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RESEARCH PAPER

Evaluation of cowpea varieties and hybrids tolerance to water deficit during vegetative and reproductive phases

Thibaut A. W. Tossou[1], Fatimata Bachabi[2], Ifagbémi Bienvenue Chabi[3], Vincent Ezin[1], Adam Ahanchede[1]

1 *Department of Crop Production, Faculty of Agricultural Sciences, University of Abomey-Calavi, 01 BP 526 Cotonou, Benin*
2 *AfricaRice Germplasm Health Unit, 01 BP 2551 Bouake, Cote d'Ivoire*
3 *Laboratory of Human Nutrition and Valorization of Food Bio-Ingredients, Faculty of Agricultural Sciences, University of Abomey-Calavi, 03 BP 2819, Jericho Cotonou, Benin*

Corresponding author: Vincent Ezin (ishola.vincent@yahoo.com)

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Abstract

Cowpea (*Vigna unguiculata* L. Walp) is one of Benin's most cultivated and consumed grain legumes. However, drought remains one of the main causes of its decline in yield. The aim of this work was to identify superior cowpea genotypes tolerant to water deficit. Twenty-six (N = 26) genotypes (varieties and hybrids) were subjected to two water regime conditions (well-watered and stressed) in a greenhouse at the International Institute of Tropical Agriculture (IITA), Benin) during the 2021 dry season. The experiment was laid out in a split plot with 3 replicates. The results showed that proline content, chlorophyll content, number of pods per plant, number of seeds per pod, hundred-seed weight and seed yield were all significantly ($P < 0.001$) reduced under the effect of water deficit. However, the genotypes KVX396-18, Kpodjiguèguè x KVX 396-18, IT97K-206-1-1, IT99K573-1-1, IT07K-211-1-8 x IT97K-206-1-1, and F2_Kpodjiguèguè x Tawa provided the highest values under water deficit compared to unstressed plants which served as controls. These genotypes were the best water deficit tolerant and high-yielding genotypes. Low values were recorded for F2_ genotypes KVX61-1 x Tawa, IT07K-211-1-8 x Tawa, KVX61-1, IT07K-211-1-8 x IT99K-573-1-1, F2_IT07K-211-1-8 x IT99K-573-1-1, F2_IT06K242-3 x IT97K-206-1-1, KVX61-1 x Tawa, which are considered in this case as drought-sensitive and low-yielding genotypes. A correlation between plant height, leaf width, pod maturity days, pod length, number of pods per plant, and hundred seed weight and yield were observed. Number of pods per plant (NPP), grain yield per plant (GYP), hundred seed weight (100WS), pod length (PL), number of days to pod maturity (NDPM), number of seeds per pod (NSP), and number of leaves per plant (NLP) can therefore be exploited in cowpea breeding programs to improve yield and drought tolerance in susceptible and low-yielding genotypes.

Keywords

Abiotic stress, Drought effects, Genotypes, Heat stress, Performance, Resilience, Resistance, *Vigna unguiculata*

Introduction

In tropical and subtropical regions of Africa, Asia, Europe, and America, cowpea (*Vigna unguiculata* L. Walp) remains one of the main cultivated and consumed legumes (Taffouo et al. 2008; Gbaguidi et al. 2015). It is cultivated on over 11.8 million hectares annually, with 10.7 million hectares in West Africa alone, which is the world's largest production and consumption region (Ouali-N'goran et al. 2014; Gerrano et al. 2022). The annual global production of cowpea is estimated to be between 3 and 5.5 million tonnes of dry seeds (FAO STAT 2022). Cowpea's deep root system and ability to maintain leaf turgidity allow it to resist water deficit stress. (Singh and Matsui 2002).

However, there is a significant variation among genotypes in drought adaptation (Ezin et al. 2021; Nkomo et al. 2021; Nunes et al. 2022) despite its ability to resist drought more than any other legume grown in tropical regions (Hall 2004; Dadson et al. 2005). Water deficit is the major constraint in cowpea production, reducing its grain yield by up to 88% (Harou et al. 2018). Plants are more prone to damage due to limited water during the flowering and pod formation phases (Bahar et al. 2010). Due to low rainfall and hot temperature conditions, the Sahelian region of Africa is extremely drought-prone (Hall 2004; Sansan et al. 2024). Erratic rainfall exposes cowpea to drought at the end of rainy seasons despite the inherent ability of cowpea to resist water deficit (Singh and Mutsui 2002). When water deficit sets in during the vegetative stage, cowpea can produce 1000 kg/ha but it reduces the yield to around 350 kg/ha during the reproductive phase (Bastos et al. 2011).

It is important to improve or identify cowpea varieties that can withstand water scarcity (Batieno et al. 2016; Esan et al. 2021). The selection of cowpea parental lines is likely to tolerate stress due to water deficit then becomes a crucial factor in improving the ability of cowpea adaptation or tolerance to drought (Ngalamu 2018). In Benin, cowpea is generally grown for their edible seeds (Gbaguidi et al. 2013) and for their young leaves, but also used as fodder (Zannou et al. 2004). This crop occupies 7% of the plots dedicated to annual crops, producing 11,224 tons (Abadassi 2014). Unfortunately, as in the rest of the world, its production is constrained by severe biotic and abiotic factors (Niba 2011; Houinsou et al. 2014). Indeed, Benin has a wide range of local cowpea varieties, among which many are susceptible to biotic and abiotic stresses and therefore could be improved upon for food security (Zannou et al. 2004; Kuldau and Bacon 2008). Thus, varietal improvement and hybridization programs must know the diversity of traditional varieties and proceed to their evaluation (Hegde et al. 2009; Doumbia et al. 2013). It is also essential to understand the adaptation mechanisms of tolerant genotypes for improving cowpea yield under water deficit conditions (Halime et al. 2014). This work aims to identify drought-tolerant cowpea hybrids with high yields. The specific objectives are to (1) evaluate the effect of water deficit at the vegetative stage; (2) assess the effect of water deficit at the reproductive stage, and (3) identify drought-tolerant hybrids.

Materials and methods

The trial was conducted in the southern region of Benin from June 26, 2021 to January 25, 2022 in the municipality of Abomey-Calavi at the International Institute of Tropical Agriculture (IITA) (6°25'3"N, 2°19'46"E). The evaluation for drought tolerance of the cowpea varieties and hybrids was carried out under a controlled environment and varied temperature conditions (Fig. 1).

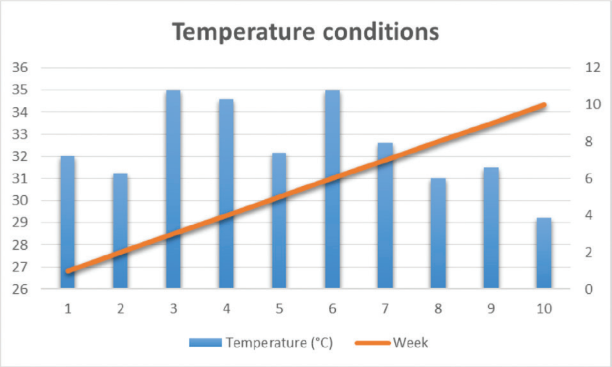

Figure 1. Average temperatures recorded in the greenhouse during the experiment.

Plant material

Twenty-six (26) cowpea genotypes were used during the screening study including eight (08) varieties, twelve (12) hybrids (F1), and six (06) hybrids (F2) (Table 1). Previously, Ezin et al. (2021) succeeded after a drought tolerance screening of 20 genotypes during the major dry season in 2019 at IITA to identify tolerant and sensitive genotypes. For this study, we chose 8 varieties among the 20 including 4 drought resistant considered as male parents and 4 susceptible varieties designated as female parents. From June 26, 2021, to August 18, 2021, we hybridized these cowpea varieties using a half diallel (4 × 4) crossing device with 2

Table 1. Twenty-six (26) cowpea genotypes used for the experiment.

Types	Descriptors	Genotypes	Response
Parents	P1	KVX 61-1	Tolerant
	P2	IT06K242-3	Tolerant
	P3	IT07K-211-1-8	Tolerant
	P4	Kpodjiguèguè	Tolerant
	P5	IT99K-573-1-1	Sensitive
	P6	Tawa	Sensitive
	P7	KVX 396-18	Sensitive
	P8	IT97K-206-1-1	Sensitive
F1 Hybrids	H7	Kpodjiguèguè x Tawa	-
	H4	IT07K-211-1-8 x IT99K-573-1-1	-
	H8	Kpodjiguèguè x KVX 396-18	-
	H6	IT07K-211-1-8 x IT97K-206-1-1	-
	H1	IT06K242-3 x Tawa	-
	H10	KVX 61-1 x Tawa	-
	H2	IT06K242-3 x KVX 61-1	-
	H9	Kpodjiguèguè x IT97K-206-1-1	
	H12	KVX 61-1 x IT97K-206-1-1	
	H3	IT06K242-3 x IT97K-206-1-1	
	H5	IT07K-211-1-8 x Tawa	
	H11	KVX 61-1 x KVX 396-18	
F2 Hybrids	H3_F2	IT06K242-3 x IT97K-206-1-1	-
	H11_F2	KVX 61-1 x KVX 396-18	-
	H8_F2	Kpodjiguèguè x KVX 396-18	-
	H7_F2	Kpodjiguèguè x Tawa	-
	H4_F2	IT07K-211-1-8 x IT99K-573-1-1	
	H3_F2	IT06K242-3 x IT97K-206-1-1	

repetitions to obtain 28F1 among which twelve (12) hybrids (F1) were selected for drought evaluation. Six (6) F1 hybrids were then selfed to obtain 6 F2 hybrids. In addition to these hybrids (F1 and F2), 8 parents were also used for the evaluation. For this study, a total of twenty-six (26) cowpea genotypes were used and subjected to water deficit conditions.

Methodology

Treatments and experimental design

The study was conducted in a greenhouse (controlled environment) at the International Institute of Tropical Agriculture (IITA) in Benin. Previously, the 26 cowpea genotypes were sown in pots under natural conditions of light, temperature, and humidity to allow good emergence and good germination of the seeds before bringing them back to the greenhouse fourteen (14) days after sowing. Pots of 16 liters and 90 cm in diameter with holes at the base were used to cultivate the plants. Each pot was filled with 20 kg of soil taken from a depth of 20 cm in the field of the station. It is then mixed with COGA 80 WP fungicide (Mancozeb) at the proportion of 800 g/kg of soil. Sowing was carried out at the rate of 2 seeds per pot followed by thinning of a plant on the 23rd day after sowing (DAS) and the irrigation was applied daily.

In the greenhouse, the experimental design was laid out in a split-plot type with 3 repetitions. The treatments consisted of two factors; the genotype at 26 levels of treatment and the water regime at three levels of treatment (R0, R1 and R2), with:

- Regime 0: Normal watering of plants until harvest. The plants are used in this case as a control.
- Regime 1: imposition of drought for 20-day duration at 23 DAS where irrigation was stopped for 20 days from November 20, 2021 to December 9, 2021 (period of the vegetative phase). The plants were then normally irrigated for 3 days to allow them to enter into flowering.
- Regime 2: A second stress of 20 days was imposed, 46 DAS, from December 13, 2021 to January 01, 2022 (period of the reproductive phase). The plants were then watered normally until harvest.

The experimental design was of the split-plot type with 3 repetitions with the water regime as the main factor in the main block and the genotype as sub-factor in the sub-block. Each block was composed of 52 pots. The spacing was of 0.6 m and 1 m between two consecutive pots and repetitions respectively.

Measurements

A total of 15 variables were collected after plant stress for evaluation of drought tolerance of the 26 genotypes, as described in Table 2.

Table 2. Fifteen (15) variables used to categorize the drought tolerance of the 26 cowpea genotypes.

Variables	Description
NPP	Number of pods per plant
GYP	Grain yield per plant
NLP	Number of leaves per plant
100WS	Hundred seed weight
NDF	Number of days to flowering
NSP	Number of seeds per pod
PL	Pod length
Ll	Leaf length
LW	Leaf width
PH	Plant heigth
NDPM	Number of days to pod maturity
LCC	Leaf chlorophyll content
LPC	Leaf proline content
Fv_Fm	Photosynthetic yield
Fv_Fo	Photosynthetic efficiency

Data for the quantitative traits in the table above were recorded (IBPGR 1983).

i. Number of pods per plant (NPP): was recorded as the average of mature pods of a plant.
ii. Yield (GYP): Grain yield per pot (g).
iii. Hundred Seed Weight (g) (100SW): Determined by randomly counting 100 seeds from a plant and weighing using a precision digital scale.
iv. Number of Days to Flower (NDF): Recorded as the number of days from sowing to the stage when the plants had open flowers.
v. Seeds per pod (NSP): was recorded as an average seed count of 10 pods, vi. Pod Length (cm) (PL): Calculated as the average of 10 randomly selected fully mature pods.
vi. Leaf length cm (Ll): it was measured using a metric ruler at the flag leaf.
vii. Leaf width cm (LW): it was measured using a metric ruler at the level of the standard leaf.
viii. Plant height (PH): was measured using a metric ruler from ground level at the base to the tip of the plant meristem expressed in cm.
ix. Number of leaves per plant (NLP): total number of leaves present on the plant.
x. Number of days of pod maturity (NDPM): recorded when a pod has reached physiological maturity.
xi. Fv/Fm = (FM-FO) / FM: measured the maximum quantum efficiency using an Os30p+ chlorophyll fluorometer.
xii. FV/FO =(FM-FO) / FO: is a more sensitive plant stress detector for stressed plant that disturb PSII. It was measured using an Os30p+ chlorophyll fluorometer.
xiii. A portable chlorophyll meter (Minolta SPAD-502, Soil Plant Analysis Development, Minolta Co., Osaka, Japan) was used to determine chlorophyll content of the cowpea plants at 30, 45, and 60 DAP.
xiv. Leaf proline content (LPC): a proline assay protocol of Ezin et al. (2023) was used for the determination of proline content of the plants.

Statistical analysis

Statistical analysis was performed with RStudio Version 1.3.1093. Analysis of variance (ANOVA) was carried out to test the significance between studied variables. The separation of the means was carried out with the LSD test (test of the least significant difference) at 5% threshold. Factoextra and factomineR packages were used to perform the principal component analysis (PCA) and the ascending hierarchical classification (HAC) for grouping similar genotypes in the same class. Pearson correlation matrix was carried out using the corrgram, corrplot, and Hmisc packages to observe the existing link associations between the different studied variables.

Results

We experienced unprecedented heat stress coupled with the drought stress during the experiment as you can see in the graph of average temperature (Fig. 1). The plants under water deficit stress and unstressed plants were affected by heat stress.

Analysis of physiological traits

Under water deficit conditions, photosynthetic yield (Fm_Fv), photosynthetic efficiency (Fv_Fo), Leaf chlorophyll content (LCC), and Leaf proline content (LPC) were significantly different among studied parameters (Table 3). However, high values in photosynthetic yield compared to controls were recorded with the genotypes KVX 61-1 x Tawa (H10), IT07K-211-1-8 x Tawa (H5), IT07K-211-1-8 x IT97K-206-1-1 (H6), F2_Kpodjiguèguè x Tawa (H7_F2), Tawa (P6) and KVX396-18 (P7) (0.753; 0.547; 0.783; 0.789; 0.642; 0.762 respectively). The low values were observed in KVX61-1 x KVX396-18 (H11), F2_ KVX61-1 x KVX396-18 (H11_F2) and IT07K-211-1-8 (P3). Photosynthetic efficiency is a parameter directly correlated with photosynthetic yield, so the highest values remain for the same genotypes. Chlorophyll content significantly reduced in stressed plants. Nevertheless, genotypes IT07K-211-1-8 x Tawa (H5), IT07K-211-1-8 x IT97K-206-1-1 (H6), F2_ Kpodjiguegue x Tawa (H7_F2), IT06K242-3 (P2) and KVX396-18 (P7) compared to the controls, were unaffected by water deficit, with significantly higher average values of 31.95; 45.23; 48.66; 44.93 and 44.98 respectively. Water deficit significantly reduced proline content in all

Table 3. Average of physiological parameters under water deficit stress.

Genotypes	R0	R1	R0	R1	R0	R1	R0	R1
	Fm_Fv		Fv_Fo		LCC		LPC	
H1	0.76^{b}	0.50ab	3.26ab	2.10abc	52.26^{a}	40.58ab	130.99abcd	48.22abcd
H10	0.50^{b}	0.75a	2.04abcde	3.10ab	37.51abc	41.31ab	118.88abcd	24.36bcd
H10_F2	0.50^{b}	0.49ab	2.12abcde	1.94abc	35.45abc	33.36ab	62.05bcd	8.41cd
H11	0.24^{b}	0.26^{b}	0.95de	1.22bc	13.03cd	17.63ab	0.00cd	28.83bcd
H11_F2	0.51^{b}	0.00^{a}	2.31abcd	0.00^{c}	40.68abc	0.00^{b}	169.64^{ab}	4.42^{d}
H12	0.00^{b}	0.51ab	0.00^{e}	2.23abc	0.00^{d}	33.30ab	0.00^{d}	34.50bcd
H2	0.74^{b}	0.50ab	2.98abcd	2.13abc	48.28ab	32.61ab	139.21abc	12.77bcd
H3	2.42^{a}	0.52ab	3.12abcd	2.67abc	46.96abc	36.76ab	18.00cd	53.00abcd
H3_F2	0.75^{b}	0.49ab	3.33ab	2.21abc	60.83^{a}	34.66ab	240.97^{a}	18.48bcd
H4	0.765^{b}	0.39ab	3.16abc	1.85abc	45.51abc	39.55ab	32.30cd	17.53bcd
H4_F2	0.50^{b}	0.51ab	2.18abcde	2.31abc	31.95abcd	31.75ab	50.54bcd	20.25bcd
H5	0.25^{b}	0.54ab	1.00cde	2.12abc	15.50bcd	31.95ab	7.44^{d}	0.00^{d}
H6	0.50^{b}	0.78ab	2.10abcde	3.69ab	28.60abcd	45.23^{a}	47.59bcd	68.88abcd
H7	0.74^{b}	0.51ab	3.02abcd	2.67abc	48.60ab	28.00ab	64.11bcd	64.07abcd
H7_F2	0.51^{b}	0.78^{a}	2.26abcd	4.08^{a}	27.20abcd	48.66^{a}	120.65abcd	77.04abcd
H8	0.75^{b}	0.75^{a}	3.20abc	3.19ab	61.25^{a}	39.15ab	67.72bcd	69.95abcd
H8_F2	0.76^{b}	0.52ab	3.22ab	2.55abc	54.45^{a}	32.31ab	70.33bcd	36.99bcd
H9	0.26^{b}	0.52ab	1.16bcde	2.43abc	16.55bcd	33.48ab	27.55cd	92.38abc
P1	0.78^{b}	0.75^{a}	3.76^{a}	3.25ab	58.50^{a}	51.95^{a}	116.02abcd	93.49abc
P2	0.51^{b}	0.51ab	2.53abcd	2.18abc	32.65abcd	44.93^{a}	74.15bcd	45.31bcd
P3	0.47^{b}	0.25ab	1.78abcde	1.14bc	31.13abcd	13.45ab	31.75cd	62.92abcd
P4	0.74^{b}	0.71^{a}	3.07abcd	2.77ab	46.31abc	43.68^{a}	56.24bcd	79.92abcd
P5	0.25^{b}	0.49ab	1.13bcde	2.03abc	14.70bcd	27.56ab	76.26bcd	77.49abcd
P6	0.75^{b}	0.64^{a}	3.18abc	2.86ab	45.15abc	44.98^{a}	61.84bcd	69.19abcd
P7	0.25^{b}	0.76^{a}	1.13bcde	3.24ab	13.98cd	41.61^{a}	49.93bcd	132.56^{a}
P8	0.76^{b}	0.77^{a}	3.12abcd	3.45ab	51.46^{a}	51.30^{a}	69.39bcd	93.87ab
P value	0.015	0.05	0.093	0.042	0.0218	0.017	0.013	0.026
Sig	*	*	ns	*	*	*	*	*
Sig	1.03	0.58	2.21	2.73	34.14	41.49	131.10	85.25

Sig: significance, *: significant ($p < 0.05$), ns: not significant, LSD: Least Significant Difference, R0: unstressed, R1: stressed Fv_Fm: photosynthetic yield, Fv_Fo: photosynthetic efficiency, LCC: leaf chlorophyll content, LPC: leaf proline content.

the genotypes except IT06K242-3 x IT97K-206-1-1 (H3), IT07K-211-1-8 x IT97K-206-1-1 (H6), Kpodjiguègué x IT97K-206-1-1 (H9), IT07K-211-1-8 (P3), Kpodjiguègué (P4), KVX396-18 (P7) and IT97K206-1-1(P8). The lowest levels were observed in F2_KVX-61-1 x Tawa (H10_F2) and F2_KVX61-1 x KVX396-18-1-1 (H11_F2) (8.41 and 4.42 respectively) (Table 3).

Analysis of agronomic variables

There was a significant difference ($P < 0.05$) between the water regimes imposed during the experiment for all the agronomic parameters (Tables 4, 5). Table 4 shows that stressed plants flowered faster than unstressed ones. However, genotypes F2_KVX-61-1 x Tawa (H10_F2), F2_IT07K-211-1-8 x IT99K-573-1-1 (H4_F2), IT07K-211-1-8 x Tawa (H5), IT07K-211-1-8 x IT97K-206-1-1 (H6), F2_Kpodjiguègué x Tawa (H7_F2) and KVX396-18 (P7) were late flowering compared to their controls, with an average number of days to flowering respectively of 37.33; 28; 30.33; 37; 37 and 54.33 days. Shorter days to flowering were observed with the genotypes IT06K242-3 x Tawa (H1), F2_KVX61-1 x KVX396-18 (H11_F2), and IT07K-211-1-8 (P3) (23.33; 18. 33 and 17.66 days respectively). Genotypes F2_KVX-61-1 x Tawa (H10_F2), F2_IT99K-573-1-1 (H4_F2), IT07K-211-1-8 x Tawa (H5), IT07K-211-1-8 x IT97K-206-1-1 (H6), F2_Kpodjiguegue x Tawa (H7_F2), Kpodjiguègué x IT97K-206-1-1 (H9) and IT06K242-3 (P2) recorded the highest average values for the 100-seed weight parameter (100WS) compared to controls. The poorest performances were observed from the genotypes (H10), F2_Kpodjiguègué x KVX396-18 (H8_F2), IT07K-211-1-8 (P3) and Kpodjiguègué (P4). Water deficits significantly reduced yield (GYP of cowpea studied genotypes. However, comparatively to controls, the genotypes F2_IT07K-211-1-8 x IT99K-573-1-1 (H4_F2), IT07K-211-1-8 x Tawa (H5), IT07K-211-1-8 x IT97K-206-1-1 (H6), F2_Kpodjiguegue x Tawa (H7_F2) and IT06K242-3 (P2) showed the best performances in water deficit conditions. The lowest values were recorded from IT06K242-3 x Tawa (H1), KVX61-1 x Tawa (H10), Kpodjiguègué x Tawa (H7) and IT07K-211-1-8 (P3). The effect of the water deficit shortened the number of days to pod maturity (NDPM), i.e. under water deficit, stressed plants accelerated their growth and reproductive phase. Plants were significantly early maturing in stressed conditions, except F2_KVX-61-

Table 4. Average of agronomic parameters under water deficit stress.

Genotypes	R0	R1	R0	R1	R0	R1	R0	R1
	NDF (days)		100WS(g)		NDPM (days)		GYP (g/plant)	
H1	35.00abcdef	23.33abc	506.33^{a}	10.99abcd	50.66^{abcd}	34.66ab	6.84^{abc}	3.26ab
H10	49.33abc	27.66abc	7.83^{b}	4.65bcd	36.33^{abcde}	37.00ab	5.74abcde	2.56ab
H10_F2	29.00abcdef	37.33bc	10.57^{b}	17.41ab	37.33abcde	51.33^{a}	5.68abcde	4.42^{a}
H11	28.00abcdef	25.33abc	7.06^{b}	9.93abcd	36.00abcde	34.00ab	0.24de	1.02ab
H11_F2	22.33bcdef	18.33bc	4.06^{b}	4.86bcd	26.00abcde	23.66ab	2.24cde	0.00^{b}
H12	33.00abcdef	0.00^{c}	10.87^{b}	0.00abcd	41.33abcde	0.00^{b}	0.00^{e}	2.29ab
H2	47.33abcde	26.00abc	13.89^{b}	7.62^{d}	60.00abc	15.00ab	4.38bcde	1.96ab
H3	35.66abcd	25.33abc	15.14^{b}	11.16abcd	51.66abcd	33.00ab	6.41abcd	2.01ab
H3_F2	48.66abc	30.33abc	16.02^{b}	10.36abcd	61.00abc	39.00ab	9.44ab	3.26ab
H4	50.00^{ab}	28.66abc	15.16^{b}	10.52abcd	61.66ab	38.00ab	3.89bcde	2.48ab
H4_F2	13.00def	28.00abc	4.78^{b}	13.98abc	17.00cde	36.66ab	2.05cde	4.29ab
H5	14.33cdef	30.33abc	3.52^{b}	8.97abcd	20.66abcde	38.33ab	0.60cde	2.10ab
H6	22.66bcdef	37.00ab	7.22^{b}	19.38^{a}	15.33de	50.33^{a}	4.18bcde	4.51^{a}
H7	41.33abcde	25.00abc	13.98^{b}	7.85abcd	53.33abcd	34.33ab	6.42abcd	1.94ab
H7_F2	29.66abcdef	37.00ab	5.95^{b}	11.32abcd	37.66abcde	49.00^{q}	1.80cde	4.26ab
H8	46.66abcd	43.00ab	11.94^{b}	10.88abcd	62.00ab	59.00^{a}	5.53abcde	1.41ab
H8_F2	41.66abcde	30.00abc	4.50^{b}	3.68cd	25.33abcde	40.33ab	1.29cde	0.93ab
H9	11.00^{ef}	26.33abc	4.22^{b}	12.30abcd	17.66bcde	32.66ab	2.40cde	1.83ab
P1	14.33^{abcde}	35.66^{ab}	3.49^{b}	9.76^{abcd}	52.66^{abcd}	48.33^{a}	0.56^{a}	2.96^{ab}
P2	20.66bcdef	25.00abc	4.79^{b}	12.48abcd	0.00^{e}	33.33ab	0.93cde	2.65ab
P3	26.66abcdef	17.66bc	11.05^{b}	3.15cd	41.33abcde	23.00ab	1.28cde	0.28ab
P4	60.00^{a}	54.66^{a}	9.56^{b}	3.15cd	42.00abcde	19.00ab	1.04cde	1.55ab
P5	39.66cdef	42.66ab	22.99^{b}	18.90abcd	18.66bcde	57.33^{a}	11.09cde	3.07ab
P6	0.00^{f}	25.00abc	0.00^{b}	12.91abcd	0.00^{e}	33.33ab	4.42bcde	0.90ab
P7	16.66bcdef	54.33^{a}	0.00^{b}	10.11abcd	20.00abcde	46.00ab	0.10de	0.99ab
P8	50.66^{ab}	37.33ab	15.43^{b}	16.58abc	64.33^{a}	50.33^{a}	2.08cde	2.72ab
P value	0.012	0.021	0.04	0.045	0.001	0.020	0.0478	0.860
Sig	**	**	*	*	**	*	*	ns
LSD	35.35	34.728	274.01	13.68	44.44	46.77	6.401	-

Sig: significance, *: significant ($p < 0.05$), ns: not significant, LSD: Least Significant Difference, R0: unstressed, R1: stressed, NDF: number of flowering days, 100WS : hundred seed weight, NDPM: number of days to pod maturity, GYP: seed yield.

Table 5. Average of agronomic parameters under water deficit stress.

Genotypes	R0	R1	R0	R1	R0	R1
	PL		NPP		NSP	
H1	12.12^{abcd}	7.24^{abcd}	7.66^{ab}	4.66^{ab}	6.70^{abc}	3.90^{abc}
H10	8.21^{abcde}	7.39^{abcd}	6.66^{abcd}	2.33^{ab}	5.00^{abcd}	3.33^{abc}
H10_F2	8.90^{abcde}	13.21^{ab}	7.33^{abc}	4.00^{ab}	4.33^{abcd}	6.37^{ab}
H11	8.90^{abcde}	8.63^{abcd}	6.66^{abcd}	4.66^{ab}	6.36^{abc}	4.65^{abc}
H11_F2	3.73^{bcde}	4.13^{bcd}	0.33^{cd}	1.00^{ab}	2.00^{bcd}	3.33^{abc}
H12	8.01^{abcde}	0.00^{d}	2.00^{bcd}	0.00^{b}	4.83^{abcd}	0.00^{c}
H2	11.40^{abcd}	3.75^{bcd}	4.66^{bcd}	2.33^{ab}	6.28^{abc}	1.53^{bc}
H3	10.97^{abcd}	6.65^{abcd}	7.33^{abc}	3.00^{ab}	5.97^{abc}	4.03^{abc}
H3_F2	10.18^{abcd}	6.38^{abcd}	13.33^{a}	4.33^{ab}	5.37^{abcd}	3.85^{abc}
H4	12.17^{abcd}	7.03^{abcd}	4.33^{bcd}	3.00^{ab}	3.56^{abcd}	5.10^{abc}
H4_F2	4.65^{bcde}	7.54^{abcd}	2.00^{bcd}	3.66^{ab}	2.58^{bcd}	3.73^{abc}
H5	2.86^{de}	7.76^{abcd}	1.33^{bcd}	2.66^{ab}	1.50^{bcd}	4.22^{abc}
H6	5.46^{abcde}	13.74^{a}	2.33^{bcd}	4.00^{ab}	2.40^{bcd}	6.50^{ab}
H7	12.62^{abc}	8.41^{abcd}	6.66^{abcd}	3.33^{ab}	6.66^{abc}	4.40^{abc}
H7_F2	8.65^{abcde}	12.33^{abc}	2.33^{bcd}	6.00^{a}	4.93^{abcd}	7.90^{a}
H8	13.28^{ab}	10.62^{abc}	6.33^{abcd}	2.00^{ab}	9.06^{a}	6.33^{ab}
H8_F2	4.55^{bcde}	3.28^{cd}	1.00^{bcd}	1.66^{ab}	3.22^{bcd}	2.22^{bc}
H9	4.15^{bcde}	7.90^{abcd}	3.00^{bcd}	2.00^{ab}	2.53^{bcd}	3.66^{abc}
P1	14.78^{a}	10.03^{abc}	7.33^{abc}	4.33^{ab}	7.15^{ab}	4.40^{abc}
P2	3.15^{cde}	7.29^{abcd}	1.33^{bcd}	3.33^{ab}	1.66^{bcd}	3.56^{abc}
P3	9.17^{abcde}	3.11^{cd}	1.33^{bcd}	0.66^{b}	5.00^{abcd}	1.33^{bc}
P4	9.45^{abcde}	4.00^{bcd}	1.00^{bcd}	3.00^{ab}	5.00^{abcd}	2.73^{abc}
P5	3.02^{cde}	6.67^{abcd}	1.00^{bcd}	4.66^{ab}	1.55^{bcd}	3.06abc
P6	0.00^{e}	7.95^{abcd}	0.00^{d}	2.00^{ab}	0.00^{d}	4.58^{abc}
P7	2.80^{de}	7.71^{abcd}	0.33^{cd}	1.00^{ab}	1.00^{cd}	4.50^{abc}
P8	11.99^{abcd}	13.10^{ab}	4.00^{bcd}	3.66^{ab}	4.46^{abcd}	4.88^{abc}
P value	0.157	0.490	0.0707 .	0.861	0.259	0.804
Sig	ns	ns	ns	ns	ns	ns
LSD	9.67	9.51	7.26	5.04	5.71	5.65

Sig: significance, ns: not significant, LSD: Least Significant Difference, R0: unstressed, R1: stressed PL: pod length, NPP: number of pods per plant, NSP: number of seeds per pod.

1 x Tawa (H10_F2), F2_IT07K-211-1-8 x IT99K-573-1-1 (H4_F2), IT07K-211-1-8 x Tawa (H5), IT07K-211-1-8 x IT97K-206-1-1 (H6), F2_Kpodjiguegue x Tawa (H7_F2), F2_Kpodjiguègué x KVX396-18 (H8_F2), Kpodjiguègué x IT97K-206-1-1 (H9), KVX61-1 (P1) and KVX396-18 (P7). IT07-211-1-8 (P3), Kpodjiguègué (P4), IT06K2423 x Tawa (H1) and KVX61-1 x KVX396-18 (H11) which are the early maturing genotypes (Table 4). Pod length (PL) for stressed plants was significantly reduced by drought (Table 5). Furthermore, F2_KVX-61-1 x Tawa (H10_F2), F2_IT07K-211-1-8 x IT99K-573-1-1 (H4_F2), IT07K-211-1-8 x Tawa (H5), IT07K-211-1-8 x IT97K-206-1-1 (H6), F2_Kpodjiguegue x Tawa (H7_F2), IT06K242-3 (P2), KVX396-18 (P7) and IT97K-206-1-1 (P8) compared to their controls recorded the longest pods (13.21 cm; 7.54 cm; 7.76 cm; 13.74 cm; 12.33 cm; 7.29 cm; 7.71 cm and 13.10 cm, respectively). The number of pods per plant (NPP) were also significantly reduced for stressed plants. The highest mean values were recorded from the genotypes IT07K-211-1-8 x Tawa (H5), IT07K-211-1-8 x IT97K-206-1-1 (H6), F2_Kpodjiguègué x Tawa (H7_F2) , Kpodjiguègué (P4), KVX61-1 (P5). The lowest values were revevealed by Kpodjiguègué x KVX396-18 (H8) and IT07K-211-1-8 (P3) with 2.00 and 0.66 pod per plant, respectively. Genotypes KVX-61-1 x Tawa, IT07K211-1-8 x Tawa, IT07K-211-1-8 x IT97K-206-1-1, F2_Kpodjiguegue x Tawa and KVX396-18 recorded the highest number of seeds per pod (NSP) under water deficit conditions with 6.37; 4.22; 6.50; 7.90; 4.50 respectively (Table 5).

Morphological performances

Significant difference (P < 0.005) between the genotypes was observed for all the morphological characters. collected in all the stressed plants (under R1) with an average of 20.80 cm, 4.55 cm, 6.32 cm and 9.43 cm respectively for the plant height (PH), leaf width (LW), leaf length (Ll), and number of leaves per plant (NLP) (Table 6). Analysis of variance shows that there was a significant difference between all genotypes under water-stressed and unstressed conditions (R1 and R0, respectively). Drought significantly decreased plant height (PH) in all genotypes. Nevertheless, KVX61-1 x Tawa, F2_Kpodjiguègué x Tawa, IT07K-211-1-8 x Tawa, IT99K-573-1-1 and KVX61-1 recorded higher values than their controls. Lowest values were observed in KVX61-1 x KVX396-18, F2_KVX61-1 x KVX39618 and IT06K242-3 x IT97K-206-1-1. F2_IT07K-211-1-8 x IT99K-573-1-1, F2_Kpodjiguègué x Tawa and KVX61-1 show the best values for number of leaves per plant (NLP). Lowest values (3.16) are obtained by genotypes KVX61-1 x KVX396-18, F2_KVX61-1 x

Table 6. Average of some morphological parameters studied under water stress.

Genotypes	R0	R1	R0	R1	R0	R1	R0	R1
	PH (cm)		LW (cm)		Ll (cm)		NLP	
H1	33.66^{abcd}	13.33^{ab}	6.45^{b}	4.76^{abc}	8.15^{abc}	4.65^{abc}	16.50^{abcde}	7.16^{abc}
H10	3.33^{e}	17.66^{ab}	3.51^{b}	6.26^{ab}	5.50^{abcde}	8.46^{ab}	13.83^{abcdef}	10.33^{abc}
H10_F2	18.00^{cde}	10.00^{ab}	4.28^{b}	4.08^{abc}	6.18^{abcde}	5.60^{abc}	15.00^{abcdef}	10.66^{abc}
H11	15.33^{cde}	3.00^{b}	1.20^{b}	1.83^{bc}	1.70^{de}	2.78^{bc}	5.00^{defg}	3.16^{bc}
H11_F2	17.33^{cde}	1.00^{b}	4.11^{b}	0.00^{c}	5.51^{abcde}	0.00^{c}	9.50^{bcdefg}	0.00^{c}
H12	1.00^{e}	18.66^{ab}	0.000^{b}	3.38^{bc}	0.00^{e}	5.41^{abc}	0.00^{g}	10.00^{abc}
H2	49.00^{a}	19.00^{ab}	4.00^{b}	3.15^{bc}	7.50^{abcd}	7.08^{ab}	16.83^{abcde}	7.33abc
H3	36.66^{abcd}	8.33^{ab}	5.91^{b}	4.76^{abc}	8.06^{abc}	5.43^{abc}	12.66^{bcdefg}	9.00^{abc}
H3_F2	34.66^{abcd}	20.00^{ab}	5.50^{b}	4.60^{abc}	8.40^{abc}	6.68^{abc}	18.33^{abc}	9.66^{abc}
H4	36.66^{abcd}	28.66^{ab}	4.53^{b}	3.85^{abc}	7.76^{abcd}	5.01^{abc}	12.16^{bcdefg}	11.83^{abc}
H4_F2	18.00^{cde}	34.00^{a}	4.33^{b}	3.98^{abc}	5.38^{abcde}	5.30^{abc}	7.66^{bcdefg}	9.66^{abc}
H5	2.00^{e}	19.33^{ab}	2.80^{b}	4.06^{abc}	3.10^{bcde}	5.93^{abc}	9.33^{bcdefg}	14.33^{ab}
H6	15.66^{cde}	37.33^{a}	3.61^{b}	6.51^{ab}	6.28^{abcd}	9.55^{ab}	6.16^{cdefg}	9.50^{abc}
H7	21.00^{bcde}	16.66^{ab}	6.81^{b}	4.90^{abc}	9.28^{ab}	6.86^{abc}	15.66^{abcdef}	7.16^{abc}
H7_F2	6.66^{e}	29.66^{ab}	3.55^{b}	7.15^{ab}	6.23^{abcd}	10.18^{a}	9.66^{bcdefg}	13.66^{ab}
H8	14.33^{de}	25.66^{ab}	5.35^{b}	5.01^{abc}	7.98^{abc}	7.38^{ab}	26.50^{a}	11.66^{abc}
H8_F2	44.66^{ab}	17.66^{ab}	4.66^{b}	3.50^{bc}	8.05^{abc}	6.70^{ab}	12.66^{bcdefg}	7.33^{abc}
H9	5.66^{e}	14.00^{ab}	1.85^{b}	3.31^{bc}	2.85^{cde}	6.25^{abc}	6.50^{bcdefg}	7.66^{abc}
P1	23.33^{bcde}	37.33^{a}	6.70^{b}	6.00^{abc}	9.96a	9.11^{ab}	19.33^{ab}	10.83^{abc}
P2	21.66^{bcde}	27.00^{ab}	21.81^{a}	9.76^{a}	4.40^{abcde}	5.16^{abc}	6.33^{bcdefg}	9.16^{abc}
P3	18.33^{cde}	14.66^{ab}	3.63^{b}	2.05^{bc}	6.70^{abcd}	3.56^{abc}	7.66^{bcdefg}	3.16^{bc}
P4	44.00^{ab}	24.00^{ab}	5.33^{b}	5.41^{abc}	8.33^{abc}	7.58ab	13.33^{bcdef}	12.00^{abc}
P5	6.66^{e}	36.66^{a}	1.61^{b}	4.18^{abc}	2.30 ^{cde}	5.46^{abc}	4.33^{efg}	15.66^{a}
P6	40.00^{abc}	17.66^{ab}	5.51^{b}	4.46^{abc}	8.00^{abc}	6.38^{abc}	17.50^{abcd}	10.83^{abc}
P7	14.33^{de}	16.00^{ab}	1.81^{b}	5.83^{abc}	3.48^{bcde}	9.91^{a}	3.33^{fg}	10.83^{abc}
P8	35.00^{abcd}	33.66^{a}	4.53^{b}	5.43^{abc}	7.33^{abcd}	7.96^{ab}	13.83^{abcdef}	12.66^{ab}
P value	0.00268	0.577	0.692	0.805	0.177	0.680	0.0641 .	0.857
Sig	**	ns	ns	ns	ns	ns	ns	ns
LSD	25.65	29.51	12.15	6.25	6.21	7.00	13.11	12.13

Sig: significance, **: significant ($p < 0.01$), ns: not significant, LSD: Least Significant Difference, R0: unstressed, R1: stressed, PH: plant height, LW: leaf width, Ll: leaf length, NLP: number of leaves per plant.

KVX39618 respectively and (0) for IT07K-211-1-8. Water deficit reduced leaf width and length leaf in all plants except H5, H6, H7_F2 and P7. The lowest averages were obtained by H11, H11_F2 and P3.

Principal component analysis of water-stress tolerant cowpea genotypes

Principal component analysis (PCA) was performed for all the collected parameters during the experiment. It made it possible to determine the performance of cowpea genotypes subjected to water deficit conditions. Indeed, two dimensions represent 70.53% of the total variation (Fig. 2). The first axis explains 54.84% of the total variability and is positively correlated with all the variables taken into account in the analysis. No negative correlation of axis 1 with any of the variables was observed. The second axis expresses 15.69% of the total diversity. It is positively correlated with the parameters: number of pods per plant (NPP), number of seeds per pod (NSP), weight of 100 grains (100WS), number of days of pod maturation (NDPM) and grain yield (GYP). A negative correlation is associated with: number of days to flowering (NDF), plant height (PH), number of leaves per plant (NLP), photosynthetic yield (Fv_Fm), photosynthetic efficiency (Fv_Fo), leaf width (LW), leaf length (Ll), chlorophyll content of plants (LCC) and proline content (LPC).

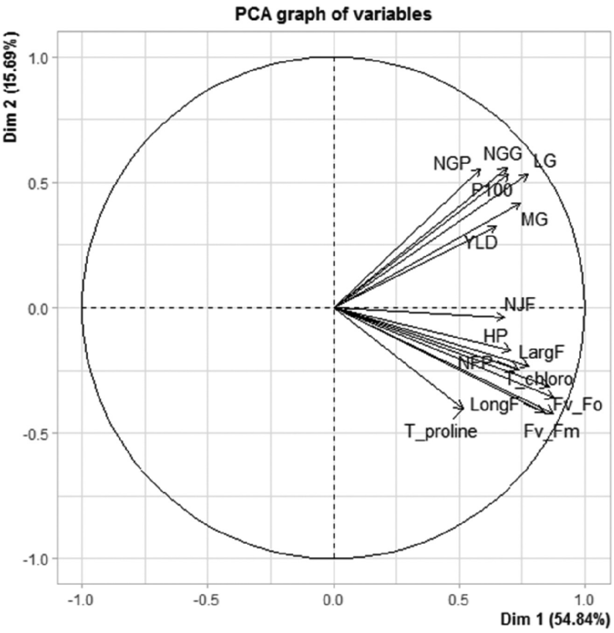

Figure 2. Principal component analysis of the parameters studied.

Projection of individuals (genotypes) and variables on the principal component analysis graph reveals that axis 1 includes individuals F2_Kpodjiguègué x Tawa (H7_F2), IT07K-311-1-8 x IT97K-206-1-1 (H6), IT99K-573-1-1 (P5), IT97K-206-1-1 (P8), KVX396-18 (P7) and Kpodjiguègué x KVX396-18 (H8). A strong positive correlation was observed between axis 1 and these genotypes with high values for all the study variables. KVX61-1 x KVX396-18 (H11), F2_KVX61-1 x KVX396-18 (H11_F2), IT07K-211-1-8 (P3), IT06K242-3 x KVX396-18 (H2), F2_ Kpodjiguègué x KVX396-18 (H8_F2) are however negatively correlated. Axis 2, that expresses 15.7% of the total variability, is positively correlated with F2_Kpodjiguègué x Tawa (H7_F2), F2_IT07K-211-1-8 x IT99K-573-1-1 (H4_F2), IT06K242-3 x Tawa (H1), IT07K-311-1-8 x IT97K-206-1-1 (H6), KVX61-1 x KVX396-18 (H11) and F2_KVX61-1 x KVX39618 (H11_F2) with high values for the variables number of pods per plant (NPP), number of seeds per pod (NSP), yield (GYP), number of days of pod maturity (NDPM) and hundred grain weight (100WS). A negative correlation is observed for KVX396-18 (P7), Kpodjiguègué (P4), KVX61-1 x Tawa (H10), IT06K242-3 x KVX396-18 (H2), IT07K-311-1-8 (P3), Tawa (P6), F2_ Kpodjiguègué x KVX396-18 (H8_F2) and IT06K242-3 x KVX396-18 (H2) with low values for the variables proline content (LPC), chlorophyll content (LCC), photosynthetic yield (Fv_Fm) , photosynthetic efficiency (Fv_Fo), leaf width (LW) and leaf length (Ll) (Fig. 3).

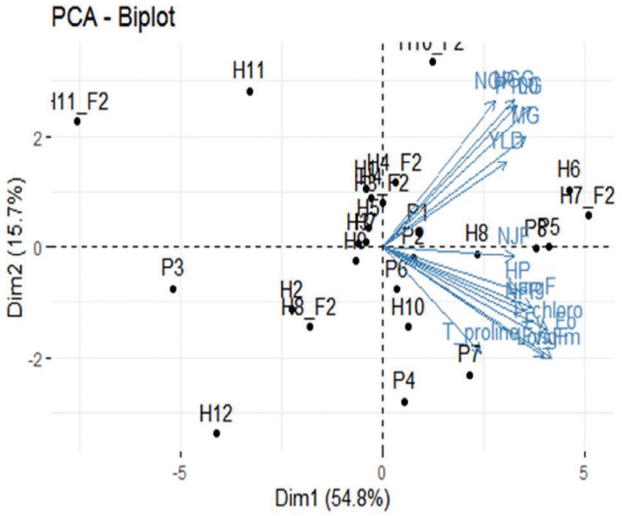

Figure 3. Projection of individuals and variables on the axes of the principal component analysis (PCA).

The ascending hierarchical classification revealed the existence of 3 classes (Fig. 4). Class 1 includes 6 individuals (genotypes), namely KVX396-18 (P7), Kpodjiguègué x KVX396-18 (H8), IT97K-206-1-1 (P8), IT99K-573-1-1 (P5), IT07K-311-1-8 x IT97K-206-1-1 (H6), and F2_ Kpodjiguègué x Tawa (H7_F2). These genotypes are characterized by high average values for all variables such as proline content, chlorophyll content, number of pods per plant, number of seeds per pod, 100 grains weight and yield. The genotypes of this class are potentially water deficit resistant. Class 2 includes the KVX61-1 x KVX396-18 (H11), F2_KVX61-1 x KVX396-18 (H11_F2), and IT07K-211-1-8 (P3) genotypes. They are characterized by high values for agronomic variables (number of pods per plant, number of seeds per pod, 100 grain weight and yield) and low values for physiological and morphological variables (proline content, chlorophyll content, photosynthetic yield, photosynthetic efficiency, leaf width, leaf length, plant height). Class 3 includes individuals F2_ KVX61-1 x Tawa (H10_F2), IT07K-211-1-8 x Tawa (H5), KVX61-1 (P1), IT07K-211-1-8 x IT99K-573-1-1 (H4), F2_IT07K-211-1-8 x IT99K-573-1-1 (H4_F2), F2_IT06K242-3 x IT97K-206-1-1 (H3_F2), KVX61-1 x Tawa (H10), Kpodjiguègué (P4), IT06K242-3 x Tawa (H1), IT06K242-3 (P2), KVX61-1 x IT97K-206-1-1 (H12), IT06K242-3 x IT97K-206-1-1 (H3), Kpodjiguègué x IT97K-206-1-1 (H9), Kpodjiguègué x Tawa (H7), Tawa (P6), IT06K242-3 (P2) and F2_ Kpodjiguègué x KVX396-18 (H8_F2). This group is characterized by low average values of proline content, chlorophyll content, number of pods per plant, number of seeds per pod, hundred grain weight and yield. It can therefore be deduced that this class includes cowpea genotypes sensitive to the effects of water deficit with low yield.

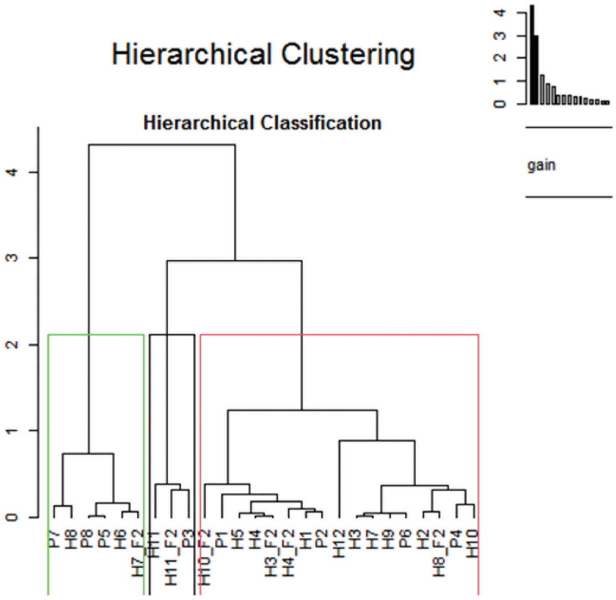

Figure 4. Hierarchical classification of the twenty-six cowpea genotypes under water deficit.

Analysis of correlations between the different variables

The correlation matrix shows the existence of strong and significant correlations between the studied variables (Table 7). Highly significant positive correlations are observed between photosynthetic yield and photosynthetic efficiency (r = 0.94***), chlorophyll content (r = 0.72***), proline content (r = 0.60***), leaf width (r = 0.70***), leaf length (r = 0.85***) respectively. There is also a very

Table 7. Correlation matrix of the studied variables.

	Fv_Fm	Fv_Fo	LCC	LPC	PH	LW	Ll	NLP	PL	NPP	NSP	100WS	NDF	NDPM	GYP
Fv_Fm	1														
Fv_Fo	0.95***	1													
LCC	0.73***	0.75***	1												
LPC	0.61***	0.66***	0.53**	1											
PH	0.48*	0.46*	0.47*	0.29	1										
LW	0.70***	0.75***	0.80***	0.51**	0.49*	1									
Ll	0.86***	0.89***	0.64***	0.53**	0.45*	0.67***	1								
NLP	0.53**	0.41*	0.48*	0.31	0.63***	0.46*	0.48*	1							
PL	0.48*	0.48*	0.44*	0.31	0.24	0.48*	0.43*	0.31	1						
NPP	0.02	0.08	0.25	0.08	0.36	0.37	0.09	0.21	0.47	1					
NSP	0.37	0.39*	0.47*	0.19	0.18	0.42*	0.32	0.35	0.87***	0.46*	1				
100WS	0.33	0.36	0.55**	0.26	0.34	0.43*	0.20	0.22	0.75***	0.52**	0.70***	1			
NDF	0.58**	0.58**	0.47*	0.41*	0.51**	0.49*	0.70***	0.69*	0.46*	0.29	0.46*	0.32	1		
NDPM	0.44*	0.47*	0.39*	0.25	0.47*	0.50*	0.50*	0.51**	0.68***	0.46*	0.68***	0.55**	0.72***	1	
GYP	0.18	0.20	0.37	-0.06	0.54**	0.46*	0.20	0.33	0.39*	0.73***	0.34	0.58**	0.29	0.481*	1

*: significant ($p < 0.05$), **: significant ($p < 0.01$), ***: significant ($p < 0.001$), Fv_Fm: photosynthetic yield, Fv_Fo: photosynthetic efficiency, LCC: leaf chlorophyll content, LPC: leaf proline contentPH: plant height, LW: leaf width, Ll: leaf length, NLP: number of leaves per plant, NDF: number of flowering days, 100WS : hundred seed weight, NDPM: number of days to pod maturity, GYP: seed yield, PL: pod length, NPP: number of pods per plant, NSP: number of seeds per pod.

significant positive correlation between yield and number of leaves per plant (r = 0.52**), number of days to flowering (r = 0.52**) respectively. A significant positive correlation was noted respectively between photosynthetic yield and plant height (r = 0.47*), pod length (r = 0.48*), and number of days to pods maturity (r = 0.44*). A very significant positive correlation is observed between chlorophyll content and proline content (r = 0.52**), hundred-grain weight (r = 0.55**) respectively. A positive correlation is recorded respectively between chlorophyll content and height of the plant (r = 0.46*), leaf width (r = 0.80***), leaf length (r = 0.63***), number of leaves per plant (r = 0.48*), pod length (r = 0.44*), number of seeds per pod (r = 0.46*), hundred kernel weight (r = 0.55**), number of days to seed flowering (r = 0.46*) and number of days to pod maturity (r = 0.38*). Proline content has respectively a positive correlation with leaf width (r = 0.50**), leaf length (r = 0.53**), number of days to flowering (r = 0.53* *) and a negative correlation with the return (r=-0.06). It should be noted that a highly significant positive correlation is observed between plant height and yield (r = 0.53**). Positive and significant correlations are recorded between all agronomic traits except number of pods per plant (NPP) and length of pods (r = 0.47) and number of days to flowering (r = 0.29) respectively; between number of seeds per pod and yield (r = 0.34).

Discussion

Our study revealed a decrease in photosynthetic yield in almost all plants subjected to water deficit conditions. Low values in photosynthetic yield were particularly observed in genotypes KVX61-1 x KVX396-18 (H11), F2_KVX61-1 x KVX396-18 (H11_F2) and IT07K-211-1-8 (P3). These results are in agreement with those of Ezin et al. (2021), Schreiber and Berry (1977) and Al-Khatib and Paulsen (1984). According to these authors, drought stress causes a decrease in maximum fluorescence (Fm), and therefore a decrease in photosynthetic yield (Fv_Fm), consequently reducing photosynthesis.

Water deficit negatively affects leaf pigment content, thereby reducing photosynthetic activity in stressed plants (Jaleel et al. 2009; Sansan et al. 2024). Leaf chlorophyll content was significantly reduced in stressed plants during our study. This is in line with the results of Harou et al. (2018) who presented a 34% reduction in chlorophyll content in the Tiligré genotype under intermittent water deficit condition and 13% and 12% respectively in genotypes KVX-61-1 and Dan-Ila under terminal water deficit condition. Similar conclusion was reached by other authors in other crops. Mafakheri et al. (2010), Ezin et al. (2010) and Ezin et al. (2019) demonstrated that the chlorophyll content in tomato plant species was reduced by the effects of water deficit. This can be explained by the fact that under water deficit conditions, chlorophylls degradation in plants leaves is faster than its synthesis compared to unstressed conditions (Impes 1989). According to Bousba et al. (2009), the drop in chlorophyll content is the consequence of the closure of stomata aimed at limiting water loss through transpiration. During our study, a decrease in proline content in stressed plants was observed, particularly in F2_KVX-61-1 x Tawa (H10_F2) and F2_KVX61-1 x KVX396-18-1-1 (H11_F2). However, genotypes such as IT06K242-3 x IT97K-206-1-1 (H3), IT07K-211-1-8 x IT97K-206-1-1 (H6), Kpodjiguègué x IT97K-206-1-1 (H9), IT07K-211-1-8 (P3), Kpodjiguègué (P4), KVX396-18 (P7) and IT97K-206-1-1 (P4) under water deficit presented better performance compared to their controls. Our results are in line with those obtained on *Phaseolus vulgaris* (Santos and Pimentel 2009), and on *Medicago truncatula* and *Medicago laciniata* (Yousfi et al. 2010). Work carried out by Costa et al. (2008) revealed a 45.32% and 57.57% increase in proline content in cowpea varieties Semper Verde and Pitiuba respectively.

In of water deficit conditions, agronomic performance of cowpea plants is reduced. In our study, results of the statistical analysis reveal that number of pods per plant (NPP) in Kpodjiguègué x KVX396-18 (H8) and IT07K-211-1-8 (P3) was considerably reduced by the effects of water deficit. These results corroborate those of Hamidou et al. (2005) who evaluated tolerance to water deficit in two varieties of cowpea (Gorom and KN1). Indeed, the number of pods per plant was lower in KN1 than in Gorom. They showed that there is a significant water regime effect on the number of pods per plant. Pod filling is the phase in which water deficit has the greatest impact on yield according to Kramer (1999). Mawuli et al. (2014) showed that the reduction in the number of pods is the consequence of the lack of water supply to the plants. These results are also similar to those obtained by Olajide and Ilori (2017) on cowpea hybrids subjected to water deficit.

During this study, a decrease in grain yield in stressed genotypes was also observed. Nevertheless, genotypes F2_IT07K-211-1-8 x IT99K-573-1-1 (H4_F2), IT07K-211-1-8 x Tawa (H5), IT07K-211-1-8 x IT97K-206-1-1 (H6), F2_Kpodjiguegue x Tawa (H7_F2) and IT06K242-3 (P2) recorded the best performances. The genotypes with lower yields were IT06K242-3 x Tawa (H1), KVX61-1 x Tawa (H10). Our results agree with those of Ezin et al. (2021, 2023) who, after a screening study of 20 cowpea varieties, showed yield variability among the varieties studied. Indeed, IT06K242-3 and Kpodjiguègué varieties have the best grain yields, while IT99K-573-1-1 and IT97K-206-1-1 recorded the lowest performance in the vegetative phase than in the reproductive phase of water deficit. Halime et al. (2014) reported a yield reduction greater than 60% in plants under water deficit during the flowering and pod filling stages. Zombre et al. (1994) observed that a water deficit causes a significant number of abortions which reduces plant yield. The work of Kamanga et al. (2003) showed a 50% reduction in grain yield in cowpea plants subjected to water deficit conditions. Sarr et al. (2001) reported that seed yield in cowpea varieties is reduced at more than 50% under water deficit conditions.

During this study, water deficit significantly reduced hundred seeds weight in all genotypes. However, genotypes IT07K-211-1-8 x Tawa (H5), IT07K-211-1-8 x IT97K-206-11 (H6), F2_Kpodjiguegue x Tawa (H7_F2) were not affected. Our results are in agreement with those of Hamidou et al. (2014) who found a reduction in the mass of 100 seeds in the cowpea variety KN1 while Gorom was not affected by water deficit. Similarly to the results presented by the genotypes H5, H6, and H7_F2, Zombre et al. (1994) suggested that hundred seeds weight was not affected by water deficit. Harou et al. (2018) found that 100-seed weight was significantly reduced by intermittent water deficit (DH1) treatments and terminal water deficit (DH2) treatments by 25% and 22% respectively. The Tiligré and KVX-61-1 genotypes were the most affected, showing the lowest 100-seed weights under DH1 and DH2 conditions. These results are in agreement with those obtained by Sarr et al. (2001).

Number of seeds per pod (NSP) during this study was significantly reduced by the effects of water deficit. Our results agree with those obtained by Hamidou et al. (2005) who showed that there is a significant effect of water deficit on the number of seeds per pod. We found during this study that the number of days to flowering (NDF) was significantly delayed by water deficit. This result is similar to that obtained by Harou et al. (2018) who reported a delay of 5 days on the 50% flowering date. According to Blum (2017), drought creates species-dependent delayed flowering. This could be explained by the fact that plants have adopted an avoidance behavior against water deficit, which has led to this extension of the appearance of flowers. Lalsaga et al. (2017) resulted in similar results than in our study. They observed during their study on ten cowpea genotypes that the number of days to 50% flowering is slightly higher under drought stress conditions. According to Pandey et al. (2006), differences in flowering days could be due to varietal character, sowing period, and growing environment. However, the decrease in the agronomics performance of some genotypes in our study may be explained by the increase in the greenhouse temperature at flowering time (Fig. 1).

The principal component analysis revealed that the agronomic and morpho-physiological performances of the varieties would be structured by the phenological characters and the yield components. The projection of the varieties in planes 1 and 2 of the PCA presented a random distribution of the varieties in the plane. This dispersion of varieties in the PCA plans would indicate significant agronomic and physiological variability. The dispersion of the varieties being greater at the PCA level, then the agronomic and morpho-physiological diversity of the varieties studied would be quite significant. The main discriminating parameters of the study would therefore be the number of days to flowering, leaf chlorophyll content, photosynthetic yield, number of days to pod maturation, number of seeds per pod, number of pods per plant, hundred seeds weight, and seed yield.

The ascending hierarchical classification reveals the existence of 3 classes. Class 1 includes genotypes P7, H8, P8, P5, H6, and H7_F2. These genotypes appear to be potentially resistant to the effects of water deficit. Class 2 includes genotypes H11, H11_F2, and P3. From the analyses, it is concluded that these genotypes are partially drought-tolerant. Class 3 includes individuals H10_F2, H5, P1, H4, H4_F2, H3_F2, H10, P4, P2, H12, H3, H9, H7, P6, P2 and H8_F2. This class includes water deficit sensitive cowpea genotypes.

In the present study, significant positive correlations were observed between proline content and photosynthetic yield ($r = 0.60^{***}$), photosynthetic efficiency ($r = 0.65^{***}$), chlorophyll content ($r = 0.52^{**}$), leaf width ($r = 0.50^{**}$), leaf length ($r = 0.53^{**}$) respectively. This means that photosynthetic yield evolves proportionally concerning these different parameters. H5, H6, H7_F2, and P7 are the individuals with high values for these parameters. Therefore, proline content could be used as a good selection criterion for cowpea genotypes with high proline content. It can also be deduced that H5, H6, H7_F2, and P7 having the highest average values of leaf width and length are likely to have very high proline contents. These genotypes can therefore be recommended to cowpea producers. Seed yield maintained a positive and significant correlation between plant height, pod length, number of pods per plant, hundred-seed weight, and number of days to pod maturity, respectively. These results are not in agreement with those obtained on *Macrotyloma geocarpum* by Coulibaly et al. (2020) who showed a weak, non-significant correlation between seed yield and number of pods per plant (r = 0.101) on the one hand and the number of seeds per pod (0.002) on the other. However, a positive and significant correlation between seed yield and number of days to 95% pod maturity (0.444*) was found by these same authors. This result is similar to that of our study.

Conclusion

This study allows us to identify genotypes tolerant to water deficit on the one hand and those sensitive on the other hand. Thus, genotypes KVX396-18, Kpodjiguègué x KVX 396-18, IT97K-206-1-1, IT99K-573-1-1, IT07K-211-1-8 x IT97K-206-1-1, and F2_Kpodjiguègué x Tawa are the best water deficit tolerant and high yielding genotypes. KVX61-1 x KVX396-18, F2_KVX61-1 x KVX396-18, and IT07K-211-1-8 showed high values for yield and its associated traits but low values for traits directly related to water deficit. They are then high yielding but drought-sensitive genotypes. Genotypes F2_ KVX61-1 x Tawa, IT07K-211-1-8 x Tawa, KVX61-1, IT07K-211-1-8 x IT99K-573-1-1, F2_IT07K-211-1-8 x IT99K-573-1-1, F2_IT06K242-3 x IT97K-206-1-1, KVX61-1 x Tawa, Kpodjiguègué, IT06K242-3 x Tawa, IT06K242-3, KVX61-1 x IT97K-206-1-1, IT06K242-3 x IT97K-206-1-1, Kpodjiguègué x IT97K-206-1-1, Kpodjiguègué x Tawa, Tawa, IT06K242-3 and F2_ Kpodjiguègué x KVX39618 showed low values for yield-related traits and its associated traits and for traits directly related to water deficit. These genotypes are therefore considered low-yielding and drought sensitive genotypes. It should be noted, however, that there is a correlation between traits related to water deficit and traits related to yield and its yield attributes. The traits including NPP, GYP, NLP, NSP, 100WS, PL and NDPM can therefore be exploited in cowpea breeding programs to improve yield and drought tolerance in susceptible and low-yielding genotypes.

Author contributions

Vincent Ezin designed the experiment. Thibaut A.W. Tossou carried out the fieldwork. Thibaut A.W. Tossou and Ifagbémi B. Chabi conducted laboratory work. Thibaut A.W. Tossou, Vincent Ezin, and Adam Ahanchede performed the statistical analysis. Thibaut A.W. Tossou drafted the manuscript. Vincent Ezin, Adam Ahanchede, Fatimata Bachabi, and Ifagbémi B. Chabi coordinated the study and contributed to the write-up of the manuscript. Vincent Ezin, Fatimata Bachabi and Adam Ahanchede edited the manuscript. All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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