even though it is classified under Group A. For SSI, the genotype G20 (0.58), which falls under Group A, showed the lowest value and is noted as the tolerant genotype, while the genotype G8 (1.54) with high SSI is identified as the most sensitive one. SSI can be used to eliminate sensitive genotypes and is regarded as the measure of yield stability (Muthuramu and Ragavan, 2020). Golabadi *et al*. (2006) pointed out that since both these indicators represent the stress sensitivity of the genotypes, selection based on these two indices favours genotypes with low yield under optimal conditions and high yield under stress conditions. All of the top-ranking genotypes (**Table 5**) based on TOL fall under Group D owing to their poor performance in both environments, making it unreliable to identify the best performers under stress. SSI, on the other hand, identifies high-yielding genotypes with tolerance but still cannot distinguish the genotypes of Group A from the other three groups.

Fischer and Wood (1979) declared that the genotypes with greater than unity RDI index are relatively tolerant to water deficit stress, while those with RDI index lesser than unity are considered susceptible. Bouslama and Schapaugh (1984) described that higher values of the Yield Stability Index (YSI) correspond to higher tolerance levels in the genotypes.Both RDI and YSI have a perfect negative correlation with SSI and higher values of RDI and YSIwere preferred to identify the tolerant genotypes. Based on RDI and YSI the genotype G20 (1.58) is identified as the most tolerant genotype, and G8 (0.25) is the most sensitive one. Though RDI, YSI, and SSI indices differ in magnitude and direction, the three indices were based on the ratios of the yield of genotypes to that of the population. Similar to SSI, both RDI and YSI also could not distinguish the Group A genotypes from the other groups.

The Drought Resistance Index (DI) identifies better-performing genotypes under both environments. The higher DI will indicate the tolerance of the genotype as higher. Based on DI, the genotype G20 (1.32) is identified as the most tolerant genotype, while the genotype G8 (0.02) is the most susceptible. Though the index is capable of identifying the good performers, it could not separate Group A genotypes.

Table 5. Ranks of the hybrids for the stress indices

G	Ys	Yp	TOL	SSI	RDI	STI	GMP	MP	YI	DI	YSI	SSPI	K1STI	K2STI
G1	31	33	1	10	10	33	33	33	31	29	10	33	33	31
G2	24	29	4	9	9	27	27	29	24	19	9	30	29	24
G3	30	32	2	11	11	31	31	31	30	26	11	32	32	30
G4	27	26	13	25	25	26	26	27	27	28	25	21	26	27
G5	21	27	6	7	7	23	23	25	21	17	7	28	27	21
G6	32	31	8	32	32	32	32	32	32	32	32	26	31	32
G7	20	25	5	4	4	21	21	23	20	15	4	29	25	20
G8	33	19	24	33	33	30	30	26	33	33	33	10	19	33
G9	29	23	17	30	30	25	25	24	29	30	30	17	23	29
G10	26	30	3	8	8	29	29	30	26	24	8	31	30	26
G11	22	24	11	16	16	22	22	22	22	18	16	23	24	22
G12	23	22	14	22	22	20	20	20	23	22	22	20	22	23
G13	12	17	10	2	2	14	14	16	12	5	2	24	17	12
G14	9	5	27	20	20	8	8	7	9	11	20	7	5	9
G15	7	9	22	12	12	10	10	10	7	6	12	12	9	7
G16	18	12	28	29	29	15	15	14	18	25	29	6	12	18
G17	3	11	16	3	3	5	5	5	3	2	3	18	11	3
G18	19	16	21	26	26	18	18	17	19	23	26	13	16	19
G19	10	3	33	23	23	7	7	4	10	13	23	1	3	10
G20	1	13	12	1	1	3	3	6	1	1	1	22	13	1
G21	28	20	18	31	31	24	24	21	28	31	31	16	20	28
G22	15	18	15	15	15	17	17	18	15	14	15	19	18	15
G23	17	15	26	27	27	16	16	15	17	21	27	8	15	17
G24	5	2	31	21	21	4	4	3	5	9	21	3	2	5
G25	13	6	29	24	24	11	11	11	13	16	24	5	6	13
G26	25	28	7	19	19	28	28	28	25	27	19	27	28	25
G27	4	1	30	18	18	1	1	1	4	4	18	4	1	4
G28	14	21	9	5	5	19	19	19	14	12	5	25	21	14
G29	2	4	20	6	6	2	2	2	2	3	6	14	4	2
G30	6	8	23	13	13	9	9	9	6	7	13	11	8	6
C1	16	10	32	28	28	13	13	13	16	20	28	2	10	16
C2	11	14	19	14	14	12	12	12	11	10	14	15	14	11
C3	8	7	25	17	17	6	6	8	8	8	17	9	7	8

Fernandez (1992) declared that selection based on the Stress Tolerance Index (STI) will result in higher stress tolerance and yield potential genotypes. Based on the STI, the genotype G27 (1.30) is the most tolerant one, while the genotype G1 (0.03) is the most sensitive one. In addition, the genotype G27 is the most tolerant one based on GMP and MP indices. The high correlation among the three indices explains the similarity. While MP has an upward bias due to a relatively larger difference between Y_s and Y_p, the Geometric Mean Productivity (GMP) suggested by Fernandez (1992) is less sensitive to such large differences. In their study, Mehrabi *et al*. (2011), pointed out that higher values of the GMP and STI indices couldhelp to identify genotypes that produce higher yields. Additionally, Golbashy *et al*. (2010) and Khatibi *et al*. (2022) noted that maize hybrids with high yields in both stress and non-stress environments couldbe selected based on the GMP and STI indices.

Based on STI, MP, and GMP the genotypes G27, G29, G20,G24, and G17werenoted as highly tolerant to water stress with high yield under both environments. While STI and GMP isolated the genotypes with high mean yields in both environments (Group A) from those with high mean yields in the optimal condition alone (Group B), MP could not separate the genotypes of Group A from Group B. Further, Khatibi *et al*. (2022) pointed out that GMP is highly suitable for discriminating Group D genotypes from the other groups.

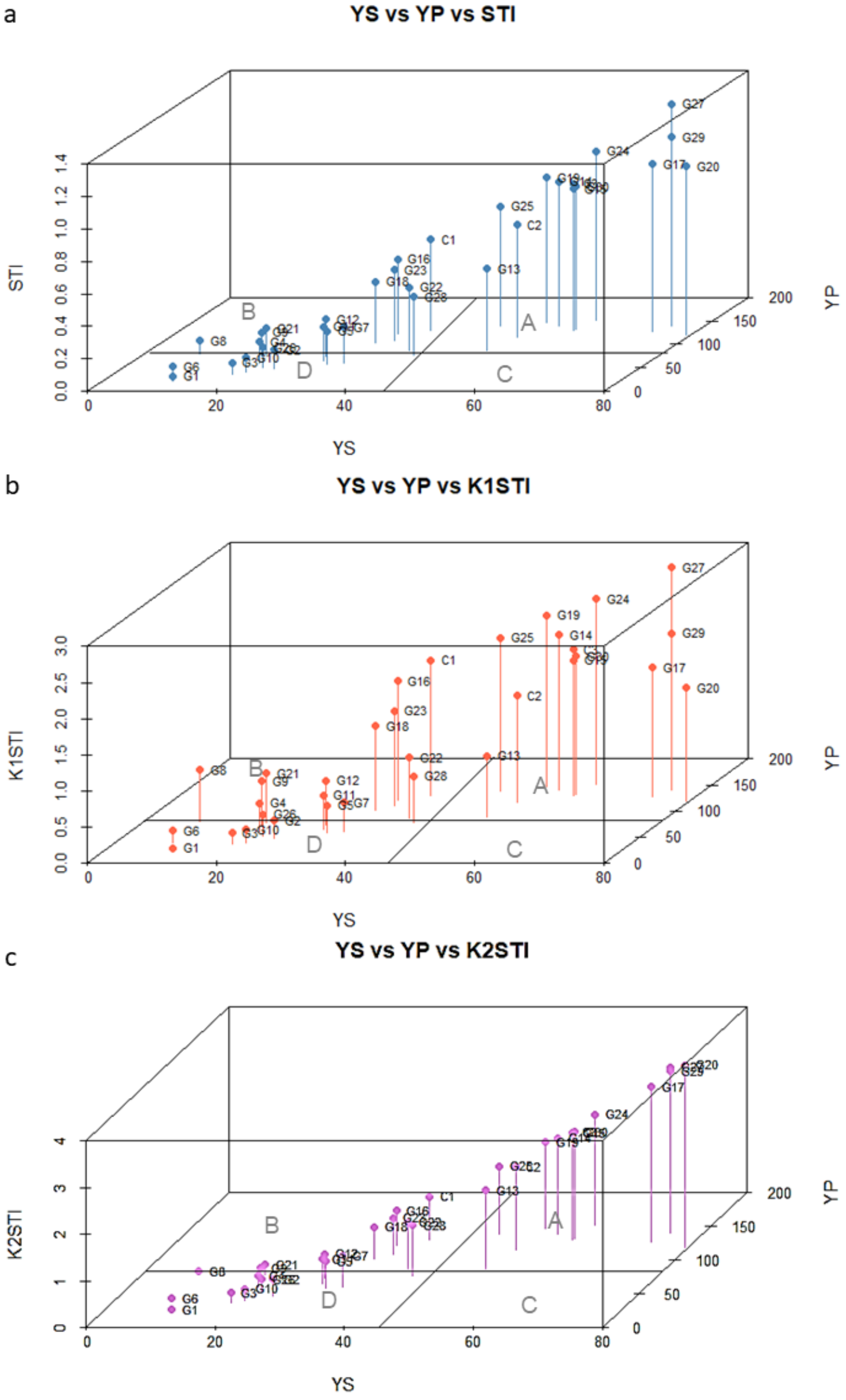

Fig. 5. Three-dimensional plots for (a)STI, (b)K_1STI, and (c)K_2STI

The YI of a genotype depends on its performance in the water-stress environment alone. Based on the index, the genotype G20 (1.98) was identified as the most tolerant genotype, and it also separates the genotypes of Group A from Group B. El-Azeem *et al*. (2023) have observed that in addition to the GMP, MP, and STI, YI can also be utilized as a most appropriate index for screening drought tolerance in genotypes.

Lower values of SSPI correspond to the relative tolerance of the genotype to the stress. Khalili *et al*. (2012) and Naghavi *et al*. (2013) observed that SSPI is among the most reliable stress indices to screen tolerant genotypes. Based on SSPI, the genotype G1 (5.78) was the most tolerant genotype and the genotype G19 (48.23) is the most susceptible one. Similar to the TOL index, to which SSPI is in perfect positive correlation, the tolerant genotype identified falls under Group D. Therefore, it appears to be unreliable in identifying the high-yielding genotypes.

The K_1STI was based on the mean yield under optimal conditions whilethe K_2STI was based on the mean yield under stress conditions. In the case of K_1STI, the genotype G27 (2.92) was the most tolerant genotype, while in the case of the index K_2STI, the genotype G20 (3.91)was the most tolerant one. K_1STI could not distinguish high-yielding genotypes in Group A from Group B. However, K_2STI could separate the genotypes of Group A (G20, G29, G17, G27, G24) from the other three groups. Khalili *et al*. (2012) and Naghavi *et al*. (2013) have also worked out the modified indices K_1STI and K_2STI and noted as most suitable indicators for screening drought-tolerant cultivars. The three-dimensional plots point out the usefulness of these indices in separating the genotypes of Group A from the other groups (**Fig.5**).

Three-dimensional plots: Three-dimensional plots depict the interrelationship among the stress index, Ys, and Yp and were capable of separating Group A from other groups. Farshadfar and Sutka (2003), Naghavi *et al*. (2013), and Kumar *et al*. (2015) have successfully derived 3D plots between STI, Ys, and Yp and demonstrated the advantage of the STI in grouping the genotypes. In the current study, three plots were presented to compare the advantages of STI, K_1STI, and K_2STI indices (**Fig. 5**). STI and K_2STI distinguish the genotypes of Group A from the rest of the groups, while K_1STI is insufficient to separate genotypes of Group A and B. Therefore, it is concluded that STI and K_2STI werebest-suited indices to identify genotypes with high yield under both environments. Based on these three indices the genotypes viz., G27, G24, G29, G17, and G20 couldbe identified under Group A, due to their high yield under both environments.

Based on the linear relationship of different indices with the yield and their ability to group the genotypes, the indices STI, GMP, YI, and K_2STI could be selected as the reliable ones to identify genotypes with high yields and drought tolerance. On the other hand, the indices SSI, DI, and RDI could be used to identify the tolerant genotypes. The index YSI could be used to select the genotypes based on their yield stability. From all the index scores, genotype-variable biplot, and 3D plots, it could be discerned that the genotypes viz., G29, G17, G20,G27, and G24 are among the top-ranking genotypes, and all being grouped under Group A with high and more stable yield under both stress and non-stress environments.

Selection based on the drought tolerance indices offers a straightforward approach to identify the tolerant and stable genotypes based on their yield performances. The method does not require for a complex understanding of the various mechanisms underlying drought stress. Based on the results, the indices STI, GMP, YI, and K_2STIcould be relied upon to screen for drought tolerance among genotypes and the genotypes viz.,G27, G29, G17, G20,and G24 were among the top-ranking genotypes. These could be selected as drought-tolerant genotypes with high mean yields.

REFERENCES

Adhikari, S., Joshi, A., Kumar, A. and Singh, N. K. 2021. Diversification of maize (Zea mays L.) through teosinte (*Zea mays* subsp. parviglumis Iltis & Doebley) allelic. *Genetic Resources and Crop Evolution*, **68**(7): 2983-2995. [Cross Ref]

Blum, A. 1988. Plant Breeding For Stress Environments (1st ed.). CRC Press. https://doi.org/10.1201/9781351075718. [Cross Ref]

Blum, A. 2005. Drought resistance, water-use efficiency, and yield potential—are they compatible, dissonant, or mutually exclusive. *Australian journal of agricultural research*, **56**(11): 1159-1168. [Cross Ref]

Bondok, A. E. T., Mousa, W. M., Rady, A. M. and Saad-Allah, K. M. 2022. Phenotypical, physiological and molecular assessment of drought tolerance of five Egyptian teosinte genotypes. *Journal of Plant Interactions*, **17**(1): 656-673. [Cross Ref]

Bonea, D. 2020. Grain yield and drought tolerance indices of maize hybrids. *Notulae Scientia Biologicae*, **12**(2): 376-386. [Cross Ref]

Bouslama, M. and Schapaugh, Jr, W. T. 1984. Stress tolerance in soybeans. I. Evaluation of three screening techniques for heat and drought tolerance 1. *Crop Science*, **24**(5): 933-937. [Cross Ref]

El-Azeem, A., El-Moula, A., Ahmed, M., Mostafa, A. K., El-Mottalb, A. A. and El Sayed, W. M. 2023. Evaluation of new white maize (*Zea mays* L) genotypes under drought stress using selection indices. *New Valley Journal of Agricultural Science*, **3**(9): 938-956. [Cross Ref]

Farshadfar, E. and Sutka, J. 2002. Screening drought tolerance criteria in maize. *Acta Agronomica Hungarica*, **50**(4): 411-416. [Cross Ref]

Farshadfar, E. and Sutka, J. 2003. Multivariate analysis of drought tolerance in wheat substitution lines. *Cereal Research Communications*, **31:** 33-40. [Cross Ref]

Farshadfar, E., Ghanadha, Sutka, J. and Zahravi, M. 2001. Generation mean analysis of drought tolerance in wheat (*Triticum aestivum* L.). *Acta Agronomica Hungarica*, **49**(1): 59-66. [Cross Ref]

Fernandez, G.C.J. 1992. Effective selection criteria for assessing stress tolerance. in proceedings of the international symposium on adaptation of vegetables and other food crops in temperature and water stress, Taibei, Taiwan, 13–16 August 1992.

Fischer, R. A. and Maurer, R. 1978. Drought resistance in spring wheat cultivars. I. Grain yield responses. *Australian Journal of Agricultural Research*, *2***9**(5): 897-912. [Cross Ref]

Fischer, R. A. and Wood, J. T. 1979. Drought resistance in spring wheat cultivars. III.* Yield associations with morpho-physiological traits. *Australian Journal of Agricultural Research*, **30**(6): 1001-1020. [Cross Ref]

Gavuzzi, P., Rizza, F., Palumbo, M., Campanile, R. G., Ricciardi, G. L. and Borghi, B. 1997. Evaluation of field and laboratory predictors of drought and heat tolerance in winter cereals. *Canadian Journal of Plant Science*, **77**(4): 523-531. [Cross Ref]

Golabadi, M., Arzani, A. S. A. M. and Maibody, S. M. 2006. Assessment of drought tolerance in segregating populations in durum wheat. *African Journal of Agricultural Research*, **1**(5): 162-171.

Golbashy, M., Ebrahimi, M., Khorasani, S. K. and Choukan, R. 2010. Evaluation of drought tolerance of some corn (*Zea mays* L.) hybrids in Iran. *African Journal of Agricultural Research*, **5**(19): 2714-2719.

Jafari, A., Paknejad, F. A. and Jami, A. M. 2009. Evaluation of selection indices for drought tolerance of corn (*Zea mays* L.) hybrids. *International Journal of Plant Production*, **3**(4):33-38

Khalili, M., Naghavi, M. R., Aboughadareh, A. P. and Talebzadeh, S. J. 2012. Evaluating of drought stress tolerance based on selection indices in spring canola cultivars (Brassica napus L.). *Journal of Agricultural Science*, **4**(11): 78. [Cross Ref]

Khatibi, A., Omrani, S., Omrani, A., Shojaei, S. H., Mousavi, S. M. N., Illés, *et al*. 2022. Response of maize hybrids in drought-stress using drought tolerance indices. *Water*, **14**(7): 1012. [Cross Ref]

Kumar, A., Bharti, B., Kumar, J., Singh, G.P., Jaiswal, J.P. and Prasad, R. 2020. Evaluation of drought tolerance indices for identification of drought tolerant and susceptible genotypes in wheat (*Triticum aestivum* L.). *Electronic Journal of Plant Breeding*, **11**(3): 727-734.

Kumar, A., Singh, N. K., Jeena, A. S., Jaiswal, J. P. and Verma, S. S. 2020. Evaluation of teosinte derived maize lines for drought tolerance. *Indian Journal of Plant Genetic Resources*, **33**(1): 60-67. [Cross Ref]

Kumar, R., Kaul, J., Dubey, R. B., Singode, A., GK, C., Manivannan, A. and Debnath, M. K. 2015. Assessment of drought tolerance in maize (*Zea mays* L.) based on different indices. *SABRAO Journal of Breeding & Genetics*, **47**(3).

Mehrabi, P., Homayoun, H. and Daliri, M. S. 2011. Study of drought tolerance of corn genotypes using STI index. *M iddle-East J. Sci. Res.,***9** (1): 68-70

Mousavi, S. S., Yazdi, S. B., Naghavi, M. R., Zali, A. A., Dashti, H. and Pourshahbazi, A. 2008. Introduction of new indices to identify relative drought tolerance and resistance in wheat genotypes. *DESERT,* **12** : 165-178

Mulvaney, M. J. and Devkota, P. J. 2020. Adjusting crop yield to a standard moisture content: SS-AGR-443/AG442, 05/2020. *Edis*, *2020*(3). [Cross Ref]

Muthuramu, S. and Ragavan, T., 2020. Studies on indices and morphological traits for drought tolerance in rainfed rice (*Oryza sativa* L.). *Electronic Journal of Plant Breeding,* **11**(01): 1-5.

Naghavi, M. R., Aboughadareh, A. P. and Khalili, M. 2013. Evaluation of drought tolerance indices for screening some of corn (*Zea mays* L.) cultivars under environmental conditions. *Notulae Scientia Biologicae*, **5**(3): 388-393. [Cross Ref]

Ngugi, K., Collins, J. O. and Muchira, S. 2013. Combining, earliness, short anthesis to silking interval and yield based selection indices under intermittent water stress to select for drought tolerant maize. *Australian Journal of Crop Science*, **7**(13): 2014-2020.

R Core Team. 2024._R: A Language and Environment for Statistical Computing_. R Foundation for Statistical Computing, Vienna, Austria. Available from: https://www.R-project.org/

Rosielle, A. A. and Hamblin, J. 1981. Theoretical aspects of selection for yield in stress and non-stress environment 1. *Crop Science*, **21**(6): 943-946. [Cross Ref]

R Studio Team. 2024. RStudio: Integrated Development for R (Version 2023.12.1+402 “Ocean Storm”). *RStudio*, PBC, Boston, MA. Available from: http://www.rstudio.com/

Sah, R. P., Chakraborty, M., Prasad, K., Pandit, M., Tudu, V. K., Chakravarty, M. K. *et al.*,2020. Impact of water deficit stress in maize: Phenology and yield components. *Scientific reports*, **10**(1): 2944. [Cross Ref]