Research Article

Genetic variation, genotype × environment interaction, and correlation among drought tolerance indices in cowpea

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Abstract

Drought tolerance indices are valuable indicators for selecting cowpea genotypes with improved drought tolerance. However, there is a limited understanding of the variability and the impact of genotype (G) × environment (E) interaction (I) on these drought tolerance indices. Therefore, the objective of this study was to assess the extent of genetic variability and the influence of GEI on drought tolerance indices in cowpeas. The experiment was conducted over two seasons under controlled conditions in a screen house. The results revealed that seed yield and all drought tolerance indices were significantly influenced by genotype, environment, and GEI. When the data from both years were combined, the yield under non-stress conditions ranged from 10.47 g in G2 to 17.27 g in G7, while under drought stress, it ranged from 2.19 g in G3 to 6.89 g in G1. Through mean rank analysis, principal component (PC) analysis, and clustering, highly tolerant accessions (G1 and G6) and highly susceptible ones (G2, G3, and G8) were identified. This study identified several indices, including geometric mean (GM), yield index (YI), mean productivity (MP), stress tolerance index (STI), modified stress tolerance index for non-stress (MST1), and stress (MST2), GMP, and HM, as effective in selecting high-yielding and drought-tolerant accessions under non-stress and drought conditions. Additionally, the drought resistance index (DRI) and yield stability index (YSI) were reliable indicators under drought stress. Most of the indices exhibited moderate (≥ 30%) to high heritability (≥ 60%) and high genetic advance (≥ 20%), except for MST2, which had low heritability (12.73%).

1. Introduction

Cowpea (*Vigna unguiculata* L. Walp) plays a critical role in food security in Nigeria and other tropical and subtropical countries in Africa and the world. Its role can never be over-emphasized

regarding capacity for soil replenishment, plasticity nature, influence on livestock and human nutrition, and income-earning (Ajayi et al., 2022). According to FAOSTAT (2020), production in Nigeria stood at 2.61 MT/annum (36% of worldwide production), out of 7.23 MT/annum produced worldwide. However, 94.9% of the total production worldwide comes from Africa. Despite its potential to guarantee food security in the face of climate change, it is one of the major crops being threatened by the consequences of climate change (de Nóvoa Pinto et al., 2021). This is reflected in its grain yield across Africa which falls far below the expected mark due to production constraints which can be biotic and abiotic (Adetumbi et al., 2020).

Drought is a major abiotic constraint and one of the consequences of climate change responsible for about 60% of crop failures attributed to climate disasters (Lao et al., 2022). Cultivation of cowpeas in tropical countries is majorly done under the rainfed system. However, tropical climate is majorly characterized by strong and unpredictable variations in rainfall patterns that can lead to water deficit with dire consequences for crop production. Drought has been reported as a recurrent phenomenon in tropical regions across the world, and it is projected to worsen in the future (Nauditt et al., 2022). In recent times, the complete failure of cowpea and other crops is not uncommon in several instances due to the increase in the prevalence of drought (Ajayi, 2020). As a result, solutions for combating the threat of drought stress to cowpea production in tropical regions must be established.

Deployment of strategies such as the introduction of drought-tolerant varieties, appropriate cultural practices, and suitable mechanization may alleviate the effect of climate change-driven drought on crop productivity (Bennani et al., 2017). However, the most cost-effective measure among these is access to drought-tolerant varieties. Hence, the urgency to develop superior cowpea genotypes with enhanced drought tolerance is a cost-effective method to address the impact of drought on the crop. Drought tolerance is a complex trait driven by various morphological and physiological traits. Therefore, selecting desirable genotypes in a breeding scheme requires an efficient screening technique (Bennani et al., 2017). Selection solely dependent on yield may automatically encompass several factors that contribute positively to drought tolerance. Nevertheless, variation and heritability for seed yield are low, especially under moisture deficit conditions (Ajayi, 2020). Furthermore, cowpea yield is highly influenced by genotype $\times$ environment interaction (GEI), hence selection must be based on the stability of performance across multiple environments (Ajayi et al., 2022).

Various drought tolerance indices have recently become pointers on which the selection of drought-tolerant genotypes of several crops can be made. These indices quantify tolerance based on calculated relationships between yield performance in drought stress and non-stress conditions (Bennani et al., 2017). Some of the most popular among these indices include geometric mean productivity (GMP), harmonic mean (HM), mean productivity (MP), stress tolerance index (STI), yield index (YI), yield stability index (YSI), drought resistance index (DRI), modified stress tolerance index for non-stress condition (MST_1), stress condition (MST_2). Al-Rawi (2016) identified different classes of tolerance among wheat genotypes. Those that were stable in non-

stress and stress conditions with lower reduction of yield by stress, and those with high yield only under non-stress conditions, and proposed GMP, STI, MP, HM, K_2STI (MST_2), and K_1STI (MST_1) as the most appropriate indices for selecting drought-tolerant genotypes. However, Ajayi (2020) proposed the combination of STI, GMP, MP, DRI, YSI, and YI, while Batieno et al. (2016) proposed STI, MP, and GMP in cowpea. Nonetheless, while these drought tolerance indices have become the key contributors to the breeding of drought-tolerant genotypes of crop species, the genetic variability and the effect of genotype by the environment interaction (GEI) on these indices have not been seriously explored. Therefore, information regarding the variability and GEI of drought tolerance indices in pinpointing cowpea genotypes with extraordinary stability for drought tolerance across different environments is a prerequisite in the breeding program of the crop. Taking cognizance of these, the objectives of the present study were:

i. To investigate the genetic variation and the effect of GEI on drought tolerance indices of cowpeas in two seasons.

ii. To assess the level of genotypic correlations among drought tolerance indices and seed yield in cowpeas.

iii. To introduce a new drought tolerance index (intensity of drought resistance, IDR), and compare its strength with the existing ones in selecting drought-tolerant genotypes of cowpea.

2. Materials and Methods

2.1 Plant materials

Ten accessions of cowpeas used for the present study were chosen based on their high yields and early flowering. The seeds of these accessions were sourced from the International Institute of Tropical Agriculture (IITA), Nigeria. Nine out of these accessions had previously been screened for drought tolerance at different stages. The accessions with their countries of origin and drought tolerance at the seedling and the vegetative stages (Ajayi et al., 2018; Ajayi et al., 2020) are presented in Table 1.

Table 1. List of accessions and their countries of origin

S/N	Accession ID	Country of origin	Seedling stage	Vegetative stage	Code
1	TVu-763	Ghana	-	-	G1
2	TVu-207	USA	Drought tolerant	Moderately tolerant	G2
3	Tvu-218	USA	Highly susceptible	Highly susceptible	G3
4	Tvu-235	Ghana	Drought tolerant	Moderately tolerant	G4
5	Tvu-236	Ghana	Moderately tolerant	Moderately tolerant	G5
6	Tvu-241	USA	Drought tolerant	Drought tolerant	G6
7	IT98K-205-8	Nigeria	Moderately tolerant	Drought tolerant	G7
8	IT98K-555-1	Nigeria	Highly susceptible	Highly susceptible	G8
9	Tvu-4886	Niger	Moderately tolerant	Moderately tolerant	G9
10	Tvu-9256	Burkina Faso	Highly susceptible	Highly susceptible	G10

2.2 Experimental environment and methods

The experimental site was located within Adekunle Ajasin University, Akungba-Akoko, at 7.20° N Latitude, and 5.44'E Longitude at 423 m above sea level. The experiment was conducted over two years in 2019 and 2021 between March and July. The accessions were assessed in plastic pots (5 L each with three perforations beneath for draining excess moisture) laid out in a completely randomized design (CRD) in three replicates for drought stress and non-stress treatments in the screen house of the Department of Plant Science and Biotechnology. Each pot contained 3.5 kg of sieved top soil which was sown with ten seeds per accession in each replicate. Each replicate consisted of five pots per accession, totaling one hundred and fifty pots for each drought stress and non-stress treatment. Two weeks after emergence, seedlings were thinned to two plants per pot. One hundred percent (100%) field capacity of the soil per pot was predetermined at approximately 250 ml according to (Ogbaga et al., 2014). Each plastic pot for the non-stress treatment was watered to 100% field capacity every other day for five weeks after which watering was applied daily till the termination of the experiment. The pots for the drought stress treatment were taken to 100% field capacity once per week till the end of the experiment.

2.3 Data collection and analyses

At maturity, pods were harvested and threshed; and seed yield was determined per plant for each accession per treatment in each year. Ten already existing drought tolerance indices and a new one (intensity of drought resistance, IDR) were adopted for each accession based on the yield per plant in the non-stress and drought stress treatment. The drought tolerance indices are as follows:

i.   Intensity of drought resistance (IDR) $= \frac{Ys/Yp}{\overline{Ys}}$ (Newly formulated)

ii.   Geometric mean productivity (GMP) $= \sqrt{Yp \times Ys}$ (Kristin et al., 1997)

iii.   Harmonic mean (HM) $= \frac{2(Yp \times Ys)}{Yp+Ys}$ (Kristin et al., 1997)

iv.   Mean productivity (MP) $= \frac{Yp+Ys}{2}$ (Rosielle and Hamblin, 1981)

v.   Stress tolerance index (STI) $= \frac{(Ys)(Yp)}{(\overline{Yp})^2}$ (Fernadez, 1992)

vi.   Yield index (YI) $= \frac{Ys}{\overline{Ys}}$ (Gavuzzi et al., 1997)

vii.   Yield stability index (YSI) $= \frac{Ys}{Yp}$ (Bouslama and Schapaugh, 1984)

viii.   Drought resistance index (DRI) $= Ys \times (\frac{Ys}{Yp}) / \ \overline{Yp}$ (Moosevi et al., 2008)

ix.   Modified stress tolerance index for the non-stress conditions (MST$_1$) = K$_1$STI (Farshadfar and Sutka, 2002)

    a. K$_1 = \frac{Yp^2}{\overline{Yp}^2}$ for non-stress treatment

x.   Modified stress tolerance index for stress conditions (MST$_2$) = K$_2$STI (Farshadfar and Sutka, 2002)

    a. K$_2 = \frac{Ys^2}{\overline{Ys}^2}$ for drought stress treatment

Where, *Yp, Ys,* $\overline{Yp}$, and $\overline{Ys}$ were the mean seed yield of an accession under non-stress, mean grain yield in stress treatment, mean seed yield for all accessions in non-stress, and mean grain yield for all accessions in stress treatment, respectively. Possession of a higher value of any of the drought tolerance indices meant higher desirability, hence a higher level of drought tolerance.

All data were analyzed statistically. Individual ANOVA and mean separation (using DMRT at *P* ≤ *0.05*) were done for each year with version 20 of SPSS, followed by combined ANOVA for the two years. ANOVA was performed using the GLM procedure of SPSS, where the environment (year) was regarded as a fixed factor while genotype (accession) and treatment were random factors. Principal Component Analysis (PCA), biplot, and cluster analysis were assessed with PAST version 4.01 (Hammer et al., 2001). The genotypic correlation was done with the Plant Breeding Tools version 1.4 (PBTools, 2014) for each year and the coefficient was compared alongside the "t" table correlation values (*P* ≤ *0.05; P* ≤ *0.01*) at *df* = n–2 (Fisher and Yates, 1963).

Estimates of genetic parameters were performed as follows:

Error variance (Ve) $= \sigma_e^2 =$ Mean square error (MSe)

Genotype × environment variance (V_{GE}) $= \sigma_{GE}^2 = (MS_{GE} - MS_e)/r$

Genotypic variance (V_G) $= \sigma_G^2 = (MS_G - MS_e)/re$

Phenotypic variance (V_P) $= V_G + V_{GE}/e + V_e/re$ (Songsri et al., 2008)

Genotypic coefficient of variation (GCV) $= \frac{\sqrt{V_G}}{\overline{X}} \times 100$

Phenotypic coefficient of variation (PCV) $= \frac{\sqrt{V_P}}{\overline{X}} \times 100$

Broad-sense heritability (H^2) $= V_G/(V_G + (V_{GE}/e) + (V_e/re))$ (Badu-apraku et al., 2021)

Genetic advance (GA) $= \frac{VG}{\sqrt{VP}} \times k$; k = 2.06 (selection differential) (Fayeun et al., 2016)

Genetic advance as percent of the mean (GAM) = $\frac{GA}{X} \times 100$; where e, $\bar{X}$, and r are the number of environments, grand mean of trait, and replicates within environments, respectively. Genetic parameters were categorized according to Ajayi et al. (2014).

Stability = V_{GE}/V_G (Hossain et al., 2013).

3. Results

Combined ANOVA for seed yield showed that the effect of accession (genotype), treatment, and their interactions was highly significant (Table 2). Combined ANOVA for seed yield under differential drought conditions and drought tolerance indices showed a highly significant accession (genotype), year (environment), and accession (genotype) × year (environment) effect (Table 3).

Table 2. Mean squares values from combined ANOVA for seed yield per plant of ten accessions of cowpeas evaluated under differential drought stress in 2019 and 2021

Source of variation	Degree of freedom	Seed yield per plant
Accession	9	49.39
Treatment	1	1703.31
Year	1	1663.92
Accession × Treatment	9	20.79
Accession × Year	9	37.97
Treatment × Year	1	379.15
Accession × Treatment × Year	9	19.63
Error	18	0.52

All sources of variation are significant at P≤0.05

Table 3. Mean square values from combined ANOVA for seed yield and drought tolerance indices of ten accessions of cowpeas evaluated under differential drought stress in 2019 and 2021

Source of variation	Df	Yp (g)	Ys (g)	ReY (%)	IDR	GMP	HM	MP	STI	YI	YSI	DRI	MST$_1$	MST$_2$
Accession	9	27.94	14.16	1254.50	0.01	12.02	15.81	10.66	0.44	0.67	0.13	0.06	13.34	15.50
Year	1	1815.82	227.26	771.96	0.26	602.60	450.66	831.96	0.28	0.29	0.08	0.02	28.70	32.25
Accession × Year	9	45.08	12.52	594.67	0.01	17.54	17.98	18.99	0.54	0.57	0.06	0.03	13.39	105.24
Error	40	4.69	0.59	134.52	0.002	1.01	0.82	1.49	0.01	0.02	0.01	0.01	0.46	0.16

All the sources of variations are significant at P≤0.05

Df: Degree of freedom; Yp: Yield under non-stress condition; Ys: Yield under stress condition; ReY: Percent reduction in yield; IDR: Intensity of drought resistance; GMP: Geometric mean productivity; HM: Harmonic mean; MP: Mean productivity; STI: Stress tolerance index; YI: Yield index; YSI: Yield stability index; DRI: Drought resistance index; MST$_1$: Modified stress tolerance index for the non-stress conditions; MST$_2$: Modified stress tolerance index for stress conditions.

The mean performances of accessions across treatments and years for yield and drought tolerance indices are presented in Table 4 (a–c). In 2019, the mean seed yield under non-stress and stress conditions respectively was 17.76 g and 6.67 g, however, the mean seed yield in 2021 under non-stress and stress conditions respectively was 6.76 g and 2.78 g while that for the combined drought stress and non-stress conditions respectively, was 12.26 g and 4.72 g. Therefore, a reduction due to drought stress in 2019, 2021, and the combined years respectively, was 60.81, 53.63, and 57.22%; the highest percentage reduction in yield (79.48%) under drought stress for the combined seasons was observed in accession G3. Furthermore, accessions G7 and G8 exhibited a consistent above-average reduction in yield across the years. Accessions G10 and G9 consistently had above-average performance under both conditions in 2019, accessions G7 and G6 performed above average in both conditions in 2021, while accessions G10 and G6 had an above-average performance under both conditions for the combined season, and no single accession had the best performance under both conditions across the years. In 2019, accessions G1, G9, and G5 had an above-average performance for all the drought tolerance indices, G10, and G6 were next in line. The values ranged from the lowest (0.02) in MST_1 to the highest (12.22) in MP. However, in 2021, accessions G6 and G7 were the only above-average performing accessions for such indices as GMP (4.26), HM (3.82), MP (4.77), STI (0.51), YI (1.14), DRI (0.20), MST_1 (1.41), and MST_2 (1.53). Nevertheless, accession G6 was the only above-average performing accession for all indices for the combined season which means ranged from the lowest (0.12) in IDR to the highest (8.49) in MP. Stability was nonetheless very high in GMP (0.74), ReY (0.82), and HM (0.87), but moderate in YSI (1.00), while other parameters were highly unstable ($\sigma^2 g \times e / \sigma^2 g > 1.0$).

The ranking of accessions for the determination of the most desirable drought-tolerant accessions based on all the drought tolerance indices is presented in Table 5. Accessions G1 and G6 which exhibited the lowest rank sum and rank means, and around the average standard deviation of rank were the most drought-tolerant accessions. These were followed by accessions G7, G9, and G10, which exhibited a combination of below-average rank sum, rank means, and above-average standard deviation of rank, and G5 which exhibited slightly below-average rank sum and the least standard deviation of rank (1.37) as moderately drought tolerant accession, while accessions G2, G3, G4, and G8 with the highest rank sum and rank means were the most drought susceptible accessions under drought stress. Cluster analysis (Figure 1) using the unweighted pair group method with arithmetic mean (UPGMA) classified the accessions into three major clusters based on their similarities for drought tolerance indices. Cluster I consisted of G8, G3, and G2 which exhibited low drought tolerance indices consistently across years with below-average tolerance indices for the combined seasons and thus were the most susceptible accessions. Cluster II, sub-cluster A consisted only of G6, a highly tolerant accession with above-average HM, YI, and DRI across years and above-average performance for all the drought tolerance indices for the combined seasons; while sub-cluster B consisted of G7, and G4, moderately tolerant and moderately susceptible accessions exhibiting around average to above average drought tolerance indices across years and for the combined seasons. Cluster III, sub-cluster A consisted of only G1, a highly tolerant accession exhibiting above-average IDR, YSI, DRI, and MST_1 consistently across years,

and above-average performance for all drought tolerance indices except MST_1 and MST_2 for the combined seasons; while sub-cluster B consisted of G10, G9, and G5, which are moderately-tolerant accessions exhibiting high GMP, HM, MP, STI, YI, MST_1, and MST_2 in 2019 and below-average values for most drought tolerance indices in 2021.

The combined estimates of genetic parameters of yield and drought tolerance indices are presented in Table 6. GCV was high in all parameters except for yield under non-stress conditions, GMP, and MP which were moderate, with a range of between 14.57 percent in MP and 203.65 percent in MST_1. PCV on the other hand was high for all parameters and ranged from the lowest (20.44%) in MP to the highest (224.38%) in MST_1. However, the differences between GCV and PCV for most parameters were also high. Broad sense heritability was low (12.73%) in MST_2 and moderate for other parameters except for ReY, DRI, and YSI, which exhibited high heritability. Nevertheless, GAM was high for all parameters and ranged from the lowest (21.39%) in MP to the highest (399.71%) in MST_2.

The Principal Component Analysis (PCA) of the measured parameters is presented in Table 7. In each year, there were two PC axes whose eigenvalues exceeded 1.0 and also accounted for more than 98 percent of the total variation. However, the combined seasons possessed three PC axes whose eigenvalues exceeded 1.0 contributing more than 98 percent of the total variation. In the 2019 season, all parameters had a high contribution (≥ 0.50) to the total variation in PC1 except for yield under non-stress conditions, in contrast to PC2 where they all had low contributions except for yield in non-stress conditions, DRI, IDR, and MST_2. However, in the 2021 season, all parameters had high contributions in PC1 except for the percent reduction in yield, DRI, and STI, while only ReY, DRI, STI, and MST_1 were the only significant contributors in PC2. Nonetheless, in the combined seasons, all parameters were high contributors in PC1 except seed yield in non-stress conditions while the major contributors in PC2 included yield in non-stress conditions, ReY, IDR, STI, MST_1, MST_2, and YSI. The contributions ranged from the lowest (0.09) in yield under non-stress conditions to the highest (0.99) in yield under drought stress, HM, and MP in PC1, while it ranged from the lowest (0.06) in HM to the highest (0.98) in yield under non-stress in PC2 for 2019. However, ranges between 0.20 (DRI) to 0.99 (GMP, HM, and MP) for PC1, and 0.0003 (MST2) to 0.98 (ReY, DRI, and STI) for PC2 were observed in 2021 while the combined seasons exhibited ranges between 0.28 in yield under non-stress conditions and 0.98 in HM and YI for PC1, between 0.09 in HM and 0.73 in MST_1 for PC2, and between 0.02 in HM and 0.62 in yield under non-stress conditions for PC3.

The biplots derived from the PCA for 2019, 2021, and combined seasons, respectively are presented in Figures 2 – 4, while Figures 5 – 7 present the polygon views of the biplots showing the vertex accessions for 2019, 2021, and the combined seasons respectively. In 2019, quadrant I contained the moderately tolerant accessions: G10 and G9; quadrant II contained the highly tolerant accessions: G1 and G6, and a moderately tolerant G5; quadrant III contained the highly susceptible accessions: G3, G8, and G2; while quadrant IV contained the moderately tolerant accessions: G7 and G4. Parameters such as HM, MST_2, GMP, and STI were positively correlated

in the upper part of quadrant I, while yield under non-stress, MST_1, and MP were also positively correlated in the lower part of quadrant I. The vertex accession in quadrant I for yield under non-stress, MST_1, and MP was G10. Yield under drought stress, YI, DRI, YSI, and IDR were positively correlated in quadrant II with the vertex accessions being G1 and G6. In 2021 however, quadrants I and II respectively contained G6, highly tolerant accession, and G7, moderately tolerant. Parameters such as yield under drought stress, YI, HM, and MST_2 were highly positively correlated at the base of quadrant I and also correlated positively with MST_1, GMP, MP, and seed yield under non-stress which were highly positively correlated at the upper quadrant II. The only vertex accession for these parameters is G6. Quadrant III contained the most susceptible accessions; G8, G3, and G2, with the vertex being G3 and G2. Quadrant IV contained highly tolerant accession: G1, and moderately tolerant accessions: G5, G4, G10, and G9. Parameters such as IDR and YSI were highly correlated in quadrant IV with vertex accession being G9. In the combined seasons nonetheless, quadrant I contained the highly tolerant G6 and the moderately tolerant G7, and quadrant II contained the moderately tolerant G10, G5, G9, and the highly tolerant G1. Quadrant III contained the highly susceptible G8, G2, and the moderately tolerant G4 while quadrant IV contained the G3, the most susceptible accession. MST_1, MST_2, STI, and MP were highly positively correlated with yield under non-stress conditions in quadrant I with the vertex accessions being G7 highly correlating with yield under non-stress and G6 highly correlating with indices such as MST_1, MST_2, STI, and MP. YI, GMP at the base of quadrant I with HM, DRI, YSI, and IDR in quadrant II were highly positively correlated with seed yield under drought stress conditions with the vertex accession being G9. While the only parameter linked to quadrant IV was the percentage reduction in yield (ReY) correlating with the vertex accession G3, the most susceptible accession to drought, no parameter was linked to quadrant III where G2 was the vertex accession.

The genotypic correlation between drought tolerance indices and yield under non-stress and drought-stress conditions for the two years is presented in Table 8. MST_1 consistently was positively correlated with seed yield under drought stress (0.71* and 0.95**) and non-stress (0.65* and 0.91**) conditions across the years. MP had a consistent positive correlation with yield for the non-stress condition for 2019 (0.76**) and 2021 (0.99**). However, yield under stress conditions consistently had a positive correlation across years with indices such as DRI (0.97** and 0.79**), GMP (0.91**, 0.95**), HM (0.98**), YI (1.00**), STI (0.92**, 0.95**), and MST_2 (0.97**, 0.93**).

Table 4a. Mean performance for seed yield per plant and drought tolerance indices of ten accessions of cowpeas evaluated under differential drought stress in 2019 and 2021

Accession	Yp (g)	Ys (g)	ReY (%)	IDR	GMP	HM	MP	STI	YI	YSI	DRI	MST$_1$	MST$_2$
G1	16.17^a	11.19^e	30.63^a	0.10^d	13.45^d	13.23^f	13.69^{cde}	0.58^c	1.68^e	0.69^d	0.44^f	0.03^{bc}	0.15^d
G2	15.66^{ab}	6.34^{cd}	59.39^c	0.06^b	9.96^{bc}	9.02^{cd}	10.99^{abc}	0.32^{ab}	0.95^{cd}	0.41^b	0.14^{bcd}	0.02^{ab}	0.05^{ab}
G3	14.49^{ab}	2.54^a	82.32^d	0.03^a	6.04^a	4.30^a	8.52^a	0.11^a	0.38^a	0.18^a	0.03^a	0.01^a	0.01^a
G4	20.35^{bc}	3.78^{ab}	81.25^d	0.03^a	8.76^b	6.37^b	12.07^{bcd}	0.24^{ab}	0.57^{ab}	0.19^a	0.04^{ab}	0.02^{ab}	0.02^a
G5	17.35^{ab}	7.78^d	53.89^{bc}	0.07^{bc}	11.59^{cd}	10.69^{de}	12.57^{b-e}	0.43^{bc}	1.17^d	0.46^{bc}	0.20^{cd}	0.02^{abc}	0.08^{bc}
G6	13.46^a	7.33^d	45.03^b	0.08^c	9.91^{bc}	9.46^{cd}	10.39^{ab}	0.31^{ab}	1.09^d	0.55^c	0.23^d	0.01^{ab}	0.05^{ab}
G7	23.61^c	4.76^{bc}	80.01^d	0.03^a	10.59^{bc}	7.91^{bc}	14.19^{de}	0.36^b	0.71^{bc}	0.19^a	0.05^{ab}	0.03^{abc}	0.04^{ab}
G8	14.90^a	5.06^{bc}	66.11^c	0.05^b	8.68^b	7.55^{bc}	9.98^{ab}	0.24^{ab}	0.76^{bc}	0.34^b	0.09^{abc}	0.01^{ab}	0.03^{ab}
G9	18.64^{abc}	10.06^e	44.09^b	0.08^c	13.53^d	12.79^{ef}	14.35^{de}	0.58^c	1.51^e	0.56^c	0.33^e	0.03^{bc}	0.13^d
G10	22.96^c	7.86^d	65.36^c	0.05^b	13.42^d	11.69^{ef}	15.41^e	0.59^c	1.18^d	0.35^b	0.15^{bcd}	0.05^c	0.11^{cd}
$\bar{X}$	**17.76**	**6.67**	**60.81**	**0.06**	**10.59**	**9.30**	**12.22**	**0.38**	**1.00**	**0.39**	**0.17**	**0.02**	**0.07**
Minimum	11.62	2.16	26.74	0.02	5.83	3.80	7.85	0.11	0.32	0.14	0.02	0.004	0.01
Maximum	29.58	12.10	86.34	0.11	16.49	14.03	19.39	0.86	1.81	0.73	0.50	0.08	0.18
LSD (0.05)	4.01	1.43	10.56	0.01	1.91	1.70	2.31	0.14	0.19	0.11	0.09	0.01	0.02
CV (%)	16.08	15.29	12.37	16.67	12.84	13.04	13.45	26.32	14.14	19.86	37.20	50.00	45.18

Mean values accompanied by the same superscript in a column are not significantly different from one another at *P ≤ 0.05* using DMRT. $\bar{X}$: Grand mean; LSD: Least significant difference; CV: Coefficient of variation; Yp: Yield under non-stress condition; Ys: Yield under stress condition; ReY: Percent reduction in yield; IDR: Intensity of drought resistance; GMP: Geometric mean productivity; HM: Harmonic mean; MP: Mean productivity; STI: Stress tolerance index; YI: Yield index; YSI: yield stability index; DRI: Drought resistance index; MST$_1$: Modified stress tolerance index for the non-stress condition; MST$_2$: Modified stress tolerance index for stress condition.

Table 4b. Mean performance for seed yield per plant and drought tolerance indices of ten accessions of cowpea evaluated under differential drought stress in 2021

Accession	Yp (g)	Ys (g)	ReY (%)	IDR	GMP	HM	MP	STI	YI	YSI	DRI	MST₁	MST₂
G1	5.13^{ab}	2.58^{bc}	49.29^{a-d}	0.21^{b-e}	3.63^{bc}	3.42^{bc}	3.86^{ab}	0.31^{ab}	1.06^{bc}	0.51^{b-e}	0.20^{bc}	0.19^{a}	0.36^{a}
G2	5.28^{ab}	1.47^{a}	71.85^{de}	0.12^{ab}	2.79^{a}	2.30^{a}	3.38^{ab}	0.19^{a}	0.60^{a}	0.28^{ab}	0.06^{a}	0.13^{a}	0.07^{a}
G3	8.08^{c}	1.86^{ab}	76.65^{e}	0.09^{a}	3.86^{c}	3.01^{ab}	4.97^{c}	0.35^{ab}	0.76^{ab}	0.23^{a}	0.07^{ab}	0.56^{a}	0.20^{a}
G4	5.10^{ab}	3.04^{cd}	40.05^{ab}	0.25^{de}	3.94^{c}	3.81^{c}	4.07^{bc}	0.37^{b}	1.25^{cd}	0.59^{de}	0.28^{cd}	0.23^{a}	0.58^{a}
G5	4.92^{ab}	2.46^{bc}	45.76^{abc}	0.22^{cde}	3.45^{abc}	3.24^{bc}	3.69^{ab}	0.29^{ab}	1.01^{bc}	0.54^{cde}	0.20^{bc}	0.21^{a}	0.31^{a}
G6	14.31^{e}	5.75^{e}	59.47^{b-e}	0.17^{a-d}	9.06^{e}	8.19^{e}	10.03^{e}	1.95^{d}	2.35^{e}	0.41^{a-d}	0.36^{d}	9.61^{c}	10.80^{c}
G7	10.94^{d}	3.68^{d}	65.52^{cde}	0.14^{abc}	6.28^{d}	5.43^{d}	7.31^{d}	0.94^{c}	1.51^{d}	0.34^{abc}	0.21^{bc}	2.64^{b}	2.33^{b}
G8	6.36^{bc}	1.95^{ab}	69.02^{cde}	0.13^{abc}	3.49^{abc}	2.96^{ab}	4.15^{bc}	0.29^{ab}	0.79^{ab}	0.31^{abc}	0.09^{ab}	0.32^{a}	0.22^{a}
G9	3.33^{a}	2.48^{bc}	24.68^{a}	0.31^{e}	2.87^{ab}	2.83^{ab}	2.90^{a}	0.19^{ab}	1.02^{bc}	0.75^{e}	0.29^{cd}	0.05^{a}	0.20^{a}
G10	4.14^{a}	2.49^{bc}	34.05^{a}	0.27^{e}	3.17^{abc}	3.03^{ab}	3.32^{ab}	0.24^{ab}	1.02^{bc}	0.66^{e}	0.26^{cd}	0.11^{a}	0.25^{a}
X̄	6.76	2.78	53.63	0.19	4.26	3.82	4.77	0.51	1.14	0.46	0.20	1.41	1.53
Minimum	6.00	5.94	80.24	0.40	9.52	8.37	10.83	2.15	2.43	11.60	0.42	13.01	11.60
Maximum	2.84	1.35	2.22	0.08	2.44	2.07	2.67	0.14	0.55	0.04	0.05	0.40	0.04
LSD (0.05)	1.54	0.53	18.41	0.08	0.59	0.58	0.76	0.13	0.24	0.79	0.11	1.34	0.79
CV (%)	16.27	13.46	24.45	28.83	9.96	10.79	11.29	17.54	15.19	30.74	38.73	67.66	36.97

Mean values accompanied by the same superscript in a column are not significantly different from one another at $P \leq 0.05$ using DMRT. X̄: Grand mean; LSD: Least significant difference; CV: Coefficient of variation; Yp: Yield under non-stress condition; Ys: Yield under stress condition; ReY: Percent reduction in yield; IDR: Intensity of drought resistance; GMP: Geometric mean productivity; HM: Harmonic mean; MP: Mean productivity; STI: Stress tolerance index; YI: Yield index; YSI: yield stability index; DRI: Drought resistance index; MST₁: Modified stress tolerance index for the non-stress condition; MST₂: Modified stress tolerance index for stress condition.

Table 4c. Combined mean performance for seed yield per plant and drought tolerance indices of ten accessions of cowpea evaluated under differential drought stress in 2019 and 2021

Accession	Yp (g)	Ys (g)	ReY (%)	IDR	GMP	HM	MP	STI	YI	YSI	DRI	MST$_1$	MST$_2$
G1	10.65^a	6.89^e	39.96^{ab}	0.16d^e	8.54^{de}	8.32^{fg}	8.77^b	0.44^d	1.37^d	0.60^{de}	0.32^d	0.11^a	0.25^a
G2	10.47^a	3.91^b	65.62^d	0.09^{abc}	6.38^{bc}	5.66^{bc}	7.19^a	0.25^{ab}	0.78^b	0.34^b	0.10^{ab}	0.07^a	0.06^a
G3	11.29^{ab}	2.19^a	79.48^e	0.06^a	4.95^a	3.66^a	6.74^a	0.23^a	0.57^a	0.21^a	0.05^a	0.28^a	0.11^a
G4	12.73^{abc}	3.41^b	60.65^{cd}	0.14^{cd}	6.35^{bc}	5.09^b	8.07^{ab}	0.31^{abc}	0.91^b	0.39^{bc}	0.16^{bc}	0.12^a	0.29^a
G5	11.13^{ab}	5.13^{cd}	49.83^{bc}	0.15^d	7.52^{cd}	6.97^{de}	8.13^{ab}	0.36^{bcd}	1.09^c	0.50^{cd}	0.20^c	0.12^a	0.19^a
G6	13.89^c	6.54^e	52.25^{bc}	0.12^{bcd}	9.49^e	8.82^g	10.21^c	1.13^f	1.73^e	0.48^{cd}	0.29^d	4.81^c	5.43^c
G7	17.27^d	4.22^{bc}	72.76^{de}	0.09^{ab}	8.44^{de}	6.67^{cd}	10.75^c	0.65^e	1.11^c	0.27^{ab}	0.13^{abc}	1.33^b	1.18^b
G8	10.63^a	3.50^b	67.56^{de}	0.09^{abc}	6.09^b	5.25^b	7.07^a	0.27^{ab}	0.78^b	0.32^{ab}	0.09^{ab}	0.16^a	0.13^a
G9	10.98^a	6.27^e	34.38^a	0.19^e	8.19^d	7.81^{efg}	8.62^b	0.39^{cd}	1.26^{cd}	0.66^e	0.31^d	0.04^a	0.17^a
G10	13.55^{bc}	5.18^d	49.70^{bc}	0.16^{de}	8.29d^e	7.36^{def}	9.36^{bc}	0.41^{cd}	1.10^c	0.50^{cd}	0.21^c	0.08^a	0.18^a
$\bar{X}$	12.26	4.72	57.22	0.12	7.42	6.56	8.49	0.44	1.07	0.43	0.19	0.71	0.79
Minimum	9.80	2.05	19.11	0.06	4.75	3.41	6.58	0.21	0.55	0.20	0.04	0.03	0.04
Maximum	18.78	7.42	80.23	0.24	9.88	9.20	11.70	1.21	0.81	0.81	0.44	6.51	5.82
LSD (0.05)	2.97	1.05	15.94	0.06	1.37	1.24	1.67	0.14	0.19	0.14	0.14	0.93	0.55
CV (%)	17.66	16.27	20.27	37.27	13.54	13.8	14.38	22.73	13.22	23.26	52.63	95.53	50.63

Mean values accompanied by the same superscript in a column are not significantly different from one another at *P ≤ 0.05* using DMRT. $\bar{X}$: Grand mean; LSD: Least significant difference; CV: Coefficient of variation; Yp: Yield under non-stress condition; Ys: Yield under stress condition; ReY: Percent reduction in yield; IDR: Intensity of drought resistance; GMP: Geometric mean productivity; HM: Harmonic mean; MP: Mean productivity; STI: Stress tolerance index; YI: Yield index; YSI: yield stability index; DRI: Drought resistance index; MST$_1$: Modified stress tolerance index for the non-stress condition; MST$_2$: Modified stress tolerance index for stress condition.

Table 5. The ranking of accessions of cowpeas evaluated under differential drought stress in 2019 and 2021 based on their superiority for seed yield and drought tolerance indices

Accession	Yp	Ys	ReY	IDR	GMP	HM	MP	STI	YI	YSI	DRI	MST₁	MST₂
							2019						
G1	6	1	1	1	10	1	4	3	1	1	1	3	1
G2	7	6	5	5	6	6	7	6	6	5	6	6	6
G3	9	10	10	10	2	10	10	10	10	10	10	10	10
G4	3	9	9	9	8	9	6	8	9	9	9	7	9
G5	5	4	4	4	4	4	5	4	4	4	4	5	4
G6	10	5	3	3	7	5	8	7	5	3	3	8	5
G7	1	8	8	8	5	7	3	5	8	8	8	4	7
G8	8	7	7	7	9	8	9	9	7	7	7	9	8
G9	4	2	2	2	1	2	2	2	2	2	2	2	2
G10	2	3	6	6	3	3	1	1	3	6	5	1	3
$\bar{X}$													

Yp: Yield under non-stress condition; Ys: Yield under stress condition; ReY: Percent reduction in yield; IDR: Intensity of drought resistance; GMP: Geometric mean productivity; HM: Harmonic mean; MP: Mean productivity; STI: Stress tolerance index; YI: Yield index; YSI: yield stability index; DRI: Drought resistance index; MST₁: Modified stress tolerance index for the non-stress condition; MST₂: Modified stress tolerance index for stress condition.

Table 5 contd.

Accession	Yp	Ys	ReY	IDR	GMP	HM	MP	STI	YI	YSI	DRI	MST₁	MST₂	RS	$\bar{R}$	SDR
						2021										
G1	6	4	5	5	5	4	6	5	4	5	6	7	4	100	**3.85**	**2.36**
G2	5	10	9	9	10	10	8	10	10	9	10	8	10	195	7.50	**1.94**
G3	3	9	10	10	4	7	3	4	9	10	9	3	8	210	8.08	2.86
G4	7	3	3	3	3	3	5	3	3	3	3	5	3	151	**5.81**	2.69
G5	8	7	4	4	7	5	7	7	7	4	7	6	5	133	**5.12**	**1.37**
G6	1	1	6	6	1	1	1	1	1	6	1	1	1	100	**3.85**	2.79
G7	2	2	7	7	2	2	2	2	2	7	5	2	2	124	**4.77**	2.64
G8	4	8	8	8	6	8	4	6	8	8	8	4	7	189	7.27	**1.46**
G9	10	6	1	1	9	9	10	9	6	1	2	10	9	110	**4.23**	3.46
G10	9	5	2	2	8	6	9	8	5	2	4	9	6	118	**4.54**	2.61
$\bar{X}$														143	5.502	2.418

RS: Rank sum; $\bar{R}$*: Rank mean; SDR: Standard deviation of rank.* $\bar{X}$: Grand mean; Yp: Yield under non-stress conditions; Ys: Yield under stress condition; ReY: Percent reduction in yield; IDR: Intensity of drought resistance; GMP: Geometric mean productivity; HM: Harmonic mean; MP: Mean productivity; STI: Stress tolerance index; YI: Yield index; YSI: yield stability index; DRI: Drought resistance index; MST₁: Modified stress tolerance index for the non-stress condition; MST₂: Modified stress tolerance index for stress condition.
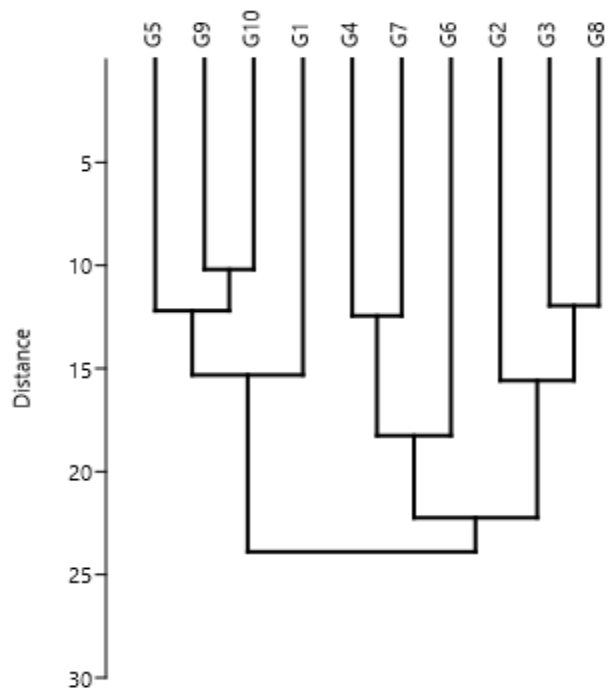
Figure 1. Dendrogram (UPGMA) shows the classification of accessions of cowpeas based on the ranking of their drought tolerance indices. G1 – G10 are codes for accessions of cowpea evaluated.

Table 6. Combined estimates of genetic parameters of seed yield and drought tolerance indices of ten accessions of cowpeas evaluated under differential drought stress in 2019 and 2021

Trait	Mean	σ^2g	σ^2ge	σ^2p	σ^2e	GCV (%)	PCV (%)	h^2B (%)	GAM (%)	Stability
Yp	12.26	3.88	13.46	8.57	4.69	16.06	23.88	34.06	22.27	3.46
Ys	4.73	2.26	3.99	2.83	0.59	31.78	35.57	52.07	58.51	1.77
ReY	57.22	186.66	153.38	321.18	134.52	23.88	31.34	65.32	37.49	**0.82**
DRI	0.19	0.008	0.01	0.018	0.01	47.08	70.61	60.79	64.64	1.25
GMP	7.43	1.84	5.51	2.85	1.01	18.26	22.72	38.57	30.22	**0.74**
HM	6.56	2.49	5.72	3.32	0.82	24.05	27.78	45.05	42.91	**0.87**
IDR	0.13	0.001	0.003	0.003	0.002	24.33	42.13	35.33	28.93	3.00
YI	1.07	0.11	0.18	0.13	0.02	30.99	33.69	54.09	58.74	1.64
MP	8.49	1.53	5.83	3.01	1.49	14.57	20.44	32.56	21.39	3.81
STI	0.45	0.07	0.18	0.08	0.01	58.79	62.85	43.29	113.29	2.57
MST$_1$	0.72	2.15	4.31	2.61	0.46	203.65	224.38	49.08	346.36	2.00
MST$_2$	0.80	2.56	35.03	2.72	0.16	200.00	206.16	12.73	399.71	13.68
YSI	0.43	0.02	0.02	0.03	0.01	32.89	40.28	63.12	55.33	**1.00**

In bold: High stability ($\sigma^2g \times e / \sigma^2g \leq 1.0$).

σ^2g: Genotypic variance; σ^2ge: Genotype × environment variance; σ^2p: Phenotypic variance; σ^2e: Error variance; GCV: Genotypic coefficient of variation; PCV: Phenotypic coefficient of variation; h^2B: broad sense heritability; GAM: Genetic advance as percent of the mean. Yp: Yield under non-stress conditions; Ys: Yield under stress conditions; ReY: Percent reduction in yield; IDR: Intensity of drought resistance; GMP: Geometric mean productivity; HM: Harmonic mean; MP: Mean productivity; STI: Stress tolerance index; YI: Yield index; YSI: yield stability index; DRI: Drought resistance index; MST$_1$: Modified stress tolerance index for the non-stress condition; MST$_2$: Modified stress tolerance index for stress condition.

Table 7. Principal Component Analysis (PCA) of seed yield and drought tolerance indices of ten accessions of cowpea evaluated under differential drought stress in 2019, 2021, and combined seasons

Parameters	2019		2021		Combined		
	PC1	PC2	PC1	PC2	PC1	PC2	PC3
Yp (g)	0.09	**0.98**	**0.93**	-0.34	0.28	**0.72**	**0.62**
Ys (g)	**0.99**	-0.11	**0.95**	0.29	**0.94**	-0.29	-0.07
ReY (%)	**-0.88**	0.48	0.21	**-0.98**	**-0.77**	**0.64**	0.04
DRI	**0.86**	**-0.51**	-0.2	**0.98**	**0.92**	-0.34	-0.07
GMP	**0.94**	0.32	**0.99**	-0.05	**0.96**	0.11	0.19
HM	**0.99**	0.06	**0.99**	0.09	**0.98**	-0.09	0.02
IDR	**0.67**	**0.71**	**0.98**	-0.18	**0.67**	**-0.66**	0.19
YI	**0.94**	0.33	**0.99**	-0.01	**0.98**	0.12	-0.09
MP	**0.99**	-0.11	**0.95**	0.29	**0.77**	0.44	0.46
STI	**0.87**	-0.48	-0.21	**0.98**	**0.76**	**0.63**	-0.15
MST$_1$	**0.92**	-0.33	**0.55**	**0.83**	**0.57**	**0.73**	-0.37
MST$_2$	**0.57**	**0.78**	**0.98**	-0.0003	**0.61**	**0.67**	-0.39
YSI	**0.97**	0.09	**0.97**	0.06	**0.77**	**-0.63**	-0.09
Eigenvalue	9.61	3.15	8.94	3.89	8.17	3.57	1.01
Percentage variance	73.90	24.22	68.74	29.96	62.87	27.43	7.73
Cumulative variance (%)	73.90	98.12	68.74	98.70	62.87	90.30	98.03

Bold indicates high loading (≥0.50). PC: Principal Component.
Yp: Yield under non-stress conditions; Ys: Yield under stress conditions; ReY: Percent reduction in yield; IDR: Intensity of drought resistance; GMP: Geometric mean productivity; HM: Harmonic mean; MP: Mean productivity; STI: Stress tolerance index; YI: Yield index; YSI: yield stability index; DRI: Drought resistance index; MST$_1$: Modified stress tolerance index for the non-stress condition; MST$_2$: Modified stress tolerance index for stress condition.
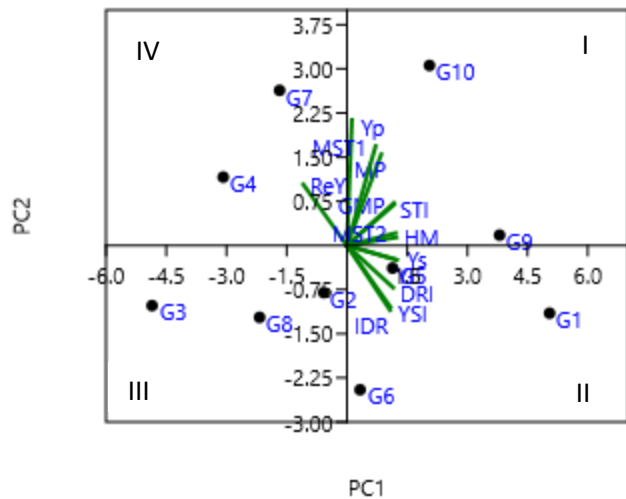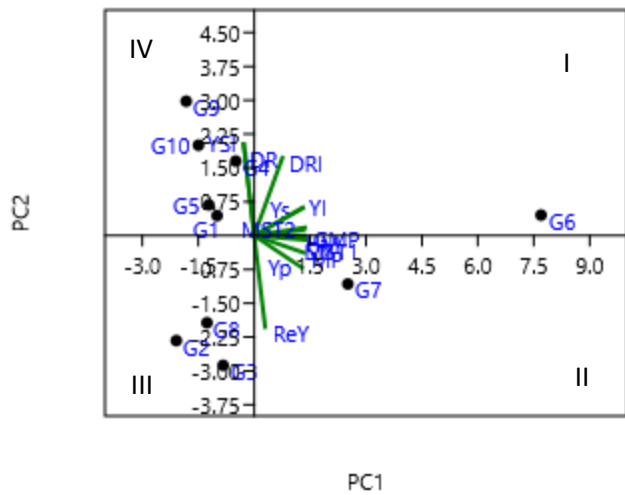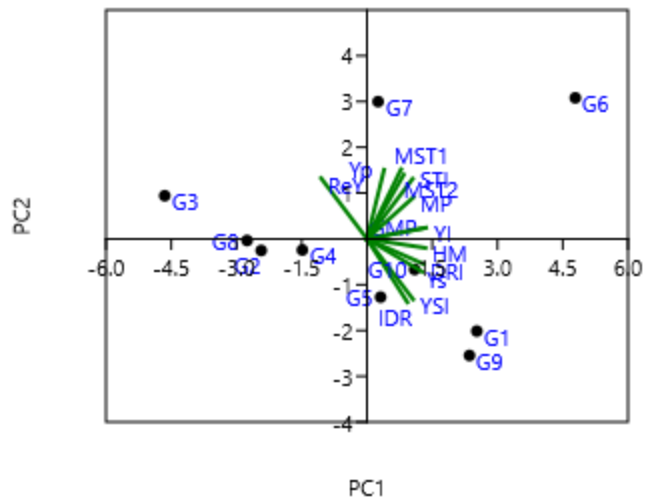
Figure 2. Bi-plot showing the interrelationships among seed yield and drought tolerance indices of ten accessions of cowpeas evaluated under differential drought stress in 2019. Yp: Yield under non-stress conditions; Ys: Yield under stress conditions; ReY: Percent reduction in yield; IDR: Intensity of drought resistance; GMP: Geometric mean productivity; HM: Harmonic mean; MP: Mean productivity; STI: Stress tolerance index; YI: Yield index; YSI: yield stability index; DRI: Drought resistance index; MST_1: Modified stress tolerance index for the non-stress conditions; MST_2: Modified stress tolerance index for stress conditions. G1 – G10 are codes for accessions of cowpea evaluated.
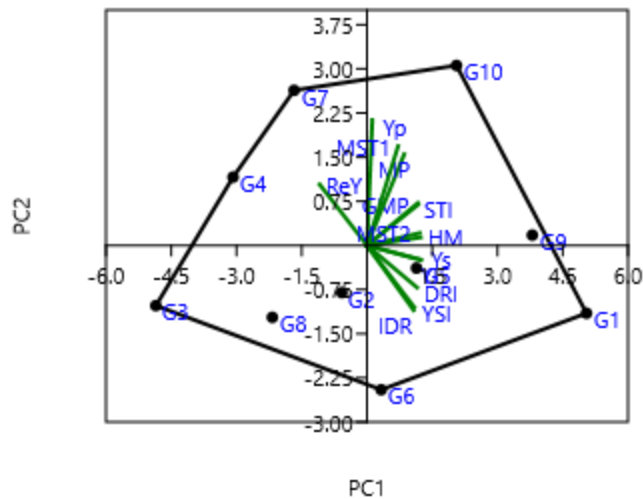
Figure 3. Bi-plot showing the interrelationships among seed yield and drought tolerance indices of ten accessions of cowpeas evaluated under differential drought stress in 2021. Yp: Yield under non-stress conditions; Ys: Yield under stress conditions; ReY: Percent reduction in yield; IDR: Intensity of drought resistance; GMP: Geometric mean productivity; HM: Harmonic mean; MP: Mean productivity; STI: Stress tolerance index; YI: Yield index; YSI: yield stability index; DRI: Drought resistance index; MST_1: Modified stress tolerance index for the non-stress conditions; MST_2: Modified stress tolerance index for stress conditions. G1 – G10 are codes for accessions of cowpea evaluated.
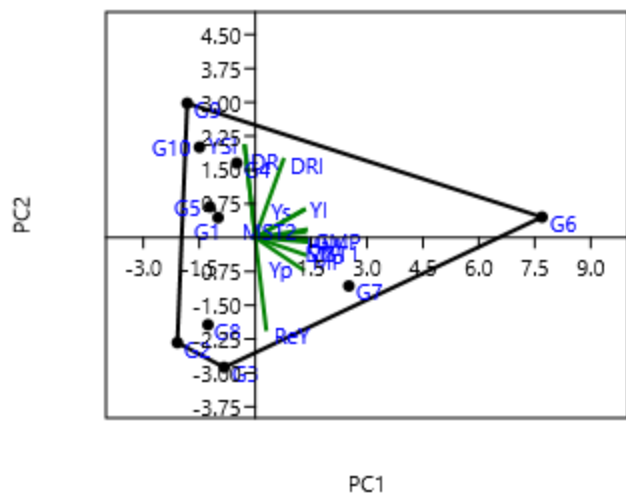
Figure 4. Bi-plot showing the interrelationships among seed yield and drought tolerance indices of ten accessions of cowpeas evaluated under differential drought stress for the combined seasons. Yp: Yield under non-stress conditions; Ys: Yield under stress conditions; ReY: Percent reduction in yield; IDR: Intensity of drought resistance; GMP: Geometric mean productivity; HM: Harmonic mean; MP: Mean productivity; STI: Stress tolerance index; YI: Yield index; YSI: yield stability index; DRI: Drought resistance index; MST$_1$: Modified stress tolerance index for the non-stress condition; MST$_2$: Modified stress tolerance index for stress conditions. G1 – G10 are codes for accessions of cowpea evaluated.
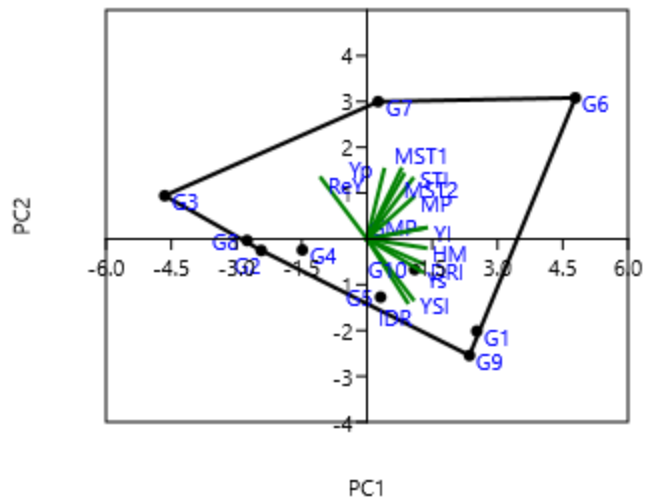
Figure 5. Polygon view of the interrelationships among seed yield and drought tolerance indices of ten accessions of cowpeas evaluated under differential drought stress in 2019. Yp: Yield under non-stress conditions; Ys: Yield under stress conditions; ReY: Percent reduction in yield; IDR: Intensity of drought resistance; GMP: Geometric mean productivity; HM: Harmonic mean; MP: Mean productivity; STI: Stress tolerance index; YI: Yield index; YSI: yield stability index; DRI: Drought resistance index; MST$_1$: Modified stress tolerance index for the non-stress condition; MST$_2$: Modified stress tolerance index for stress conditions. G1 – G10 are codes for accessions of cowpea evaluated.

Figure 6. Polygon view of the interrelationships among seed yield and drought tolerance indices of ten accessions of cowpeas evaluated under differential drought stress in 2021. Yp: Yield under non-stress conditions; Ys: Yield under stress conditions; ReY: Percent reduction in yield; IDR: Intensity of drought resistance; GMP: Geometric mean productivity; HM: Harmonic mean; MP: Mean productivity; STI: Stress tolerance index; YI: Yield index; YSI: yield stability index; DRI: Drought resistance index; MST$_1$: Modified stress tolerance index for the non-stress conditions; MST$_2$: Modified stress tolerance index for stress conditions. G1 – G10 are codes for accessions of cowpea evaluated.

Figure 7. Polygon view of the interrelationships among seed yield and drought tolerance indices of ten accessions of cowpeas evaluated under differential drought stress for the combined seasons. Yp: Yield under non-stress conditions; Ys: Yield under stress conditions; ReY: Percent reduction in yield; IDR: Intensity of drought resistance; GMP: Geometric mean productivity; HM: Harmonic mean; MP: Mean productivity; STI: Stress tolerance index; YI: Yield index; YSI: yield stability index; DRI: Drought resistance index; MST_1: Modified stress tolerance index for the non-stress conditions; MST_2: Modified stress tolerance index for stress conditions. G1 – G10 are codes for accessions of cowpea evaluated.

Table 8. Genotypic correlation among seed yield and drought tolerance indices of cowpea evaluated under differential drought stress in 2019 and 2021

Trait	Year	Yp	Ys	ReY	DRI	GMP	HM	IDR	YI	MP	STI	MST₁	MST₂	YSI
Yp	2019	1	-0.04	0.37	-0.22	0.36	0.11	-0.37	-0.05	0.76**	0.34	0.65*	0.12	-0.37
	2021	1	0.82**	0.53	0.31	0.96**	0.91**	-0.53	0.82**	0.99**	0.94**	0.91**	0.87**	-0.53
Ys	2019			0.37	0.97**	0.91**	0.98**	0.94**	1.00**	0.61	0.92**	0.71*	0.97**	0.94**
	2021			-0.05	0.79**	0.95**	0.98**	0.05	1.00**	0.89**	0.95**	0.93**	0.05	-1.00**
ReY	2019				-0.96**	-0.72*	-0.87**	-1.00**	-0.94**	-0.31	-0.72*	-0.41	-0.83	-1.00**
	2021				-0.64*	0.27	0.14	-1.00**	-0.05	0.39	0.24	0.22	0.18	-1.00**
DRI	2019					0.79**	0.91**	0.97**	0.96**	0.45	0.81**	0.54	0.93**	0.97**
	2021					0.57	0.67*	0.65*	0.79**	0.45	0.59	0.61	0.62	0.64*
GMP	2019						0.97**	0.72*	0.91**	0.87**	0.99**	0.93**	0.94**	0.72*
	2021						0.99**	-0.27	0.95**	0.99**	0.99**	0.97**	0.95**	-0.14
HM	2019							0.87**	0.98**	0.71*	0.96**	0.81**	0.97**	0.88**
	2021							-0.14	0.98**	0.96**	0.99**	0.98**	0.96**	-0.14
IDR	2019								0.94**	0.31	0.72*	0.42	0.84**	1.00**
	2021								0.05	-0.39	-0.24	-0.22	-0.17	1.00**
YI	2019									0.61	0.92**	0.71*	0.97**	0.94**
	2021									0.89**	0.95**	0.95**	0.93**	0.05
MP	2019										0.86**	0.97**	0.72*	0.31
	2021										0.98**	0.95**	0.92**	-0.39
STI	2019											0.93**	0.96**	0.72*
	2021											0.99**	0.97**	-0.24
MST₁	2019												0.80**	0.41
	2021												1.00**	-0.22
MST₂	2019													0.83**
	2021													-0.17

**: *Significant at P ≤ 0.01; *: Significant at P ≤ 0.05.*

Yp: Yield under non-stress conditions; Ys: Yield under stress conditions; ReY: Percent reduction in yield; IDR: Intensity of drought resistance; GMP: Geometric mean productivity; HM: Harmonic mean; MP: Mean productivity; STI: Stress tolerance index; YI: Yield index; YSI: yield stability index; DRI: Drought resistance index; MST₁: Modified stress tolerance index for the non-stress condition; MST₂: Modified stress tolerance index for stress condition.

4. Discussion

Plant breeding programs for drought tolerance principally focus on yield which reflects the adaptability and stability of genotypes. Various drought tolerance indices have been used as key contributors in the selection of drought-tolerant genotypes of crop species. However, their genetic variability and the effect of genotype by environment interaction (GEI) on these indices have not been seriously explored. Variability has three primary components: genotypic (G), environmental (E), and G × E interaction (I). GEI brings ambiguity into the selection process, influencing trait heritability estimates and responsiveness to selection. The variance component ratio of $\sigma^2 g \times e / \sigma^2 g$ can be used to quantify the magnitude of the GEI to genetic effects. A ratio smaller than 1.0 shows that genetic factors have a larger effect and stability in comparison to the variability associated with the interaction of genotype and environment (Hossain et al., 2013).

The significant mean squares shown regarding seed yield under the differential drought stress indicated high genetic differences among the accessions under both non-stress and drought-stress conditions. The significant genotype × environment and environmental effects for yield and drought tolerance indices indicated that accessions performed differently under differential moisture conditions within each year (environment), and that differences in the environment were significant enough to reveal the differences among genotypes. Similar levels of variations have been reported in such crops as maize (Lao et al., 2022; Badu-apraku et al., 2021), cowpea (Ajayi, 2020; Batieno et al., 2016), peanut (Songsri et al., 2008), sorghum (Choudhary et al., 2021), rice (Hussain et al., 2021), and wheat (Bennani et al., 2017; Al-rawi, 2016). These results also suggested large differences in environmental factors such as soil nutrient status and water holding capacity, ranges of temperatures, and relative humidity of the screen house at the experimental site (Badu-apraku et al., 2021). These findings highlight the importance of considering genetic variation and GEI when studying drought tolerance in cowpeas. The results indicate the need for further investigation into specific cowpea genotypes that exhibit higher seed yield under drought stress conditions, which could contribute to the development of drought-tolerant varieties in cowpea breeding programs. Seed yield in non-stress conditions for the two years was generally higher than that of the drought stress conditions, and the reduction in seed yield was also higher in the first year compared to the value observed in the second year. Overall, an above-average reduction in seed yield was associated with accessions G8, G7, G4, G3, and G2. Mostly, accessions with exceptional performance in non-stress conditions had the highest reduction in seed yield while those with low yield under non-stress did not have their yield seriously affected by drought stress in agreement with Batieno et al. (2016) in cowpea. Above all, the percentage reduction in seed yield stayed within the previously reported range in cowpea (Batieno et al., 2016), wheat (Bennani et al., 2017; Al-rawi, 2016; Guendouz et al., 2021), rice (Hussain et al., 2021), and maize (Bonea, 2020). Even though accessions G3, G7, and G8 were consistent across years with an above-average reduction in yield, no accession had the highest yield in both conditions consistently across years suggesting that indirect selection for drought stress could not be projected based on their performance under optimum conditions (Bennani et al., 2017; Al-rawi, 2016), however, accessions

G6 and G10 had an above-average yield in both conditions for the combined seasons. On average, accessions G1, G9, G10, G6, and G7 which had close to average and above-average yield under non-stress and drought-stress conditions were more drought-resistant and desirable. These accessions are promising accessions for optimum and drought stress conditions as reported for cowpeas (Ajayi, 2020).

Highly significant differences in drought tolerance indices indicated that these indices exhibited high genetic diversity and could discriminate among the accessions under the differential drought stress (Bonea, 2020). The range of each tolerance index obtained in the present study is similar in many cases to the ones previously reported (Anwar et al., 2011; Al-rawi, 2016; Eid and Sabry, 2019; Ajayi, 2020; El haddad et al., 2020; Lao et al., 2022; Sareen et al., 2023; Yahaya et al., 2023). GMP, HM, and ReY exhibited high stability and should be considered in any plant breeding program for drought tolerance. Therefore, accessions such as G1 and G5 exhibiting higher and consistent GMP and HM across environments with a lesser reduction in yield would be more stable. STI combined accessions which hard large differences in seed yield between non-stress and drought stress conditions. GMP, MP, and YI pinpointed accessions desirable under drought-stress conditions in the agreement with (Mahdi, 2012), Al-rawi (2016), and El haddad et al. (2020). Accessions G1 and G6 were the most tolerant accessions according to ranking and combined high values of drought tolerance indices across years; moderately tolerant accessions combined mostly moderate values of the indices across years, while the most susceptible accessions (G8, G2, and G3) combined low values of the indices across years in agreement with the findings of Ajayi (2020), Bonea (2020), Eid and Sabry (2019), Guendouz et al. (2021), Yahaya et al. (2023). Similar trends were also shown by the cluster analysis in agreement with Teklay et al. (2020) and Hussain et al. (2021) who reported the effectiveness of cluster analysis in the classification of genotypes into different classes of drought tolerance. The combined ANOVA results reveal significant genetic variation among cowpea accessions for seed yield and various drought tolerance indices. The effects of the year and the interaction between accession and year highlight the importance of considering environmental factors and GEI in studying drought tolerance in cowpeas. These findings provide valuable insights for further research on identifying and selecting cowpea genotypes with improved drought tolerance.

Based on the rankings provided in the results, where 1 to 5 indicates a high ranking and above-average seed yield is considered high, we can assess whether genotypes with high drought tolerance also exhibited high seed yield under non-stress conditions. In the 2019 season, genotype G1 had a high ranking in several drought tolerance indices (1st or close to the top) and also had a relatively high ranking for seed yield under non-stress conditions (6th). This suggests that G1 exhibited both high drought tolerance and a relatively high seed yield in the absence of drought stress. Other genotypes such as G4, G9, and G10 also had above-average seed yield rankings (2nd, 4th, and 3rd, respectively) and showed varying levels of drought tolerance, although not as consistently high as G1. However, in the 2021 season, genotype G6 had high rankings in most drought tolerance indices (1st or close to the top) and achieved the highest ranking for seed yield

under non-stress conditions. This indicates that G6 exhibited both high drought tolerance and a high seed yield in the absence of drought stress. Other genotypes such as G2, G4, G5, G7, and G8 also had above-average seed yield rankings (6th, 3rd, 4th, 7th, and 8th, respectively) and showed varying levels of drought tolerance. Based on these observations, there is some indication that genotypes with high drought tolerance, as measured by their rankings in drought tolerance indices, also exhibited above-average seed yield under non-stress conditions.

A combination of high GCV and PCV for such parameters as seed yield under drought stress, ReY, DRI, HM, IDR, YI, STI, MST_1, MST_2, and YSI indicated that the accessions had a broad genetic base for these parameters, suggesting that selection for them would be effective. Moderate GCV showed by parameters such as seed yield in non-stress conditions, GMP, and MP indicated the existence of moderate variability among the studied accessions for these parameters. Furthermore, higher PCV compared to GCV indicated the influence of the environment on these parameters. However, the influence of the environment was minimal on most of the parameters which suggests that they are amenable to improvement. These results agree with the findings of Anwar et al. (2011) and Eid and Sabry (2019). High broad sense heritability coupled with high GAM exhibited among parameters such as DRI, YSI, and ReY indicate that they are governed by additive gene effects and hence selection for them would be effective. These results agree with Bennani et al. (2017) on ReY; Anwar et al. (2011), and Ajayi (2020) on YSI and DRI. Apart from MST_2 which showed low heritability, other parameters had moderate to high heritability combined with high GAM, indicating that the parameters were less influenced by the effect of the environment, making them effectively transmitted to the progeny. Seed yield also exhibited lower heritability under drought stress compared to the non-stress condition as reported by Bogale et al. (2012), Sellammal et al. (2014), and Ajayi (2020), in maize, rice, and cowpea, respectively. Information on the heritability of drought-tolerant traits is important in that it determines the degree to which improvement based on selection is possible (El-Rawy and Hassan, 2014). Hence, moderate to high heritability combined with high GAM exhibited among accessions for the yield and most of the drought tolerance indices indicated that these parameters can be directly used as selection criteria for yield enhancement of cowpeas for drought stress. Overall, the combination of moderate to high heritability and high GAM provides strong support for the effectiveness of breeding efforts in improving drought tolerance in cowpeas. It indicates that genetic improvement through selection is feasible and can lead to the development of drought-tolerant varieties with enhanced performance and productivity under water-limited conditions. This information can be practically utilized in selecting superior genotypes of cowpeas in ways such as phenotypic evaluation, determination of selection criteria, genetic gain estimation, multi-trait selection, selection indices, replication, and validation.

The extracted PCs (1 and 2) accounted for the highest variability of more than 90 percent of the total variation indicating a successful PCA according to Hammer et al. (2001). Therefore, selection based on the first two PCs is appropriate. All parameters were important contributors to PC1 consistently in both years and combined seasons except seed yield in the non-stress condition in

2019 and combined years respectively, and ReY, DRI, and STI in 2021. However, yield in non-stress conditions was among the major contributors in PC2 of 2019 and combined years. Overall, PC1 can be referred to as drought tolerant and yield potential component (accessions with high tolerance and high yield in both conditions were highly associated with this axis), while PC2 can be regarded as a yield potential component (high yielding accessions under optimum conditions are strongly associated with this axis). The present findings are similar to Batieno et al. (2016), Ajayi (2020), and Sanogo et al. (2023) in cowpea, Teklay et al. (2020), and Choudhary et al. (2021) in sorghum, Guendouz et al. (2021) in wheat, Lao et al. (2022) in maize, and Padmashree et al. (2023) in rice. For the biplot analyses, different trends of relationships were observed under different years because of the G × E interaction effects. The combined biplot may be regarded as the representative of the results across years; a high positive correlation between yield in non-stress conditions with MST_1, MST_2, STI, MP, GMP, and YI indicated that these indices are capable of selecting accessions for optimum conditions. However, the positive correlation of yield under drought stress with indices such as GMP, YI, HM, DRI, YSI, and IDR indicated that these indices were more effective at selecting accessions with superior performance under drought stress conditions. Nevertheless, a high, positive correlation of GMP and YI with seed yield under drought stress and non-stress conditions indicated that selection for these indices will pinpoint superior accessions in both drought stress and non-stress conditions. Therefore, the combination of these indices selected both the highly tolerant accessions such as G6, G1, G9, and G10 and the moderately tolerant G7 and G5. The polygon view of the biplot identified the best accessions for a specific trait or a group of traits in the study. Accessions G6, G7, G9, G2, and G3 vertex accessions, hence, were the most responsive for the combined seasons. Vertex accessions exhibit higher values for the traits contained within the same sector in the biplot (Atnaf et al., 2017). Therefore, G7 had the highest seed yield under non-stress conditions, G6 had higher values for drought tolerance indices such as MST_1, MST_2; G9 combined higher values of YSI, IDR, and DRI with seed yield under drought stress conditions, G3 had the highest values for a reduction in yield while G2 had no corresponding trait nor indices in its sector.

Genotypic correlation analysis was done among parameters to determine the most suitable tolerance indices. Previous reports have indicated that the most suitable indices for the selection of drought-tolerant genotypes are those that show a positive correlation with grain yield in both the conditions of drought stress and non-stress (Al-rawi, 2016; Bonea, 2020; Hosseini et al., 2020). The lack of correlation between yield in non-stress and drought stress conditions in 2019 suggests that higher yield under non-stress conditions does not always anticipate high yield under drought stress conditions (Ajayi, 2020). This agrees with Bonea (2020) in maize. On the contrary, the high positive correlation of seed yield in non-stress conditions with seed yield under drought stress, GMP, HM, YI, MP, STI, MST_1, and MST_2 in 2021 indicated that these indices can discriminate accessions exhibiting superior performance under both drought and non-stress conditions from the others and would be the best indices to screen accessions of cowpea under drought stress. These results align with the findings of Hussain et al. (2021) for GMP and STI, El haddad et al. (2020) for STI, GMP, MP, and HM, and also the findings of Teklay et al. (2020) for MP, HM, GMP, STI,

and YI. The importance of MP, MST$_1$, STI, GMP, and HM for selection under both stress and non-stress conditions has been emphasized by Bennani et al. (2017) in agreement with the present study. Lao et al. (2022) stated that GMP, MP, and STI should be the preferred indices for screening drought-tolerant maize genotypes. A consistently significant positive correlation of MST$_1$ and MP with seed yield under non-stress indicates that these indices are useful in discriminating superior accessions under optimum conditions, which corroborates the biplot results. However, the consistently high positive correlation of seed yield under stress with DRI, GMP, HM, YI, STI, MST$_1$, and YSI indicated that these indices are effective at discriminating superior accessions under drought stress conditions in agreement with El-Rawy and Hassan (2014) for HM, STI, and YSI, and Ajayi (2020) for DRI, GMP, YI, and YSI. The newly introduced IDR exhibited a high positive correlation with the seed yield under drought stress in 2019 and was only useful for selection under drought stress. Furthermore, the following interaction was consistent across the two years: higher DRI was associated with higher HM, IDR, YI, and YSI. Higher GMP was associated with higher HM, YI, MP, STI, MST$_1$, and MST$_2$. Higher MP was associated with higher STI, MST$_1$, and MST$_2$. Higher YI was associated with higher STI, MST$_1$, and MST$_2$. Higher IDR was associated with higher YSI. Higher HM was associated with higher YI, MP, STI, MST$_1$, and MST$_2$. Higher STI was associated with higher MST$_1$ and MST$_2$. Higher MST$_1$ was associated with higher MST$_2$. However, a higher percent reduction (ReY) was consistently negatively associated with higher DRI, IDR, and YSI which indicated selection based on these indices would discriminate accessions exhibiting a higher level of resistance to yield loss under drought stress. Higher positive correlations indicate similar capabilities of discriminating accessions under drought stress.

5. Conclusion

This study, which reveals that drought significantly reduces seed yield in cowpeas, shows that seed yield and all drought tolerance indices are greatly influenced by genotype effect, environment (year), and genotype x environment interaction. However, the magnitude of G × E about genetic effects indicated high stability of GMP, HM, and ReY. All analyses pinpointed highly tolerant accessions (G1 and G6) from the highly susceptible ones (G2, G3, and G8). Genotypes with high drought tolerance generally exhibited better seed yield under drought stress conditions, indicating their suitability for cultivation in arid and semi-arid regions. However, the study also identified genotypes that displayed high seed yield in the absence of drought stress, suggesting the presence of genotypes with both high drought tolerance and high seed yield potential in non-stress conditions. This study also confirmed MST$_1$, MST$_2$, STI, and MP as suitable for selecting high-yielding accessions for non-stress conditions and hence are recommended for optimum conditions. HM, DRI, YSI, and IDR were the most suitable for selecting drought-tolerant accessions and hence recommended for environments prone to drought while GMP and YI were effective under both non-stress and drought-stress conditions. Furthermore, all the indices showed moderate to high heritability and high GAM except MST$_2$ which showed low heritability. The results of the correlation analysis highlighted the relationships between various drought tolerance traits and seed

yield. Positive correlations were observed between seed yield under non-stress conditions and traits such as yield under stress conditions, DRI, GMP, and MP. Similarly, Yield under stress showed positive correlations with ReY, DRI, GMP, and other productivity indices, indicating their relevance for drought tolerance and productivity improvement. Nonetheless, it is recommended that in-depth multi-environment studies using Additive Main Effects and Multiplicative Interaction (AMMI), Genotype and Genotype × Environment (GGE), and Finlay and Wilkinson (FW) analyses should be conducted to shed more light on the importance of GEI on drought tolerance indices of cowpea for its improvement.

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