

Full Length Research Paper

Evaluation of cowpea genotypes for water stress tolerance in the Sudano-Sahelian zone of Mali

Nana Koureissi^{1*}, Sory Diallo¹, Abdrahamane Sylla¹, Mohamed Lamine Tekete¹, Joseph Sekou B. Dembele², Aiché Dite Diop Traore¹, Sayon Kamissoko¹, Sekouba Sanogo¹, Aboubacar Toure¹, Niaba Teme¹, Michel Vaksman³, Harouna Coulibaly¹, Mamoutou Kouressy¹ and Bernard Sodio²

¹Institute of Rural Economy, (IER) Rue Mohamed V, BP 258, Bamako Mali.

²Faculté de pharmacie, Université des Sciences, des Techniques et des Technologies (USTTB), E 423 Bamako-Mali.

³Center for International Cooperation in Agricultural Research for Development (CIRAD), UMR AGAP Institut, F-34398 Montpellier, France.

Received 23 July, 2025; Accepted 6 October, 2025

Cowpea (*Vigna unguiculata* L. Walp) is a leguminous crop widely grown in Mali. Its grains are used for human consumption and the fodder for animal feed. Despite its importance, cowpea grain yield remains low, with around 500 kg/ha, due mainly to drought. To overcome this constraint, it is relevant to screen cowpea varieties that are tolerant to water stress. The aim of this study was to identify drought-tolerant genotypes in the vegetative phase based on agro-morphological and physiological parameter indices. Thus, forty cowpea genotypes were evaluated under two water regimes, no water stress and water stress conditions, using an Alpha Lattice Design with three replications in 2022 and 2023. Results showed significant variability among cowpea genotypes across water regimes on grain yields and their components in both years. Analysis of variance (ANOVA) showed a significant difference between genotypes for both environments. Five genotypes, such as (CZ16-3-2-37, CZ16-3-71, CZ16-3-2-48, WILIBALI, CZ16-3-2-21), recorded the highest pod and grain yields under watered conditions. Under stress conditions, the following genotypes (CZ16-6-56, CZ16-4-2-3, WILIBALI, K VX775-33-2X693-2/BC4F12-P6-1Fkb, KT1-44-8) showed the highest grain yield with the highest leaf area index and the lowest fodder biomass. The (PCA) results showed ten genotypes (K VX61-1, ACAR 1, TOURE SHO, WILIBALI, WASSA SHO, CZ16-4-2-3, CZ16-2-2-23, CZ16-3-2-48, CZ16-3-1-92, and CZ16-3-2-21) tolerant to vegetative water stress based on drought indices, mean productivity (MP), geometric mean productivity (GMP), and stress tolerance index (STI).

Key words: Cowpea, grain yield, water stress, drought indices,

INTRODUCTION

Cowpea (*Vigna unguiculata* (L.) Walp) is an important leguminous crop grown in semi-arid tropical zones, particularly in sub-Saharan Africa (Santos et al., 2020; Jakai and Adalla, 1997). Cowpea is a cash crop grown for grain and fodder. West Africa alone is the world's largest

production and consumption region (Ouali-N'goran et al., 2014; Gerrano et al., 2022) and produces 7,617,458 tons compared to 8,901,644 tons worldwide. In Mali, cowpea ranks fourth in terms of production and cultivated area (Doumbia et al., 2022). Cowpea is generally grown in

association with cereals or as a sole crop in farming systems (Doumbia et al., 2022). It is a legume frequently used as a source of food for humans and animals for the richness of its grains and leaves in protein and mineral elements (Boukar et al., 2019).

The amount of nitrogen fixed by rhizobia in the rhizosphere can enrich and improve the availability of this element to crops (Golabadi et al., 2006; Fustec et al., 2010). As with other legumes, cowpea can fix up to 134 kg/ha of atmospheric nitrogen. Hence, it is presented as a key rotating crop in farming systems with infertile soils. Despite these agronomic, ecological, and socio-economic advantages, cowpea yield remained low (Egbe et al., 2010). Cowpea's low productivity is linked to its purely rainfed production condition in the Sahel (Hayatu et al., 2014) and more specifically in Mali. This Sahel zone is characterized by poor rainfall distribution resulting in intermittent drought combined with high temperature and phytosanitary problems (Ntare and Waliyar, 2000; Nkomo et al., 2021). Faced with this situation, the selection of drought-tolerant cowpea varieties would be an important step in improving cowpea production under climatic constraints in Mali. The processes by which crops cope with drought are a highly complex mechanism, making the selection of cowpea varieties a difficult task (Agbicodo et al., 2009).

Drought, also known as water deficit, is one of the abiotic factors that significantly limit crop production (Fahad et al., 2017). It is caused by low rainfall, which results in insufficient soil moisture for optimal plant growth (Hayatu et al., 2014). Numerous research studies have identified drought as one of the environmental stresses that most affects crop productivity in arid and semi-arid regions. It must be strongly taken into account for future climate change scenarios (Salman et al., 2021). Iwuagwu et al. (2017) reported that the effects of drought vary and depend on the intensity, development stage, and duration of stress, as well as on the plant's adaptive strategy to drought tolerance.

Cowpea has proven to be one of the most drought-tolerant crops, more so than any other legume grown in semi-arid regions with low rainfall (Ndiso et al., 2015; Santos et al., 2020). In sub-Saharan Africa, where around two-thirds of the world's cowpeas are grown, drought remains one of the main limitations to production. Cowpea is more sensitive to water stress during flowering and pod filling. Similarly, water stress during the vegetative stage followed by re-irrigation has little influence on cowpea seed yield (Abdelshakoor and Faisal, 2010; Hall, 2012). In contrast to the latter, Marino

et al. (2007) and Ravelombola et al. (2018) reported in their studies that water stress imposed at the vegetative stage adversely affected the agro-morphological and physiological parameters of cowpea. However, it has been well documented that early varieties are more sensitive to drought at the vegetative stage than late varieties. This would be explained by the fact that stress occurs before the pod initiation phase when plants have more capacity to recover after further watering (Radhouane et al., 2014; Gano et al., 2021). However, these late-maturing varieties are no longer suitable for farming systems in semi-arid regions due to a shortened rainy season (Gano et al., 2021). Nevertheless, it would be important to understand the morpho-physiological and agronomic responses of cowpea under vegetative stress in order to determine the appropriate characteristics for its genetic improvement and adaptation. Reducing cowpea production is a major challenge for breeders due to the low yields recorded by farmers under water-stressed conditions. However, stress indices that provide an accurate measure of drought have been widely used for screening drought-tolerant varieties in cowpea (PEJIĆ et al., 2013), bean (Wasae, 2021), and sorghum (Yahaya et al., 2023). According to Fernandez (1992) and Deffo et al. (2024), the best indices are those that correlate positively with grain yield under both stressed and unstressed water conditions. High-performance varieties are those with better yields in both stressed and unstressed conditions. Although there are several studies on the relationship between drought tolerance indices and crop yield, very few studies have been carried out on cowpea varieties from the Cinzana collection under water stress at the vegetative stage, which is one of the most important cowpea growing areas in Mali. To overcome this constraint, it is relevant to select cowpea varieties that are tolerant to water stress based on agronomic, morphological, and physiological indices. The main objective was to enhance cowpea production. The specific objectives were to determine the effect of water stress on grain yield and components, and to identify the best genotypes under vegetative water stress in terms of agronomic, physiological traits, and stress indices at Cinzana.

MATERIALS AND METHODS

Study site

Two consecutive experiments were conducted at the end of the rainy season during 2022 and 2023 at the Cinzana agricultural

*Corresponding author. E-mail: nkoureissi@yahoo.com.

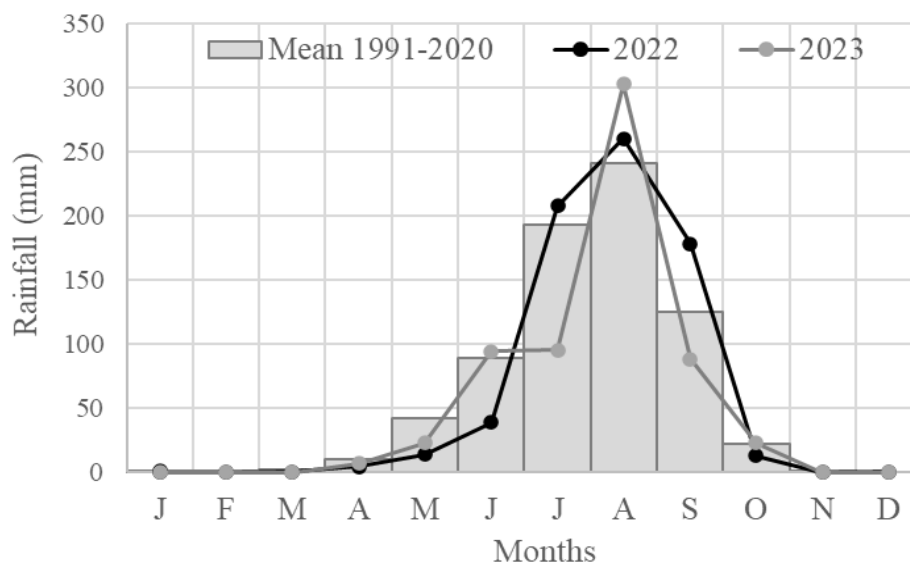


Figure 1. Evolution of monthly rainfall in 2022 and 2023 compared to the period of 30 years from 1991 to 2020 at Cinzana.

research station (Latitude: 13.15 N; longitude: 05.58 W; and altitude: 281 m), and the soil type is sandy loam. The area's climate is Sudano-Sahelian, with a rainy season spanning between June and the end of October. The annual rainfall recorded in 2022 and 2023 was slightly below the average for the last 30 years (1991 to 2020) at Cinzana (Figure 1). Rainfall in 2022 and 2023 was 719.3 and 635 mm, respectively, compared with 728.4 mm for the 30-year period. A 48% reduction was observed in the wettest month (August), compared to the period from 1991 to 2022.

Plant material

The experimental material consisted of 40 genotypes from the Cowpea Improvement Program of the Institute of Rural Economy of Mali, located at the Agricultural Research Station of Cinzana (ARSC) in Ségou. These 40 genotypes were selected based on their agro-morphological and physiological characteristics. The selected genotypes under this study represent a diversity of improved cowpea varieties grown in Mali. Distinguishing characteristics of each genotype are shown in Table 1. Variety K VX61-1 was used as the drought tolerance control.

Experimental design

The experiment was carried out in two environments (normal water regime and stressed water regime). For each environment, an Alpha lattice design with three replications was used. There were 5 blocks with 8 genotypes per block, with a total of 40 genotypes for the whole experiment. Each elementary plot comprised 5 rows of 5 m. Row spacing was 0.75 and 0.3 m, respectively, between and within rows. The distance between the replicates was 2 m. The two water treatments (irrigated and stressed) were spaced 10 m to avoid water exchanges during irrigation. Plowing and harrowing were carried out to prepare the soil. Sowing was realized on October 20 and October 27, respectively, in 2022 and 2023. For

drought stress, the plots were left without water application for 30 days, and non-irrigated plots were irrigated every 3 days until physiological maturity. Thereafter, optimal irrigation was provided using a sprinkler system (oscillating booms). Before sowing, seeds were treated with metalaxyl-m (fungicide) at a quantity of 1 kg/ha. Weeding was carried out manually on all elementary plots. Diammonium phosphate DAP (18N-46P-0K) was applied homogeneously three weeks after sowing at a dose of 50 kg/ha. The insecticides SUNHALOTRIN at 5% EC, Cyhalothrin, and SUNPYRIFOS at 48% EC were applied at a rate of 1 Lha⁻¹. These treatments were carried flowering onset.

Phenological, agronomic, and physiological measurements

The 50% flowering date parameter was observed on all net plots. Plant physiological characteristics such as leaf area index (LAI) and chlorophyll content were measured before, during, and after stress. The leaf area index was determined on a one-square-meter plot defined in each net plot according to the method of Wilhelm et al. (2000). LAI 2200C (Plant Canopy Analyzer) was used to determine the leaf area index. Chlorophyll content was measured on the three youngest leaves of the third branch of the main branch from top to bottom. This measurement was carried out using SPAD (SPAD 502-Minolta, Japan) and involved three randomly selected plants in each net plot. Agronomic data included pod biomass (fodder), grain, and 100 g weights were measured. These measurements were carried out in each main plot on 2.9 m². After harvest, pods and haulms were sun-dried for three weeks. The drought index calculus from grain yield under stressed and non-stressed conditions was recorded in Table 2.

The reduction will be calculated using this formula:

$$\text{Reduction} = \frac{(YI - YS) \times 100}{YI}$$

Table 1. List of the cowpea genotypes used in this study, including their maturity and origin during the 2022 and 2023 cropping seasons at Cinzana, Mali.

No	Genotypes	Maturity	Origin
1	CZ16-3-2-37	Early	Mali
2	SIMBO	Early	Mali
3	IT15K-2386-1	Early	Nigeria
4	KVX61-1	Early	Burkina Faso
5	KT1-44-8	Early	Mali
6	TILIGRE PLANT-6	Early	Burkina Faso
7	MAOUDO	Early	Mali
8	IT13K-12 1-5	Early	Nigeria
9	SANGATIGUI	Early	Mali
10	ACAR 1	Early	Mali
11	Kirkhouse Benga	Early	Burkina Faso
12	KVX78 -6 PLANT-1	Late	Burkina Faso
13	IT13K-1424-12	Late	Nigeria
14	CZ16-3-2-21	Late	Mali
15	CZ16-2-2-8	Medium	Mali
16	CZ16-3-2-48	Medium	Mali
17	L1-126-1	Medium	Mali
18	WASSA SHO	Medium	Mali
19	IT14K-2132-1	Medium	Nigeria
20	CZ-16-3-1-64	Medium	Mali
21	L1-160	Medium	Mali
22	KT2-23-5	Medium	Mali
23	KOROBALLEN	Medium	Mali
24	WILIBALI	Medium	Mali
25	KVX775-33-2 X693-2 /BC4F12-P6-1 Fkb	Medium	Burkina Faso
26	MoussaX693-2 F7 Gbr	Medium	Niger
27	JIGUIFA	Medium	Mali
28	CZ16-3-1-92 75	Medium	Mali
29	L1-140	Medium	Mali
30	CZ-16-1-1-91	Medium	Mali
31	CZ-16-4-2-3	Medium	Mali
32	KVX 396-4-5-2DX693-2/F16	Medium	Burkina Faso
33	CZ16-3-71	Medium	Mali
34	CZ16-2-1-15 75	Medium	Mali
35	FAKSON	Medium	Mali
36	TOURE SHO	Medium	Mali
37	CZ16-6-56	Medium	Mali
38	L1-154	Medium	Mali
39	CZ16-1-1-147	Medium	Mali
40	CZ16-2-2-23 75	Medium	Mali

Static analysis

Combined analysis of variance (ANOVA) was performed on data from both years (2022 and 2023) to test for statistical differences between genotypes and water regimes (NWS and WS) using the method of ANOVA over combined locations suggested by McIntosh

(1983). The “Shapiro and Wilk” normality and “Bartlett” homogeneity tests were performed to identify and eliminate outliers for each variable studied. Treatment means were compared using the least significant difference (LSD) at the 5% probability level. Principal Component Analysis (PCA) combined with hierarchical clustering analysis was performed to obtain the behavioral groups using the

Table 2. Code name and formula applied to estimate drought tolerance indices from grain yield under stressed and unstressed conditions conducted at Cinzana during the 2022 and 2023 cropping seasons.

Index code	Formule	Reference	Signification
Stress sensitivity index (SSI)	$SSI = [1 - (YS / YI)] / [1 - YS' / YI']$	Fischer and Maurer (1978)	Lower index across stress levels indicates lower differences in yield or more resistance to drought
Tolerance	$TOL = YI - YS$	Rosielle and Hamblin (1981)	A lower index means stability in two different environments. water stress and no water stress condition
Mean productivity (MP)	$MP = (YI + YS) / 2$	Rosielle and Hamblin (1981)	A higher index means tolerance to drought between water stress and no water stress conditions
Geometric mean productivity (GMP)	$GMP = \sqrt{YI \times YS}$	Rosielle and Hamblin (1981)	The higher the GMP value, the greater the degree of relative tolerance
Stress tolerance index (STI)	$STI = (YI \times YS) / (YI')^2$	Fernandez (1992)	A higher index means tolerance to drought
Sensitivity drought index (DSI)	$DSI = (YI - YS) / YI$	Fernandez (1992)	The genotypes with a small value of this index will be more desirable

YS is the average yield of the water-stressed genotype; YS' is the average of all stressed genotypes; YI is the average yield of the non-water-stressed genotype; and YI' is the average yield of all non-stressed genotypes.

packages FactoMineR (Sebastien et al., 2008) and Factoextra (Kassambara et al., 2020). Data analysis was performed using R software version 4.3.2.

The combined analysis of data from the two environments (stressed and unstressed regimes) was carried out according to the model:

$$Y_{hij} = \mu + \rho_h + \alpha_i + \eta_{hi} + \beta_j + \delta_{hj} + \alpha\beta_{ij} + \varepsilon_{hij}$$

where $h=1.2. \dots r$, $i=1.2. \dots a$, and $j=1.2. \dots b$. Y_{hij} is the response for the hij th experimental unit, μ is a general mean effect, ρ_h is the h th block or replicate effect, and is identically and independently distributed with mean zero and variance σ^2_{ρ} . IID ($0, \sigma^2_{\rho}$), α_i is the effect of the i th level of factor A, η_{hi} is a random error effect for factor A and η_{hi} is identically and independently distributed as IID ($0, \sigma^2_{\eta}$), β_j is the effect of the j th level of factor B, δ_{hj} is a random error effect for factor B and δ_{hj} is identically and independently distributed IID ($0, \sigma^2_{\delta}$), $\alpha\beta_{ij}$ is the ij th interaction effect of the two factors A and B, and ε_{hij} is a random error effect for the interaction effects and is identically and independently

distributed as IID ($0, \sigma^2_{\varepsilon}$). The different random effects ρ_h , δ_{hj} and ε_{hij} are assumed to be independent.

RESULTS

ANOVA on parameters measured under no water stress and water stress conditions in 2022 and 2023 years

ANOVA on parameters measured under water stress and no water stress conditions was significant for both years ($p < 0.05$). The highly significant difference was recorded among genotypes for the variables studied in water stress, no water stress ($p < 0.01$) for both years, and combined, except for the leaf area index. For this variable, there is no significant difference between genotypes in the year 2022. The

interaction between genotypes $\times$ environment was significantly different between genotypes for flowering and not significantly different between all the variables studied (Table 3).

Yield performance and yield components of each genotype under no water-stressed and water-stressed conditions in 2022 and 2023

ANOVA showed significant differences among genotypes for grain yield and yield components (pod yield and weight of 100 g) under no water stress (NWS) and water stress (WS) conditions (Table 4). Genotype yield averages varied from 2113.29 to 722.08 kg/ha in unstressed conditions and from 969.63 to 196.50 kg/ha in water-stressed conditions (WS). The average grain yield genotypes under watered and stressed conditions

Table 3. Mean values of parameters measured under water stress, no water stress, and interaction in 2022 and 2023 of whole genotypes.

Traits	2022			2023			Combine			Interaction	
	YI	YS	Signficativity	YI	YS	Signficativity	YI	YS	Signficativity	G×E	Signficativity
Flowering (days)	51.61 ^a	38.74 ^b	***	48.55 ^a	46.12 ^b	*	50.08 ^a	42.55 ^b	**	0.04	**
Pod yield (kg/ha)	1457.51 ^a	713.90 ^b	***	1777.77 ^a	524.84 ^b	***	1617.64 ^a	614.57 ^b	**	0.47	ns
Grain yield (kg/ha)	1035.01 ^a	586.64 ^b	***	1630.64 ^a	629.01 ^b	***	1332.82 ^a	608.90 ^b	*	0.99	ns
Biomass yield (kg/ha)	2162.56 ^a	680.38 ^b	***	4996.18 ^a	2136.80 ^b	***	3579.37 ^a	1537.10 ^b	**	0.98	ns
100 grains weight (g)	18.05 ^a	16.78 ^b	***	18.76 ^a	16.11 ^b	***	18.41 ^a	16.47 ^b	**	0.74	ns
Chlorophyll content	57.45 ^a	47.32 ^b	***	61.28 ^a	56.43 ^b	***	59.37 ^a	52.97 ^b	*	0.96	ns
LAI	0.94	0.46	ns	3.62 ^a	1.45 ^b	***	2.29 ^a	1.10 ^b	*	0.57	ns

YI: Yield under no water stress condition; YS: yield under water stress conditions; ns: no significant; *: significant at $p = 0.05$; **: significant at $p = 0.01$; ***: significant at $p = 0.001$.

were 1235.07 and 548.49 kg/ha, respectively. Higher-yielding genotypes reduced their grain yield more. Water stress reduced grain yield, while the genetic material reacted differently. Grain yields of CZ16-4-2-3, KVX61-1, WASSA SHO, KT1-44-8, ACAR 1, TOURE SHO, and CZ16-3-2-21 were reduced more than 40% whereas the genotypes CZ16-1-1-91 (Medium), IT15K-2386-1, Kirkhouse Benga, and IT13K-12 1-5 (Early) were not affected (Table 4). Table 4 shows the mean grain yield reductions per genotype.

PCA of genotype variables under no watered conditions in 2022 and 2023 years

PCA was performed based on the variables' contribution to genotypes' divergence under irrigated conditions. The PCA results showed the existence of five homogeneous groups. The two main dimensions (1 and 2) explained 53.4% of the variability (Figure 2A). Group 1 included genotypes such as CZ16-1-1-91, CZ16-3-1-92, JIGUIFA,

TILIGREPLANT-6, and MoussaX693-2F7Gbr, which are showing high biomass yields. The genotypes KVX775-33-2X693-2/BC4F12-P6-1Fkb, L1-140, TOURESHO, CZ16-2-2-23, and L1-160 formed the second group in accordance with low chlorophyll content.

Group 3 was composed of SANGATIGUI, Kirkhouse Benga, CZ16-2-1-15, IT13K-1424-12, and IT13K-121-5, which recorded the highest chlorophyll content.

Genotypes CZ16-1-1-147 and KOROBALEN had a high LAI, constituting Group 4, whereas genotypes CZ16-3-2-37, CZ16-3-71, CZ16-3-2-21, CZ16-3-2-48, and WILIBALI of Group 5 showed high pod and grain yields.

PCA of genotype variables on agronomic and physiological variables under water-stressed conditions in 2022 and 2023

The results of the PCA of variables under stressed conditions are shown in Figure 2B. The PCA-biplot

showed the existence of three homogeneous groups. Axes 1 and 2 explain 21 and 28.9% of the variation, respectively. Group 1 includes genotypes IT13K-121-5, JIGUIFA, CZ16-3-1-92, CZ16-3-1-64, and CZ16-1-1-91. This group is characterized by high biomass and low grain yields. Group 2 includes genotypes CZ16-6-56, CZ16-4-2-3, WILIBALI, KT1-44-8, and KVX775-33-2X693-2/BC4F12-P6-1Fkb, characterized by moderate grain yield, high LAI, and low biomass. Group 3 contains genotypes such as IT13K-1424-12, IT14K-2132-1, CZ16-2-2-8, CZ16-3-71, and TILIGREPLANT-6, indicating moderate pod yield and high chlorophyll content. Biomass yield was negatively correlated with grain and pod yields and LAI. The study showed a positive correlation between grain, pod yield, and LAI in both environments. In both no water stress and water stress conditions, the PCA results showed that the genotypes WILIBALI, CZ16-3-2-21, and WASSASHO performed well in both environments in terms of grain and pod yields. The L1-154 genotype performed well in the non-stressed

Table 4. Yield and yield components performance of each genotype under no water stress and water-stressed conditions, Cinzana Research Station in the 2022 and 2023 cropping seasons.

Yield potential	Genotypes	Grain yield (kg/ha)			Pod yield (kg/ha)			Weight for 100 g		
		YI	YS	Reduction (%)	YI	YS	Reduction (%)	YI	YS	Reduction (%)
Highly	CZ16-2-2-8	1688.92	592.00	35.05	1986.03	841.10	42.35	19.00	15.70	82.61
	CZ16-4-2-3	1170.00	684.44	58.50	1702.92	695.60	40.84	19.00	9.54	50.22
	KVX61-1	1425.83	877.50	61.54	2016.67	1113.10	55.19	16.00	14.30	89.38
	WASSA SHO	1603.33	793.33	49.48	2142.08	835.60	39.01	21.50	21.00	97.67
	WILIBALI	1670.83	661.71	39.60	2186.67	881.50	40.31	18.00	19.38	107.64
	KT1-44-8	1180.42	796.54	67.48	1718.75	522.60	30.41	17.75	15.77	88.83
	CZ16-3-2-48	2037.01	698.33	34.28	2680.83	683.80	25.50	17.75	18.38	103.54
	CZ16-2-2-23	1298.47	499.69	38.48	1744.44	565.60	32.42	19.25	18.00	93.5
	ACAR 1	1126.81	808.33	71.74	1620.42	1186.70	73.23	18.25	17.00	93.15
	TOURE SHO	1075.42	785.68	73.06	1422.5	503.90	35.42	17.75	15.75	88.76
Moderately	CZ16-3-2-21	1485.83	969.63	65.26	2072.08	759.20	36.64	17.00	16.59	97.61
	CZ16-2-1-15	1011.67	468.89	46.35	1577.92	961.30	60.92	14.50	18.78	129.52
	L1-140	1138.75	462.59	40.62	1568.33	601.80	38.37	16.75	15.94	95.18
	L1-154	1351.67	320.00	23.67	1835.83	355.20	19.35	16.25	14.47	89.03
	CZ16-1-1-147	1057.50	471.67	44.60	1814.58	605.00	33.34	18.25	16.23	88.95
	IT14K-2132-1	1290.83	680.37	52.71	1890.42	851.90	45.06	18.25	13.60	74.52
	CZ16-3-71	1946.59	721.48	37.06	1701.67	686.30	40.33	18.28	14.77	80.77
	IT13K-1424-12	1069.17	631.56	59.07	1445.14	896.50	62.03	23.50	23.48	99.92
	SANGATIGUI	950.00	570.74	60.08	1398.75	842.20	60.21	23.00	18.78	81.63
	KT2-23-5	1022.36	433.11	42.36	1475.42	647.00	43.85	16.75	17.74	105.92
Lower	CZ16-3-1-92	979.58	427.88	43.68	1397.5	592.40	42.39	13.75	14.74	107.23
	CZ16-3-1-64	1607.01	535.84	33.34	1842.5	377.20	20.47	18.00	13.18	73.19
	SIMBO	722.08	371.67	51.47	1155.42	613.30	53.08	19.50	10.00	51.28
	MoussaX693-2 F7 Gbr	910.42	342.41	37.61	1474.58	388.70	26.36	16.50	14.17	85.86
	IT13K-12 1-5	1509.25	487.20	32.28	2113.29	369.31	17.48	22.50	15.98	71
	Kirkhouse Benga	1047.08	333.85	31.88	1421.25	327.20	23.02	18.00	14.26	79.22
	L1-160	1225.83	417.78	34.08	1720.00	491.10	28.55	17.75	13.00	73.24
	KOROBALLEN	1412.5	679.47	48.10	1895.56	397.60	20.97	19.75	19.94	100.97
	MAOUDO	1237.08	558.33	45.13	1721.94	756.70	43.94	19.75	8.50	43.04

Table 4. Contd.

CZ16-6-56	1327.50	641.39	48.32	1867.50	428.60	22.95	17.25	14.25	82.61
CZ16-3-2-37	1249.77	457.78	36.63	1684.86	963.30	57.18	20	19.91	99.57
KVX78 -6 PLANT-1	1131.25	672.94	59.49	1775.42	386.50	21.77	18.75	17.17	91.56
KVX775-33-2 X693-2 /BC4F12-P6-1 Fkb	849.27	342.78	40.36	1327.36	506.50	38.16	17.5	13.70	78.29
CZ16-1-1-91	1812.46	434.26	23.95	1852.08	486.50	23.27	19.5	17.58	90.17
IT15K-2386-1	1131.67	196.50	17.36	1786.67	438.10	24.52	17.75	15.95	89.86
TILIGRE PLANT-6	1140.42	478.17	41.93	1691.67	353.30	20.89	21.64	20.07	92.74
L1-126-1	744.42	450.37	60.50	1247.78	679.10	54.42	17.75	18.27	102.91
JIGUIFA	750.83	303.33	40.40	1010.00	408.30	40.43	19	19.40	102.12
FAKSON	777.92	331.85	42.66	1156.25	577.80	49.97	17.25	12.60	73.06
Mean	1235.07	548.49	45.38	1695.97	633.21	38.14	18.42	16.10	87.85
CV	53.72	51.87		35.30	56.72		11.97	20.40	
Significance	***	***		***	***		***	***	

YI: yield under no water stress condition; YS: yield under water stress conditions; CV%: coefficient of variation percentage; ***: significant at p = 0.001.

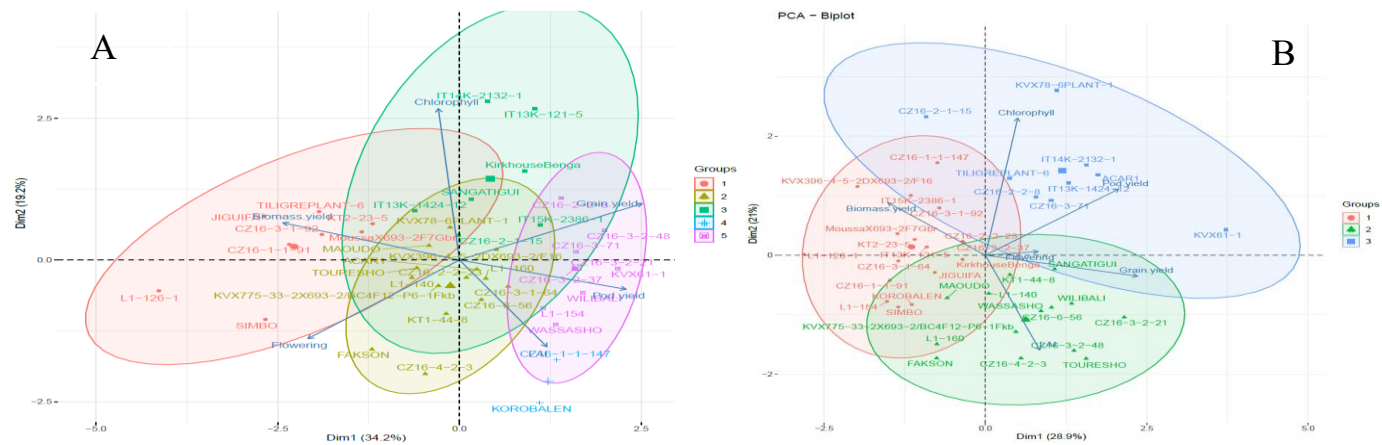


Figure 2. (A) PCA on variables and genotypes under irrigated conditions and (B) PCA on variables and genotypes under stress conditions.

Table 5. Tolerance index of 40 cowpea genotypes to water stress during the vegetative phase at Cinzana Research Station during the 2022 and 2023 cropping seasons.

Tolerance type	Genotypes	GMP	TOL	MP	STI	SSI	DSI
Highly tolerant	CZ16-2-2-8	1097717	1050.83	1172.08	0.38	1.44	0.62
	CZ16-4-2-3	887496.3	612.22	990.56	0.53	1.1	0.47
	KVX61-1	1251169	548.33	1151.67	0.62	0.9	0.38
	WASSA SHO	1297100	841.67	1214.17	0.49	1.2	0.51
	WILIBALI	1229581	830.28	1184.03	0.48	1.21	0.52
	KT1-44-8	1182378	125	1089.17	0.89	0.25	0.11
	CZ16-3-2-48	1052704	146.11	1028.61	0.87	0.31	0.13
	CZ16-2-2-23	1022754	482.78	1039.72	0.62	0.88	0.38
	CZ16-3-2-21	958537	280.28	989.03	0.75	0.58	0.25
Tolerant	ACAR 1	832134.3	221.11	918.89	0.79	0.5	0.21
	IT14K-2132-1	711037	863.61	947.36	0.37	1.46	0.63
	CZ16-3-71	1096567	334.17	1060.42	0.73	0.64	0.27
	TOURE SHO	898644.4	265.56	957.22	0.76	0.57	0.24
	KT2-23-5	857247.7	323.06	939.86	0.71	0.68	0.29
	CZ16-3-1-92	857318.5	113.06	927.64	0.89	0.27	0.11
	SANGATIGUI	632611.1	17.5	795.42	0.98	0.05	0.02
Highly susceptible	L1-140	661905.6	423.61	840.69	0.6	0.94	0.4
	L1-154	755933.3	431.67	895.83	0.61	0.91	0.39
	IT13K-1424-12	616048.2	356.39	804.86	0.64	0.85	0.36
	CZ16-1-1-147	579555.6	553.33	810	0.49	1.19	0.51
	CZ16-2-1-15	557587	720.28	829.03	0.39	1.41	0.61
	CZ16-3-1-64	456922.2	768.33	777.5	0.34	1.54	0.66
	SIMBO	237866.7	268.33	505.83	0.58	0.98	0.42
	MoussaX693-2 F7 Gbr	539916.7	250.83	745.42	0.71	0.67	0.29
	IT13K-12 1-5	380527.8	765	725.83	0.31	1.61	0.69
	Kirkhouse Benga	444763	600.56	731.39	0.42	1.36	0.58
	L1-160	402459.3	545.56	690.56	0.43	1.32	0.57
	KOROBALLEN	425700	527.5	703.75	0.45	1.27	0.55
	MAOUDO	513608.3	600.83	777.08	0.44	1.3	0.56
	CZ16-6-56	501569.4	340	728.33	0.62	0.88	0.38
	CZ16-3-2-37	383548.2	543.89	676.39	0.43	1.34	0.57

Table 5. Contd.

	KVX78 -6 PLANT-1	310764.2	646.67	644.44	0.33	1.56	0.67
	KVX775-33-2 X693-2 /BC4F12-P6-1 Fkb	339911.1	455	625.83	0.47	1.24	0.53
	CZ16-1-1-91	358105.6	249.17	611.25	0.66	0.79	0.34
	KVX 396-4-5-2DX693-2/F16	141737	433.06	434.31	0.33	1.55	0.67
	IT15K-2386-1	261577.8	393.89	548.06	0.47	1.23	0.53
Susceptible	TILIGRE PLANT-6	230287	261.39	497.36	0.58	0.97	0.42
	L1-126-1	209552.8	387.5	497.08	0.44	1.31	0.56
	JIGUIFA	316088.9	137.22	566.39	0.78	0.5	0.22
	FAKSON	244005.6	118.33	497.5	0.79	0.5	0.21

GMP: geometric mean of production; MP: mean of production; TOL: tolerant index; DSI: Drought Stress Sensitivity Index; STI: susceptible-tolerant index; SSI: susceptible stress index.

condition and less well in the stressed condition in terms of grain and pod yield.

Tolerance indices of genotype for grain yields under no water and water stress conditions

The tolerance indices of genotypes under no water stress and water stress conditions are shown in Table 5. It is divided into four groups (highly tolerant, tolerant, sensitive, and highly sensitive) according to the values of geometric mean production (GMP), mean production (MP), and stress tolerance index (STI). Genotypes CZ16-2-2-8, CZ16-4-2-3, KVX61-1, WASSA SHO, WILIBALI, KT1-44-8, CZ16-3-2-48, CZ16-2-2-23, CZ16-3-2-21, ACAR 1 and TOURE SHO including the tolerant check (KVX61-1) showed tolerance. The genotypes MoussaX693-2 F7 Gbr, L1-160, CZ16-6-56, CZ16-3-2-37, CZ16-1-1-91, TILIGRE PLANT-6, and JIGUIFA were susceptible. The genotypes in the sensitive group had low drought

stress indices (DSI) values.

PCA on variables and genotypes for the tolerant index under watered and stressed conditions

The results of the PCA on the combined mean of the variables in the two conditions and genotypes are shown in Figure 3. The two main axes (PC1 and PC2) explained 99.3% of the total variability among the cowpea genotypes studied. Based on this analysis, four homogeneous groups of genotypes were identified. Group 1 is made up of ACAR1, TOURESHO, CZ16-3-2-48, CZ16-3-2-21, and CZ16-3-1-92. It is characterized by a high STI and a low stress index (DSI). Group 2 includes sensitive genotypes such as CZ16-1-1-91, CZ16-6-56, MoussaX693-2F7Gbr, IT13K-1424-12, and SIMBO. Low GMP, TOL, and MP values characterize it. Group 3 includes tolerant genotypes such as WILIBALI, WASSASHO,

CZ16-4-2-3, KVX61-1, and CZ16-2-2-23. High GMP, MP, and TOL values define this group. Group 4 includes sensitive genotypes comprised of Kirkhouse Benga, CZ16-3-2-37, L1-160, KOROBALEN, and MAOUDO, which are characterized by high Stress Sensitivity Index (SSI) and DSI values.

DISCUSSION

Cowpea production is frequently subjected to drought, which compromises negatively its yield potential. However, little is known about the response and adaptation of cowpea genotypes to drought at the vegetative stage in semi-arid regions of Africa (Santos et al., 2020; Yahaya et al., 2023), particularly in Mali. The results of this recent study showed significant variability between genotypes for grain, pod, biomass yield, 100 g weight, chlorophyll, and flowering under water and no water stress conditions (Table 3). This

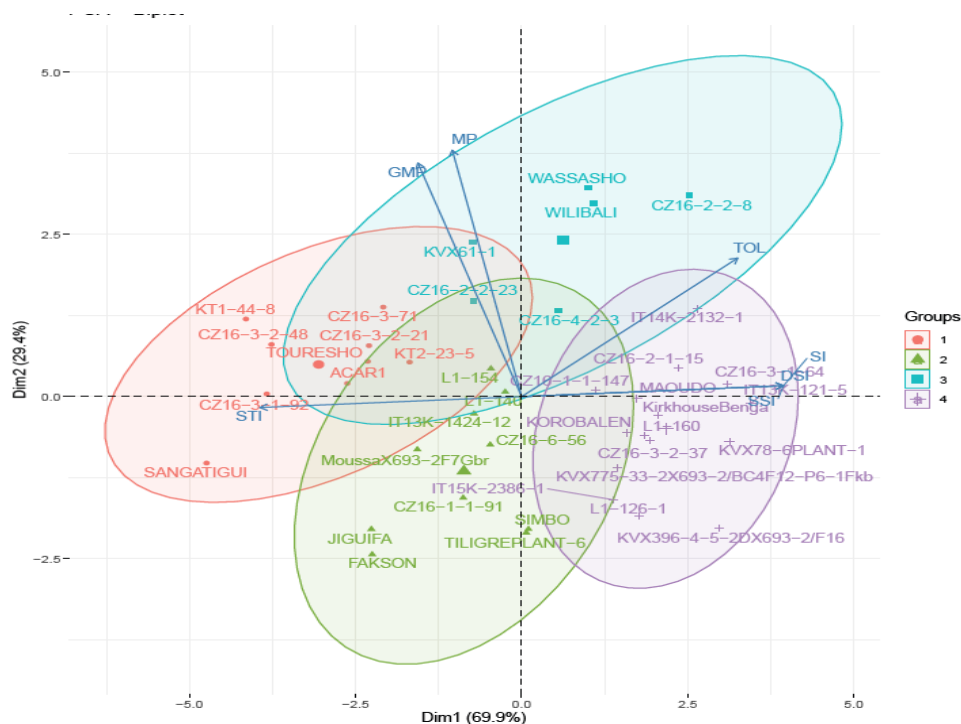


Figure 3. PCA on the combined average (stress and non-stress) of tolerance indices and genotypes.

variability could be explained by inherent differences in the genetic background of the genotypes used in the study environments. Researchers (Derese et al., 2018; Yahaya et al., 2023) found that varied genotype responses to different water regimes would be due to the differential expression of phenotypes. Yield components are generally good indicators of water stress. Thus, yield components under this study showed a significant reduction in pod and 100 g weights under water stress and no water stress. The reduction in pod weight may be due to poor grain filling, resulting in reduced pod weight after water. The findings of Abayomi and Abidoye (2009) and Hayatu et al. (2014) confirmed this result by indicating that reduced soil moisture would cause a decrease in pod weight under a water-stressed regime in cowpea.

Genotypes showed a yield reduction. Average grain yield was 1235.07 kg/ha under no water stress compared to 548.49 kg/ha under water stress conditions, a drop of 45% (Table 4). Genotype averages ranged from 2113.29 to 722.08 kg/ha in NWS conditions and from 969.63 to 196.50 kg/ha in WS conditions (Table 4). Darkwa et al. (2016) and Muñoz-Perea et al. (2007) have indicated that yield decline is caused by the reduction and poor distribution of carbon assimilates after vegetative water stress. In addition, Daouda et al. (2017) demonstrated in

their studies that tolerant genotypes are those that produce high grain yield with a strong capacity to photosynthesize and better carbohydrate remobilization during drought episodes. Similar results were reported in Batieno et al. (2016) and Deffo et al. (2024), who claimed a grain yield reduction of over 45% after vegetative water stress in cowpea.

PCA-biplot of agronomic and physiological parameters yielded homogeneous groups of cowpea genotypes in unstressed and stressed conditions. Under normal conditions, Group 5 genotypes (CZ16-3-2-37, CZ16-3-71, CZ16-3-2-21, CZ16-3-2-48, and WILIBALI) recorded the highest pod and grain yields; they are early and medium-maturing. In contrast, under stressed conditions, Group 2 genotypes made up of CZ16-6-56, CZ16-4-2-3, WILIBALI, KT1-44-8, and KVVX75-33-2X693-2/BC4F12-P6-1Fkb recorded higher grain yield and LAI. The WILIBALI genotype performed better in both environments in terms of grain yield. This result clearly demonstrates the adaptation of this genotype in both stressed and unstressed environments. According to Sinclair et al. (2018) and Gano et al. (2021), agro-physiological performance is a function of genotype, drought severity, and application period. Vegetative water stress affects different varieties and stages of development in different ways. Thus, selecting a genotype

capable of tolerating stress at the vegetative stage with minimal disruption to its physiology and growth results in higher yields than a sensitive genotype (Narayana et al., 2024).

GMP, MP, TOL, and STI indices, PCA-biplot, and correlation data revealed a positive and significant relationship among these indices under stressed and unstressed conditions. Doumbia et al. (2022) and Deffo et al. (2024) have indicated the usefulness of these indices as tools for the selection of drought-tolerant high-yielding genotypes. Our results showed the existence of four homogeneous groups: highly tolerant, tolerant, susceptible, and highly susceptible. The best genotypes in groups 1 and 3, comprising WILIBALI, WASSA SHO, CZ16-4-2-3, K VX61-1, CZ16-2-2-23, ACAR 1, TOURE SHO, CZ16-3-2-21, CZ16-3-2-48, and CZ16-3-1-92, are characterized by the highest GMP, MP, and STI index values, and they are early, medium, and late maturity. The genotypes in this group would have high stability in terms of grain yield under both water regimes. The same parameters enabled Ali and El-Sadek (2016) in their research work to select drought-tolerant varieties. Other studies carried out on cowpea (PEJIĆ et al., 2013), maize (Shojaei et al., 2022), sorghum, and rice (Hussain et al., 2021) have made it possible to discriminate tolerant genotypes in terms of drought tolerance indices. According to Fernandez (1992), sensitive genotypes are those that recorded low grain yields under normal and stressed regimes with low SSI and DSI index values. This study's results showed that groups 2 and 4 were made up of susceptible genotypes. They include early (Kirkhouse Benga, MAOUDO, CZ16-3-2-37, and SIMBO), medium (L1-160, KOROBALEN, CZ16-1-1-91, CZ16-6-56, MoussaX693-2F7Gbr, and IT13K-1424-12), and late maturity. These genotypes recorded reduced SSI and DSI values and are considered drought-susceptible genotypes with low grain yields. Darkwa et al. (2016) obtained similar results. These authors have identified sensitive genotypes in terms of drought tolerance indices (SSI and DSI) based on grain yield in *Phaseolus vulgaris*.

Conclusion

This study of cowpea under drought conditions in Mali showed significant variability between the genotypes. The imposition of stress caused a reduction in grain and pod yields, in 100 g weight, and chlorophyll. The performance genotypes during water stress are early, medium, and one late maturity. The WILIBALI genotype produced the best grain yield in both no water and water stress conditions. In addition, WILIBALI genotype (K VX61-1, ACAR 1, WILIBALI, WASSA SHO, CZ16-4-2-3, CZ16-2-2-23, TOURE SHO, CZ16-3-2-48, CZ16-3-1-92, and CZ16-3-2-21) also recorded the best grain yields under

contrasting moisture conditions. These genotypes also obtained high stress index values, such as GMP, MP, and tolerant stress index. These results are a potential guide to disseminate these genotypes to growers to mitigate the impacts of drought on cowpea production and to be used in varietal improvement programs in Mali.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

ACKNOWLEDGEMENT

The authors thank the Institut d'Economie Rurale (IER) for the availability of the different cowpea genotypes and the facilities to conduct this study. This research was funded by UE-APSAN Mali.

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