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Characterisation of spider plant (*Cleome gynandra L.*) accessions for drought tolerance traits

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Background: Spider plant, a nutrient-rich native leafy vegetable that grows in marginal environments, can be vital in preventing malnutrition and supporting sustainable livelihoods. Despite this, knowledge about the crop is lacking, especially on its drought tolerance and genetic variation, which hinders the crop breeding efforts.

Aim: To evaluate diverse spider plant genotypes for growth, yield and response to drought to identify tolerant and sensitive genotypes.

Setting: Botswana University of Agriculture and Natural Resources (BUAN) in the drought screening greenhouse located in Gaborone, Botswana.

Methods: A factorial split-plot design trial involving 25 African and Asian spider plant genotypes under well-watered and drought stress conditions was undertaken. Growth, yield and photosynthetic performance were measured, and drought tolerance indices, principal components analysis (PCA) and cluster analysis were used to identify tolerant and sensitive genotypes.

Results: Significant variation in growth, yield and physiological responses was observed among the 25 genotypes, with drought tolerance being highest in ODS15061, ODS15103 and ODS15044, while susceptible genotypes were BUAN1, BC02B and ODS15019.

Conclusion: The study reports the genetic diversity of spider plant genotypes and their potential for drought tolerance breeding. This will enhance spider plant resilience and sustainability in low rainfall production areas and thereby address food security challenges.

Contribution: The selected genotypes based on drought tolerance can further be used in multi-location field studies before being released for production in low rainfall areas. Furthermore, similar approaches can be applied for drought tolerance selection of other leafy vegetables.

Keywords: drought stress; *Cleome gynandra*; genetic diversity; drought tolerance; sustainable agriculture; indigenous vegetables; yield performance; climate-smart crops.

Introduction

The spider plant (*Cleome gynandra* L.) is a native leafy vegetable widely consumed in Asia and sub-Saharan Africa because of its high nutritional content, including vitamins, phytochemicals and essential minerals (Gonye et al. 2017). It is renowned for having a high nutritional content and being abundant in vitamins, phytochemicals and vital minerals (Moyo & Aremu 2020). These elements make the plant essential for enhancing diets and livelihoods in communities with limited resources because they not only nourish but are also said to offer protection from non-communicable diseases and other degenerative problems (Ambuko et al. 2020; Wakhisi, Michael & Mwangi 2020). Its delicate leaves, tender stems and flower buds are cooked as stew or as potherbs, making it an essential part of the diet in households with limited resources (Onyango, Onwonga & Kimenju 2016). Beyond its nutritional advantages, the spider plant thrives in marginal locations where exotic leafy vegetable crops fail, greatly enhancing the food security and economic resilience of underprivileged groups. The spider plant is a critical crop for combating malnutrition and creating sustainable livelihoods in areas prone to drought because of its resilience and ability to promote nutritional diversity (Ochieng, Owaga & Njoroge 2018).

The spider plant's natural resistance to severe environmental factors, such as drought, has made it a promising climate-smart crop. Studies have indicated that although drought stress (DS) lowers its yield, it also raises levels of important micronutrients, including zinc, iron and beta-carotene, highlighting its potential to prevent malnutrition in water-scarce communities

(Jamalluddin et al. 2021; Mosenda et al. 2020). The genetic diversity and stress tolerance mechanisms of plants remain poorly understood, limiting their full domestication and effective utilisation in crop improvement programmes. Low-yielding cultivars and a shortage of focused breeding programmes aggravate these issues (Onyango et al. 2016). Nonetheless, research shows the unrealised potential of spider plants as a high-yielding, drought-resistant crop, where domestication and better management techniques have resulted in production gains surpassing tenfold (Afolayan & Jimoh 2009). To fully realise its promise as a climate-adaptive crop, it is imperative to close the information gap about its reactions to DS and find genotypes with improved tolerance features.

This study is based on the idea that native vegetables, such as spider plants, respond to abiotic stress primarily through their morpho-physiological characteristics (Maseko et al. 2019). The conceptual framework combines the identification of important traits that contribute to crop resilience with the assessment of genotypic diversity under DS. To meet the nutritional demands of vulnerable groups and increase productivity in water-limited environments, breeding techniques will be informed by these observations. This study aims to characterise the diversity of *C. gynandra* accessions and their stress tolerance, identifying genotypes with improved drought resilience for crop improvement programmes. Specifically, the study aimed to: (1) assess the phenotypic diversity of selected genotypes, (2) evaluate their physiological and biochemical responses to DS and (3) identify key traits associated with enhanced stress tolerance.

Materials and methods

Study area description, plant materials and origin

Greenhouse experiments were carried out in Gaborone, Southern Botswana (24°59′ S, 25°94′ E). Gaborone sits at an altitude of 1000 m above sea level, experiencing an average rainfall of 250 mm – 500 mm and a mean outdoor temperature of 20.7 °C. Two greenhouse experiments were carried out from February to April 2021 and from August to November 2022. Additionally, these two experiments were replicated from February to April 2023 and from October to December 2023. Soil from the university research field, traditionally used for growing vegetables and field crops, was used for planting. Soil analysis indicated a sandy texture with 0.62% organic carbon (OC) and 0.0008% nitrogen.

Preliminary genotype screening

TABLE 1: Accessions and country of origin used in the study (*N* = 25).

Countries of origin	Regions	Accession names
Ghana	West Africa	ODS 15121, ODS 15103
Benin	West Africa	ODS 15037, ODS 15020, ODS 15019, ODS 15044, NC 05015
Kenya	East Africa	GA01, KSI 2407A, ELG 19/07A, TOT 8926
Malawi	Southern Africa	BC 02B
Tanzania	East Africa	TOT 6426
Malaysia	Southern Asia	TOT 7196
Togo	West Africa	ODS 15061, ODS15059, ODS 15075
Lao's Republic	Southern Asia	ODS 15045, TOT 3536
Uganda	East Africa	TOT 8887
Thailand	Southern Asia	TOT 5799
Namibia	Southern Africa	LAIOGONGO
Botswana	Southern Africa	ROTHWE 1, ROTHWE 2 BUAN1

BUAN, Botswana University of Agriculture and Natural Resources.

A total of 25 diverse spider plant germplasms obtained from different regions of the world were used in this study (Table 1). Of these, 21 were obtained from the World Vegetable Centre (AVRDC), Arusha (Tanzania), through the University of Namibia, Department of Crop Science. The AVRDC accessions represent germplasm originally collected from 11 different African and Asian countries. Additionally, one accession was received from the National Botanical Research Institute of Namibia, two were sourced from the National Plant Genetic Resource Centre of Botswana and one was collected from a crop research field near Gaborone.

Treatments, experimental design and crop husbandry genotype selection studies

Twenty-five spider plant accessions were screened for drought tolerance in 0.216 m^3 rectangular stress boxes (1.2 m × 0.9 m × 0.2 m) as per Madumane et al. (2024). Each box contained about 165 kg of air-dried sandy loam soil with physicochemical characteristics including 0.62% OC, 5.8 pH ($CaCl_2$), 4.0 meq/100 g CEC, 0.08% total N, 15.9 ppm P and 0.08 ppm exchangeable K. A single application of phosphorus fertiliser (superphosphate) at 60 kg P ha^{-1} was given to each box before planting to fulfil the crop's phosphorus requirement. The experiment followed a factorial split-plot design with four replications, with DS and well-watered (WW) conditions as the main plot treatments and the 25 spider plant accessions as subplots. Plants were spaced 0.1 m within rows and 0.15 m between rows, aiming for approximately 67 plants per square metre. Seedlings were thinned to two per hill 2 weeks after planting (WAP). Regular watering maintained soil moisture until 3 WAP. Each treatment received a total of 140 kg N ha^{-1}, split into two applications at 2 and 5 WAP.

Two water treatments were applied during the vegetative growth phase at three WAP, when plants had 5–7 leaves. In the control (WW), daily irrigation maintained soil moisture at 80% – 70% field capacity following (Junker et al. 2015) with modification to suit plant needs. In the DS treatment, irrigation was withheld, gradually drying the soil. The soil moisture was monitored with the ML3 ThetaProbe Soil Moisture Sensor (Delta-T Devices, Cambridge, UK) every 2 days from the start of drought until reaching 20% FC, then rewatered to above 80% FC and repeated for 8 weeks. To manage aphids and whiteflies, treatments were sprayed with lambda-cyhalothrin at 1 g/L 5 days after emergence (DAE), during both the vegetative and flowering stages.

Drought stress evaluation

From the preliminary screening, nine accessions were selected for further evaluation under moisture stress and assess the leaf photosynthetic responses. These accessions were categorised into three groups, each comprising three accessions, for the purpose of this research. The selected genotypes were categorised as follows: drought-tolerant (ODS15061, ODS15044 and ODS15021), intermediate-tolerant (NC05015, TOT3536 and ROTHWE2) and sensitive (ODS15019, BC02B and Botswana University of Agriculture and Natural Resources [BUAN1]) based on genotype selection studies to validate the outcome of preliminary genotypes screening.

The setup consisted of 0.216 m^3 rectangular boxes (1.2 m × 0.9 m × 0.2 m) loaded with approximately 165 kg of air-dried soil. The study used a factorial design in a split-plot layout with four replications to investigate two major water treatments: DS and WW as main plots, with the nine spider plant accessions serving as subplots. The protocols for planting, care and watering were analogous to those implemented in the preliminary genotype screening study.

Data collection

Preliminary genotype screening

Economic yield harvesting was done every 2 weeks from 3 WAP until the end of the 9-week experimental period. The economic yield fresh weight (EYFW) of leaves, tender shoots and flower buds was weighed immediately after harvesting, followed by oven drying at 60 °C for 72 h to determine economic yield dry weight (EYDW). Growth parameters, including plant height (PH), number of leaves (NOL), number of primary branches (NPB) and chlorophyll content (significant for chlorophyll content [SPAD]), were monitored from 3 WAP and every 2 weeks thereafter until the plants were 8 WAP. Plant height was measured from the base to the tip of the plant, NOL was counted biweekly and NPB was assessed by counting well-extended branches from the main stem. Drought tolerance was evaluated using Fernandez's theory (Fernandez 1992) and drought-tolerance indices based on EYDW yield data.

Physiological study – Leaf photosynthetic parameters

Physiological leaf fluorescence parameters (Phi2, FmP/FvP, SPAD and leaf stomatal conductance) were measured every 2 weeks, starting at three WAP, and continued throughout the 8-week experimental period. These measurements were taken using multispeQ V 2.0 (PhotosynQ INC, East Lansing, United States). Leaf stomatal conductance was assessed with an SC-1 leaf stomatal conductance porometer (Melbourne, Victoria, Australia). Economic yield, fresh and dry weight, alongside other plant growth parameters, were quantified using methods and equipment consistent with those used in the genotype selection experiment.

Data analysis

To analyse significant variations among treatment means, growth and yield data from the genotype selection underwent multivariate analysis of variance (MANOVA) at a 95% confidence level using the 'doebioreseach' R package. Visualisations, including bar graphs and correlation coefficient charts for growth data, were created with 'ggplot2' and 'ggcorrplot' R programmes. The economic yields (Yp and Ys) were utilised to compute drought-tolerant indices used for selection. Four different selection strategies, which include: (1) best linear unbiased prediction (BLUP) with *Meta-R*, (2) principal components analysis (PCA), (3) indices-based genotype ranking and (4) dendrogram clustering analysis using the unweighted pair-group method with arithmetic mean (UPGMA) approach, were performed with the 'factoextra' and 'dendextend' packages in R (Sharma et al. 2022). The potential contradiction of relying on a single index for identifying drought tolerance during preliminary screening was addressed by ranking genotypes based on multiple drought tolerance indices. The average sum of ranks (ASR) and the standard deviation of ranks (SDR) across all indices were calculated to identify the most ideal drought-tolerant genotypes. Similarly, data from the leaf photosynthetic parameters experiment underwent MANOVA at a 95% confidence level using the 'doebioreseach' package in R (Etminan et al. 2019), with group averages summarised for mean separation to display observed variations.

Ethical considerations

Ethics approval was obtained from the Economic and Management Sciences Research Ethics Committee (EMS-REC) at the North-West University (NWU-01957-23-A4).

Results

Soil moisture levels during the experiment

Soil moisture levels for DS decreased gradually throughout the growth and stress periods. Soil moisture levels in WW plants ranged from 32% (4th week) to 26.5% (8th week), whereas DS plants showed levels ranging from 19.82% (vegetative stage) to 12.62% (reproductive stage).

Preliminary genotype screening

Significant differences were observed among genotypes (A) for PH, NOL, EYFW and EYDW. Growth stages (B) significantly impacted all measured parameters except for EYFW, EYDW and economic yield moisture content (EYMC). Soil water stress (C) significantly affected all parameters except for the NPB and EYFW. Interactions between growth stages and soil water stress (B × C) were SPAD, PH and EYDW, while interactions between genotypes and growth stages (A × B) did not show significant variation for any parameters (Table 2). Additionally, there were no significant interactions observed among the three factors: genotypes (A), growth stages (B) and soil water stress (C) for any of the parameters.

Leaf chlorophyll content

Leaf chlorophyll content (SPAD values) was significantly influenced by growth stages-genotype and growth stages-soil water stress interactions (Table 2). Genotypes exposed to DS at 4 weeks had significantly lower chlorophyll levels than those at 6 weeks, whereas WW genotypes maintained consistent chlorophyll content regardless of growth stage (Figure 1a). Figure 1b demonstrates that, except for a few genotypes, chlorophyll content was notably lower under DS, increasing as plants receive optimum soil water treatment. The genotypes ELG 1907A, ODS 15103, ODS 15044 and ODS 15061 demonstrated significantly similar yet elevated chlorophyll content (57.69, 49.80, 45.86 and 44.96) under optimal soil water conditions. Among these genotypes, ELG 1907A exhibited lower chlorophyll content (32.24) under low soil water treatment. Conversely, genotypes BUAN 1, ODS 15019 and ROTHWE 1 showed significantly lower chlorophyll content in both soil water treatments (Figure 1b).

Plant height

Spider PH was significantly influenced by genotypes and interactions between growth stages and water stress (Table 2). As illustrated in Figure 2, ODS 15061 and ODS 15103 demonstrated a greater height in comparison to ROTHWE1. Notably, early PH was unaffected by DS, but as plants matured, WW ones showed significant height increases over drought-stressed plants.

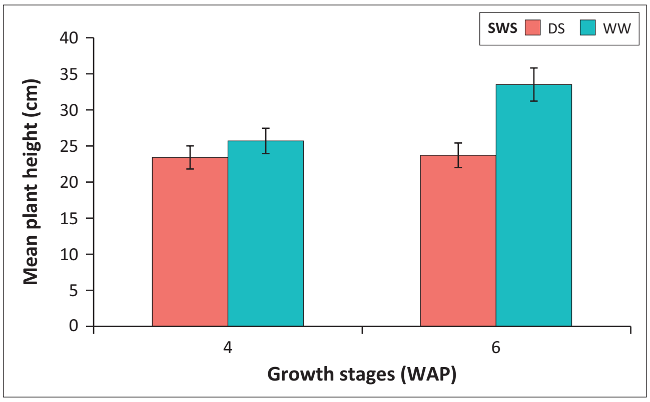
Number of branches and leaves

The number of branches in spider plants was significantly impacted by genotypes, while the NOL was influenced by all three factors (Table 2). Genotypes displayed considerable variation in branch numbers, ranging from 5 to 14 branches. However, ODS15061 exhibited the highest number of branches (14), while ROTHWE1 had the lowest (4). Genotypes also significantly affected the NOL, with ODS15061, NCO5015 and ODS15044 showing higher leaf counts, while ROTHWE1, ODS1915, BC02B and BUAN1 had fewer leaves. Younger spider plants generally produced more leaves than older ones. Also, DS plants had significantly fewer leaves than the control (Figure 3).

TABLE 2: The analysis of variance (ANOVA) for measured agronomic and economic yield traits of spider plant under drought stress at vegetative and reproductive stages.

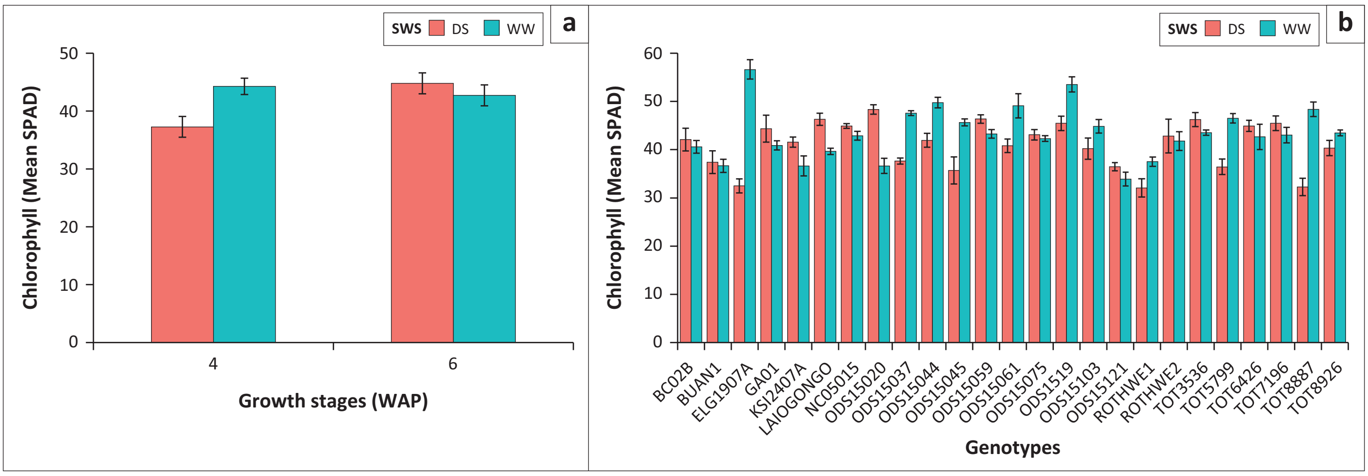
Sources of variations	Genotypes (A)	Growth stages (B)	Soil water stress (C)	AB	AC	BC	ABC
df	24	1	1	24	24	2	24
SPAD	ns	**	*	ns	**	***	ns
PH	***	***	***	ns	ns	**	ns
NPB	ns	***	ns	ns	ns	ns	ns
NOL	**	***	***	ns	ns	***	ns
EYFW	***	ns	***	ns	ns	ns	ns
EYDW	***	ns	***	ns	ns	ns	ns

df, degrees of freedom; SPAD, leaf chlorophyll content (SPAD values); PH, plant height (cm); NPB, number of primary branches; NOL, number of leaves; EYFW, economic yield fresh weight; EYDW, economic yield of fresh weight and EYMC, economic yield moisture content (%); ns, *, ** and *** indicate non-significant at 5%, significant at 5%, 1% and 0.1% probability levels, respectively.



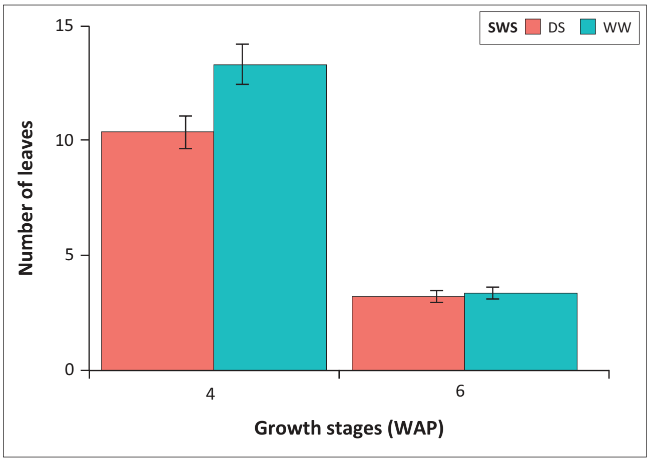
SWS, soil water stress; DS, drought stress; WW, well watered; WAP, weeks after planting; SEM, standard error of mean; MANOVA, multivariate analysis of variance.

FIGURE 2: The interactive effects of growth stages and soil water stress on the plant height of spider plant grown in greenhouse conditions. All the data are expressed as mean ± SEM, $n = 3$ according to the MANOVA test ($p \leq 0.05$). Weeks indicate the two growth periods during the 4th and 6th weeks after sowing (WAS), and DS and WW indicate the drought stress and well-watered treatments of the soil, respectively.



DS, drought stress; WW, well watered; WAP, weeks after planting; SWS, soil water stress; MANOVA, multivariate analysis of variance.

FIGURE 1: The interactive effects of growth stages and soil water stress (a) and genotypes and soil water stress (b) on the chlorophyll content (SPAD) of spider plants. All the data are expressed as mean ± standard error of mean (SEM), $n = 3$, according to the MANOVA test ($p \leq 0.05$). Weeks indicate the two growth stages at 4th and 6th weeks after sowing (WAS), and DS and WW indicate the soil water stress and well-watered treatments of the soil, respectively.

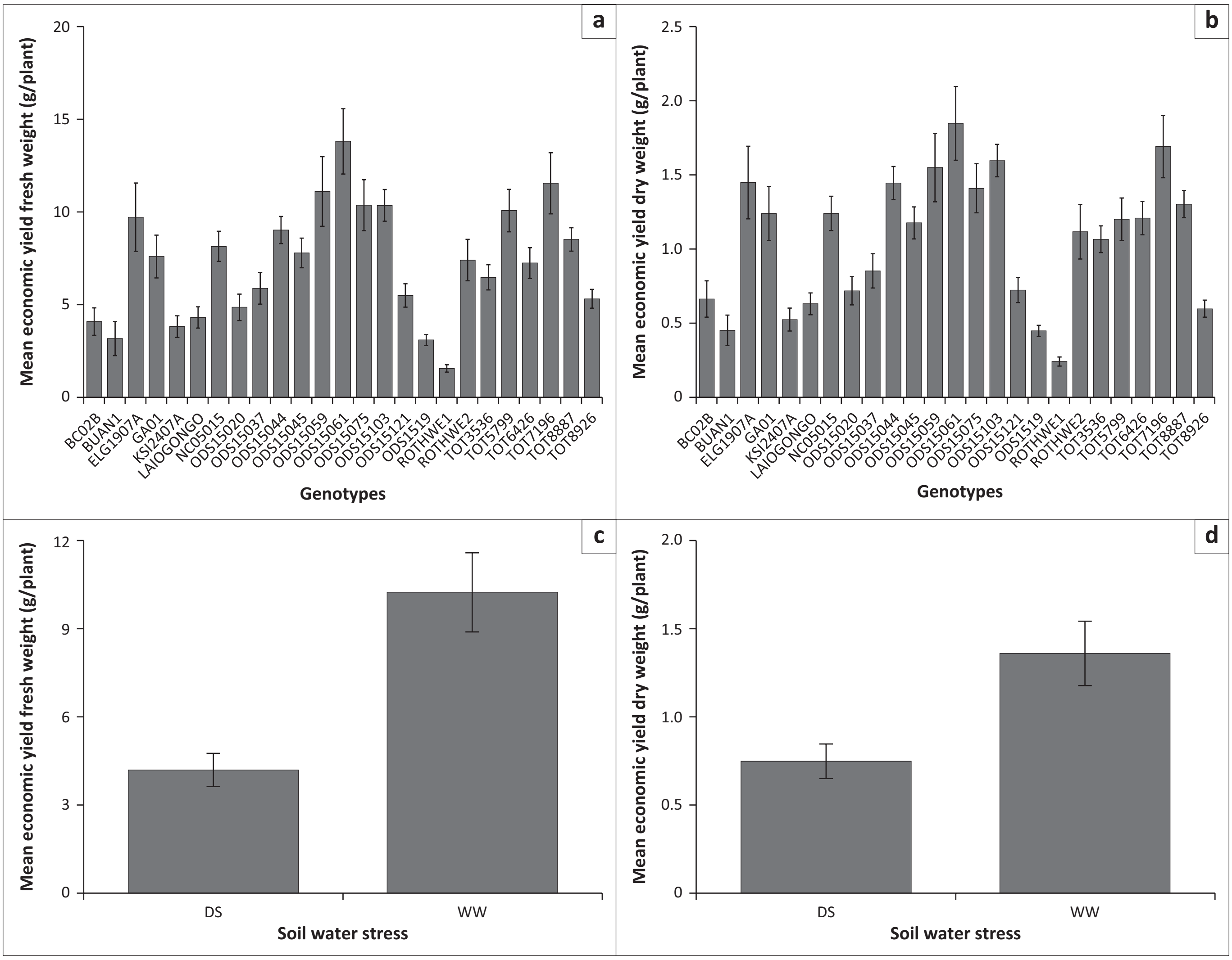


DS, drought stress; WW, well watered; WAP, weeks after planting; SWS, soil water stress; SEM, standard error of mean; MANOVA, multivariate analysis of variance.

FIGURE 3: The influence of growth stage and soil water stress on the number of leaves of spider plant grown in greenhouse conditions. All the data are expressed as mean ± SEM, *n* = 3 according to the MANOVA test ($p \leq 0.05$). Growth stages indicate the two growth stages during the 4th and 6th weeks after sowing (WAS), and DS and WW indicate the drought stress and WW nature of the soil, respectively.

Economic yield

The MANOVA indicated that the variation in spider plant economic yield, fresh and dry weight, was mainly because of genotypic variations and soil water stress (Table 2). The EYFW of different spider plant genotypes varied significantly, with the highest reported (ODS 15061) showing a mean yield of 10.24 g/plant, while the lowest (ROTHWE 1) indicates a mean yield of 1.5 g/plant. Additionally, genotypes ODS 15059, ODS 15075, ODS 15103 and TOT 17196 have shown a significantly higher economic yield in fresh weight. Conversely, BUAN 1, BC 02B, ODS 1519 and TOT 8926 exhibited a significantly lower economic yield in both fresh and dry weight (Figure 4a and b). Under WW conditions, spider plants produce an average EYFW of 10.2 g per plant, whereas 4.2 g per plant was recorded during DS conditions. Similar trends were observed in EYDW, ranging from 0.75 during DS to 28.4 g/plant, as indicated in Figure 4c and d.



SEM, standard error of mean; MANOVA, multivariate analysis of variance; DS, drought stress; WW, well watered.

FIGURE 4: Genotype effects on fresh (a) and dry (b) weight of spider plants in greenhouses. Soil water stress impacts on fresh (c) and dry (d) weight of spider plants in greenhouses. All data are expressed as mean ± SEM, *n* = 3, based on the MANOVA test ($p \leq 0.05$). Furthermore, DS and WW indicate DS and WW soil conditions, respectively.

Correlations among the growth and economic yield parameters of the spider plant

Bivariate scatter plots with fitted lines based on Pearson's correlation coefficients analysed the relationship among traits, depicted in Figure 5a and b, to show the effects of soil water stress. Under both conditions, EYFW had a strong positive correlation with EYDW ($r^2 = 0.93$) and PH ($r^2 = 0.72$). Additionally, EYDW showed a significant positive correlation with PH ($r^2 = 0.70$), while a negative correlation was observed between NPB and NOL ($r^2 = -0.50$). However, other parameters showed insignificant relationships, with r^2 values ranging between –0.04 and 0.42.

Principal components analysis

We have utilised PCA to explore drought tolerance variability among spider plant genotypes, focusing on key qualities contributing most to total variation (Figure 6). Among the 11 DS indices, only the first two principal components (PCs), Yp and Ys, were significant, collectively explaining 96.9% of total variability, with eigenvalues exceeding one each. However, PC1, associated with Ys, explained 67.2% of the total variation and was positively influenced by tolerance index (TOL), mean productivity (MP), geometric mean productivity (GMP), stress tolerance index (STI) and harmonic mean (HM). Furthermore, PC2, linked to YS2, accounted for 29.7% of the total variation, with STI, YI, MP, GMP, stress tolerance index (STI), HM and relative stress index (RSI) contributing significantly. Two groups of characters emerged in the biplot and correlation chart: one positively correlated with both PC1 and PC2 (MP, GMP, STI and HM), while the other displayed a negative correlation with PC2. Additionally, indices within the first group were positively correlated, while TOL and SSI were negatively correlated with YSI.

Using the above indices, the biplot (Figure 6) categorised genotypes into five distinct categories based on their performance under drought and WW soil conditions: (1) tolerant and high-yielding genotypes (ODS15044, ODS15061, ODS15103, ODS15059, TOT7196 and ODS15075) form a group that clusters in the first quadrant (+X; –Y) of the biplot around the Ys and Yp indices, indicating significantly high yields under both stress (Ys) and optimal (Yp) water conditions; (2) moderately tolerant genotypes (TOT6426, TOT3536, NC05015 and ROTHWE2) cluster around the biplot's centre (0;0) and perform at an average level in both conditions; (3) genotypes characterised by drought tolerance but low yield under WW soil conditions (GA01, ELG1907A and ODS15037) are situated in the biplot's second quadrant (–X; +Y), which indicates that these genotypes exhibit high yield in DS conditions but conversely demonstrate low yield under optimal soil moisture conditions; (4) drought-sensitive and low-yielding genotypes (ROTHWE 1, ODS15020, LAIOGONGO,

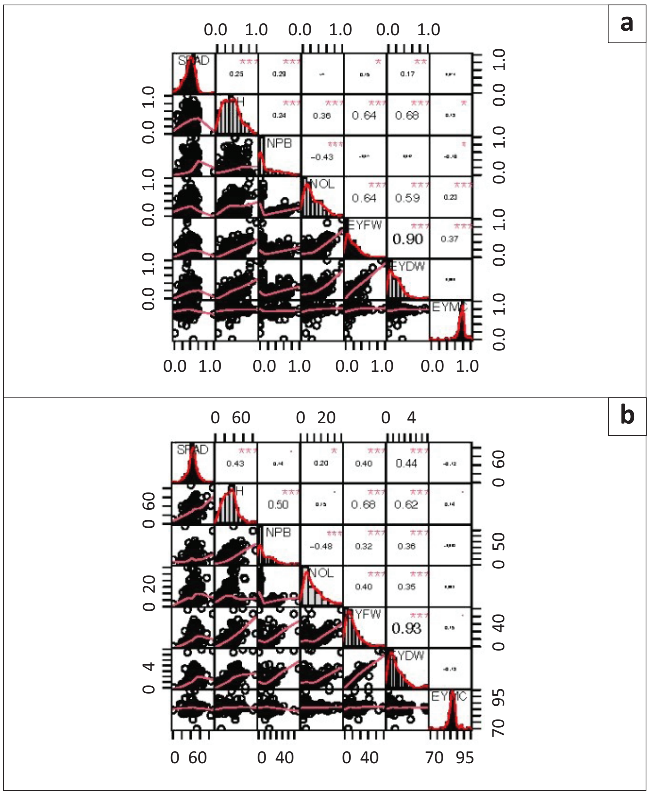


FIGURE 5: The correlation matrix illustrates the relationships between measured growth and economic yield variables under drought stress (a) and well-watered (b) conditions. The diagonal histogram depicts the distribution of each variable in both correlation charts. A bivariate scatter plot with a fitted line at the foot of the diagonal shows the pairwise correlation between the two relevant variables. The correlation's r^2-values are displayed above the diagonal. Variables included are PH (plant height in centimetres), NPB, number of primary branches; NOL, number of leaves; EYFW, economic yield fresh weight, EYDW, economic yield dry weight; EYMC, economic yield moisture content %. Furthermore, *p*-values at the 5%, 1% and 0.1% confidence levels are represented by the symbols '*', '**' and '***', respectively.

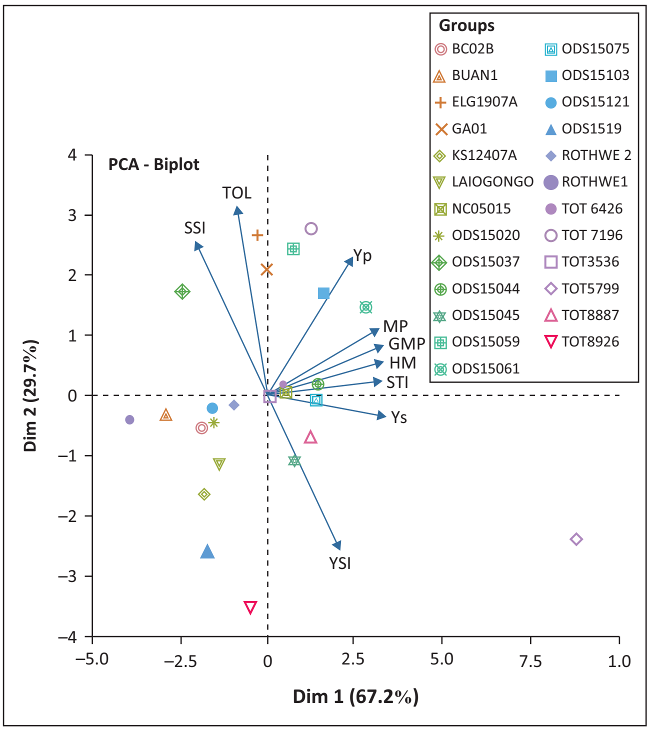


FIGURE 6: A biplot illustrates drought stress tolerance indices of EYDW for 25 spider plant genotypes under both well-watered and drought-stressed conditions, based on the first two main components Dim1 and Dim2. Variables displayed include TOL, stress tolerance; MP, mean productivity; STI, stress tolerance index; GMP, geometric mean productivity; HM, harmonic mean; Yp, economic yield under well-watered conditions; Ys, economic yield under drought stress conditions; SSI, stress susceptibility index; YI, yield index and YSI, yield stability index. Genotype (group) names are represented by various shapes in the biplot.

KSI2407A, BC02B and TOT8926) cluster in the third quadrant (–X; –Y) of the biplot, indicating low yields under both DS and optimal water conditions and (5) drought-sensitive yet high-yielding genotypes (ODS15045, TOT8887 and TOT5799) cluster in the fourth quadrant (–X; –Y) of the biplot, indicating low yield under DS but high yield under optimal soil water conditions.

Correlation analysis among the drought stress tolerance indices based on economic yield dry weight of spider plant genotypes

The WW treatment yield (Yp) was significantly ($p < 0.01$) positively correlated with TOL, MP, GMP, STI and HM indices (Figure 7). Drought-stressed treatment yield (Ys) showed significant ($p < 0.01$) positive correlations with SSI, YSI, YI, MP, GMP, STI, HM and RSI indices. The MP, STI, GMP and HM were highly positively correlated with both Ys and Yp, as well as with each other ($p < 0.01$). However, TOL and SSI had strong negative correlations with YSI ($p < 0.01$).

Cluster analysis

The UPGMA clustering divided 25 spider plant genotypes into four clusters using Euclidean distance on economic yield parameters. Cluster-2 was the largest, with 11 genotypes (44%), followed by Cluster-4 (10 genotypes, 40%), Cluster-3 (3 genotypes, 12%) and Cluster-1 with a single genotype (4%). Notably, Cluster-1 included genotype ODS15121, with a higher yield under DS but a lower yield under WW conditions. Conversely, Cluster-2 comprised genotypes with consistently low yields, like ROTHWE1, BUAN1, ODS15019, BC02B and KSI247A. Cluster-3 grouped high yield genotypes (ODS15061, ODS15059 and TOT7196), while Cluster-4 contained genotypes with intermediate yield under both conditions (TOT6426, TOT8887, GA01, NC05015 and ELG1907A) (Figure 8).

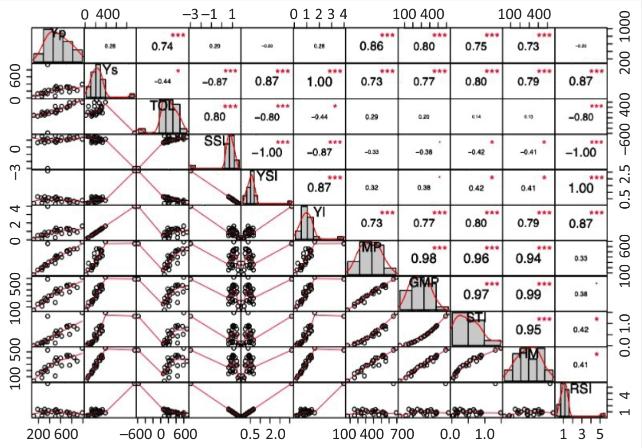


FIGURE 7: Correlation matrix for the relationships between the measured stress indices of economic yield under well-watered and drought stress conditions. The diagonal histogram displays each variable's distribution and a correlation chart. A bivariate scatter plot showing the pairwise correlation between the two relevant variables is located at the foot of the diagonal. It has a fitted line at that position. The correlation's r^2 values are located above the diagonal. Yp, economic dry yield under well-watered conditions; Ys, economic dry yield under drought stress conditions; TOL, stress tolerance; SSI, stress susceptibility index; YSI, yield stability index; YI, yield index; MP, mean productivity; GMP, geometric mean productivity; STI, stress tolerance index; HM, harmonic mean. The p-values at the 5%, 1% and 0.1% confidence levels are represented by the symbols '*', '**' and '***', respectively.

Drought-stress indices ranking

Drought-tolerance indices showed that genotypes ODS15061, ODS15075, ODS15103 and ODS15044 were the most drought tolerant with consistently high rankings and low variability. Conversely, ROTHWE1, BUAN1, BCO2B and ODS1519 were identified as sensitive genotypes. Genotypes GAO1, TOT 6426 and TOT3536 showed intermediate yields under both conditions, placing them in the intermediate category (Table 3).

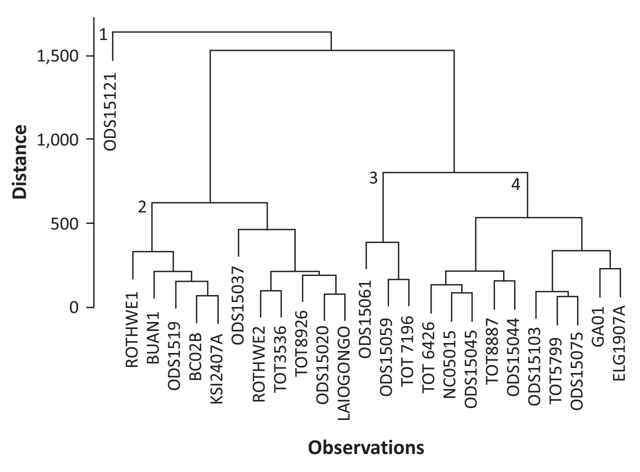


FIGURE 8: Dendrogram of cluster analysis of 25 spider plant genotypes using the UPGMA method based on Yp, Ys and drought-tolerance indices. The numbers 1 to 4 indicate the clusters of genotypes with similar drought-tolerance characteristics.

TABLE 3: The ranking of genotypes is based on drought-tolerance indices according to average sum of ranks and the standard deviation of ranks.

Genotypes	Yp	Ys	TOL	SSI	YSI	YI	MP	GMP	STI	HM	RSI	ASR	SDR
ODS15061	1	2	2	9	17	2	14	1	1	1	17	6	5.76
ODS15075	7	4	9	14	12	4	4	4	4	3	12	7	3.69
ODS15103	5	5	5	10	16	5	18	3	3	4	16	8	5.16
ODS15044	9	6	11	18	8	6	2	8	8	8	8	8	3.90
TOT8887	12	3	17	22	4	3	11	9	9	7	4	9	5.85
ODS15121	17	1	25	25	1	1	24	2	2	2	1	9	10.60
TOT7196	2	13	1	5	21	13	3	7	7	11	21	9	5.90
ODS15059	3	9	4	7	19	9	20	5	5	5	19	10	5.77
TOT5799	6	7	8	11	15	7	25	6	6	5	15	10	5.87
ODS15045	14	8	15	19	7	8	1	11	11	10	7	10	4.69
NC05015	10	10	12	17	9	10	21	10	10	9	9	12	3.79
GA01	8	16	6	6	20	16	9	14	14	15	20	13	4.57
TOT6426	11	11	10	12	14	11	23	13	13	12	14	13	3.52
TOT3536	15	14	14	16	10	14	12	15	15	13	10	13	1.66
ROTHWE2	16	12	19	21	5	12	19	16	16	14	5	14	4.36
ELG1907A	4	17	3	4	22	17	22	12	12	25	22	15	7.72
TOT8926	20	15	22	24	2	15	17	17	17	16	2	15	5.61
LAIOGONGO	19	18	18	15	11	18	5	18	18	17	11	15	4.20
ODS15020	18	21	13	8	18	21	6	19	19	18	18	16	5.03
KSI2407A	23	19	21	20	6	19	10	20	20	19	6	17	5.06
ODS15037	13	23	7	1	25	23	8	22	22	22	25	17	8.14
ODS1519	24	22	24	23	3	22	7	23	23	21	3	18	7.21
BC02B	21	20	20	13	13	20	16	21	21	20	13	18	3.07
BUAN1	22	24	16	3	23	24	15	24	24	23	23	20	6.45
ROTHWE1	25	25	23	2	24	25	13	25	25	24	24	21	7.60

ASR, average sum of ranks; SDR, standard deviation of ranks.

Note: The table ranks genotypes using a variety of indices, including Yp, yield under well-watered conditions; Ys, yield under drought stress; TOL, tolerance index; SSI, stress susceptibility index; YSI, yield stability index; YI, yield index; MP, mean productivity; GMP, geometric mean productivity; STI, stress tolerance index; HM, harmonic mean; RSI, relative stress index, as well as ASR and SDR.

Physiology studies – Leaf photosynthetic parameters

All physiological indicators tested showed a significant impact from genotype (A). Growth stages (B) and soil water stress (C) significantly affected all physiological indicators except Fv/Fm. The interaction of genotypes with soil water stress (AC) had a substantial impact on all four physiological indicators. However, interactions between genotypes and development stages (AB) or genotypes, growth stages and soil water stress (ABC) had no significant effect on the evaluated physiological indicators (Table 4).

The physiological analysis illustrates consistent patterns across the four parameters evaluated for each genotype group (Table 5). Under DS, drought-tolerant genotypes (ODS15061, ODS15044 and ODS15021) showed higher quantum yield of photosystem II and fluorescence ratio, alongside lower chlorophyll content and leaf stomatal conductance. Conversely, sensitive genotypes (ODS15019, BC02B and BUAN1) exhibited higher quantum yield of photosystem II and fluorescence ratio under WW conditions. Intermediate-tolerant genotypes (NC05015, TOT3536 and ROTHWE2) displayed no notable variations across treatments. The trends observed in the results of this study correspond with those obtained in the preliminary genotype screening study when various screening methods were employed, thereby validating their effectiveness in drought screening.

TABLE 4: The analysis of variance for the physiological indicators of spider plant grown under well-watered and drought-stressed soil conditions.

Sources of variations	Genotypes (A)	Growth stages (A)	Soil water stress (C)	AB	AC	BC	ABC
df	8	1	1	8	1	8	8
Chlorophyll content (mean SPAD)	***	***	***	ns	**	ns	ns
Stomatal conductance (mmol/m^2.s^{-1})	***	***	***	ns	***	ns	ns
Fluorescence ratio (FvP/FmP)	***	ns	ns	ns	**	ns	ns
Quantum yield of photosystem II (Phi2)	**	***	***	ns	**	ns	ns

ns, *, ** and *** indicate non-significant at 5%, 1% and 0.1% probability level, respectively; *df*, degrees of freedom.

Discussion

This study aimed to characterise 25 spider plant genotypes from various countries, focusing on growth, yield and physiological factors critical for enhancing crop resilience, especially in harsh conditions like drought. Traits like PH, branch and leaf count are vital for stress tolerance and adaptability to changing environments. Maintaining high economic yield is crucial for food security, especially in regions vulnerable to climate change, like sub-Saharan Africa. Selective breeding for plant tolerance improves resistance to stressors like drought. Techniques like BLUP, PCA and cluster analysis reveal high diversity among genotypes, offering the potential for selecting superior varieties and discovering new recombinants for genetic enhancement (Ivić et al. 2021).

A significant decrease in chlorophyll content was observed under DS during the early stage (4 weeks), followed by an increase as plants grew older (6 weeks). These variations may result from differences in plant growth status. Younger plants might lack fully developed regulatory mechanisms for chlorophyll synthesis and breakdown. These findings align with a study on necklace orchids (*Dendrobium moniliform*) under DS, showing lower chlorophyll concentrations in early vegetative phases, increasing as plants progress to late vegetative and reproductive stages (Wu et al. 2016). Moreover, the study explored DS impact on chlorophyll content and observed decreased chlorophyll levels under drought, consistent with findings on yellowhorn, where drought hindered carbon and nitrogen metabolic processes, leading to deficits in chlorophyll content. The downregulation of genes involved in chlorophyll metabolism was associated with this decline (Hu, Zhang & Guo 2023). Interestingly, while chlorophyll content showed no significant associations under drought, it exhibited modest but positive relationships with PH, EYFW and EYDW under WW conditions, suggesting its potential use in determining plant drought resistance.

In addition to economic yield, the genetic variations among studied genotypes, fluctuations in soil moisture levels and the plant's developmental stage contributed to the observed differences in PH. The interaction between growth stages and genotypes was also identified as a significant factor affecting

TABLE 5: The effects of genotypes and soil water stress on physiological parameters of spider plant grown under well-watered and drought-stressed soil conditions.

Genotypes	Quantum yield of photosystem II (Phi2)		Fluorescence ratio (FvP/FmP)		Chlorophyll (mean SPAD)		Stomatal Conductance (mmol/m2/s1)	
	DS	WW	DS	WW	DS	WW	DS	WW
ODS15061	0.63a	0.37def	0.73ab	0.73ab	47.50b	70.23a	318.05bcdefg	552.32a
ODS15044	0.63a	0.37cdef	0.74ab	0.74ab	48.64b	75.68a	319.47bcdefg	459.83abc
ODS15121	0.58ab	0.24f	0.76ab	0.72ab	44.95bc	66.90a	328.10bcdefg	546.52a
ROTHWE2	0.65a	0.55abc	0.50a	0.64abc	29.66cd	32.72bcd	163.32g	197.07fg
TOT3536	0.42bcde	0.64a	0.71bc	0.77ab	39.18bcd	27.34d	294.1cdefg	275.85cdefg
NC05015	0.52abcd	0.56ab	0.75bc	0.68abc	37.28bcd	36.29bcd	225.32defg	222.38efg
ODS15019	0.33ef	0.65a	0.37d	0.61abc	29.75cd	39.47bcd	546.02a	508.15ab
BC02B	0.44bcde	0.67a	0.36d	0.61bc	26.74d	37.95bcd	381.56abcdef	438.40abcd
BUAN1	0.34ef	0.57ab	0.46abc	0.64abc	26.74d	34.74bcd	556.2a	436.20abcde

Note: Standard error of mean (SEM): Quantum yield of photosystem II (Phi2) = 0.05; Fluorescence ratio (FvP/FmP) = 0.05; Chlorophyll (mean SPAD) = 4.67; Stomatal Conductance (mmol/m2/s1) = 58.92.
Figures followed by the same letters under each parameter do not differ significantly from each other at the 5% level of significance.
DS, drought stress; WW, well watered; SPAD, significant for chlorophyll content.

PH, suggesting that genotype's effect on PH varied depending on the plant's growth stage. However, PH is a vital agronomic indicator, reflecting the crop's vegetative growth patterns. In this study, PH showed positive correlations with EYFW ($r = 0.70$) and EYDW ($r = 0.72$), consistent with findings on lentils (*Lens culinaris*) (Naik et al. 2024). Previous studies have highlighted PH's impact on biomass yield, with taller vegetable plants often exhibiting higher rates of photosynthesis and leaf yield (Islam et al. 2018; Munene 2017). Conversely, shorter plants tend to have lower rates of photosynthesis, resulting in reduced yield (Ahanger et al. 2016).

The study revealed significant variability in branch number among spider plant genotypes, primarily influenced by growth phases rather than genotype or soil water conditions. This underscores the dynamic nature of plant growth and development, where different stages play a crucial role in shaping branching patterns. These findings align with a recent study that highlighted the developmental influences on various plant morphological traits and the importance of developmental signals, including hormone signalling, in regulating the branching patterns of yellowhorn (Li et al. 2021). Some studies highlighted positive relationships between leaves and branches in spider plants (Ambuko et al. 2020; Gonye et al. 2017). However, this study revealed a weak negative correlation ($r = –0.48$), suggesting that genetic factors influenced the balance between branching and leaf development. These findings are consistent with a study on wild oak trees (*Quercus suber*) under DS, which reported a negative correlation between branch and leaf numbers, indicating a prioritisation of leaf creation over branch formation because of resource allocation trade-offs within the plant (Fallon & Cavender-Bares 2018). The study underscores the complex interplay of genotypes, growth stages and soil water conditions on leaf number in spider plants, highlighting the importance of considering both crop physiology and environmental factors. Moreover, interactions between the growth stage and soil water reveal the dynamic response of spider plants to changing environmental conditions, showcasing the diversity of mechanisms controlling leaf growth physiology among spider plant genotypes.

Furthermore, the study highlights the impact of growth phases on leaf number, emphasising the role of reproductive processes in regulating leaf initiation and extension. Variations in leaf quantity across growth phases are linked to diverse physiological processes, illustrating the complexity of factors influencing leaf production dynamics (Ahmed et al. 2019; Liang et al. 2020; Vashi, Patel & Bardhan 2020). The study elucidates the factors influencing leaf production in spider plants, noting that plants allocated energy to leaf initiation and expansion in early growth stages, progressively increasing leaf quantity as the canopy developed. Additionally, developmental changes, such as the onset of reproductive growth or senescence, further influenced leaf production dynamics. Hormonal regulation plays a crucial role in coordinating leaf development, with variations in hormone levels and signalling pathways governing leaf start, growth and senescence (Ambuko et al. 2020).

The relationship between growth stages and DS showed how leaf output varied between vegetative and reproductive phases under drought conditions. As plant growth progressed, leaf yield declined, attributed to DS-induced leaf shedding, which helps mitigate water loss during drought periods (Ambuko et al. 2020). These findings are supported by similar observations in other plant species, such as *Scarlet aubergine*, where a significant decrease in leaf number occurred as plants transitioned from vegetative to reproductive growth stages under drought conditions (Nakanwagi et al. 2020). Indeed, water scarcity can disrupt essential processes like water and nutrient intake, reducing the accumulation of photosynthates and leaf turgor, ultimately decreasing leaf number (Razi & Muneer 2021). It is further reported that DS leads to a decrease in leaf count, agreeing with prior research on spider plants, indicating a correlation between reduced leaf numbers and DS severity, which underscores the connection between lower leaf numbers and decreased leaf production during drought (Mosenda et al. 2020).

Variations in economic yield linked to soil moisture levels may result from reduced photosynthesis because of drought-induced stomatal closure, limiting carbon dioxide intake and biomass production (Razi & Muneer 2021). Drought stress can also reduce water and nutrient availability in the soil, hampering nutrient uptake and overall growth (Razi & Muneer 2021). Under DS, plants prioritise essential activities like root growth and stress tolerance mechanisms, diverting energy from growth and yield production (Mai et al. 2023). Moreover, the positive relationship between leaf number and economic yield under DS aligns with previous findings in crops like amaranth and potatoes (Gedam et al. 2021; Jamalluddin et al. 2021). Increased leaf count enhances photosynthetic surface area, improving light interception and carbon assimilation, thereby promoting growth and yield (Proulx 2021).

The study utilised PCA to assess economic yield performance under DS and employed indicators like MP, GMP, STI and HM, which correlated positively with both Yp and Ys (Figure 6). Similar studies on lentils (Naik et al. 2024) and wheat (Khan & Mohammad 2016) have been conducted to evaluate environmental tolerance using genotype selection indicators and PCA. The study categorised genotypes into five groups based on their performance under DS (PC1) and WW (PC2) conditions, which agrees with previous studies in lentil and wheat genotypes selection studies (Khan & Mohammad 2016; Naik et al. 2024).

In addition to the PCA, the study utilised cluster analysis and the BLUP method to identify drought-tolerant spider plant genotypes. Cluster analysis enables the grouping of genotypes into different clusters for the exploration of genetic diversity (Naik et al. 2024). Poor economic yields in Cluster-2 (Figure 8) may be attributed to increased membrane damage and altered enzyme activities, increasing their drought sensitivity (Aghaie et al. 2018). Similar selection methods have been used in tomatoes

(Aghaie et al. 2018) and wheat (Ghodke et al. 2019). Similarly, the ranking selection method was also employed to identify drought-tolerant cultivars based on all indices, mean rank and standard deviation. Genotypes were categorised as tolerant, intermediate and sensitive, based on their performance. Tolerant genotypes exhibited the best mean rank and low standard deviation, while sensitive cultivars had the highest mean rank and the lowest standard deviation (Aghaie et al. 2018).

Crop breeding heavily relies on economic yield characteristics to identify drought-tolerant genotypes, with economic yield used for all three selection methods in this study. The results consistently categorised similar genotypes as tolerant, moderate or sensitive to DS. The physiological study focusing on leaf fluorescence indices (Phi2, FmP/FvP, SPAD and stomatal conductance) validated these selections, confirming the results from ranking, PCA and cluster analysis and providing comprehensive validation of genotype classification.

The leaf fluorescence investigation revealed that drought-tolerant genotypes such as ODS15061, ODS15044 and ODS15021 exhibited higher levels of photosynthetic activity and adaptive responses to water scarcity, demonstrating effective water conservation strategies through reduced chlorophyll content and stomatal conductance. These findings underscore that these drought-tolerant genotypes have the ability to maximise photosynthetic efficiency and minimise water loss under DS. Similar trends of leaf photosynthetic parameters were recently reported on DS tomatoes and potato crops (Liang et al. 2020). Conversely, genotypes ODS15019, BC02B and BUAN1 exhibited better photosynthetic activity in WW conditions than under DS, indicating vulnerability to DS because of reliance on optimal water supply for efficient photosynthesis, consistent with research on Amaranth (*Amaranthus tricolour*) (Sarker & Oba 2018). Genotypes NC05015, TOT3536 and ROTHWE2 showed consistent physiological features, indicating moderate drought tolerance. While not as resilient as highly tolerant genotypes, these genotypes maintained stability despite water fluctuations, consistent with findings in other crops (Jamalluddin et al. 2021; Nemeskéri & Helyes 2019).

Conclusion

This study used various analytical methods, including ranking indices, BLUP, PCA and cluster analysis, to evaluate *C. gynandra* genotype selection in WW and DS conditions. Leaf photosynthesis analysis confirmed drought tolerance, identifying promising drought-tolerant and susceptible genotypes. These insights aid in enhancing drought resilience in *C. gynandra*, especially in water-scarce regions. The findings consistently categorised the genotypes, particularly regarding genotype selection and leaf photosynthesis analysis. This suggests that the photosynthetic analysis, which is more cost effective, non-destructive and consequently less labour intensive, can be utilised effectively and efficiently to conclusively identify drought-tolerant genotypes. The utility of leaf photosynthetic analysis demonstrated in this study indicates that this approach can effectively screen genotypes for drought tolerance in genetic and physiological studies. In conjunction with these findings, it is imperative that future studies undertake an assessment of these genotypes through multi-location and multi-year field trials. Incorporating leaf photosynthetic analysis under random and simulated DS conditions would further validate the results obtained in greenhouse environments. This approach would provide more robust insights that are useful for smallholder farmers who cultivate *C. gynandra* for household consumption and commercial purposes.

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Competing interests

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Authors' contributions

L.M.N. contributed to the conceptualisation, resources, formal analysis, visualisation, writing of the original draft and investigation. G.M. was responsible for the analysis, visualisation, writing, review and editing. O.O. contributed towards conceptualisation and supervision. U.B. contributed towards the conceptualisation, supervision, resources, validation, writing, review and editing. L.M.N., G.M., O.O. and U.B. read and approved the final accepted version of this article for publication.

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Data availability

The data that support the findings of this study are available from the corresponding author, U.B., upon reasonable request.

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References

Afolayan, A.J. & Jimoh, F.O., 2009, 'Nutritional quality of some wild leafy vegetables in South Africa', *International Journal of Food Sciences and Nutrition* 60(5), 424–431. https://doi.org/10.1080/09637480701777928

Aghaie, P., Hosseini Tafreshi, S.A., Ebrahimi, M.A. & Haerinasab, M., 2018, 'Tolerance evaluation and clustering of fourteen tomato cultivars grown under mild and severe drought conditions', *Scientia Horticulturae* 232, 1–12. https://doi.org/10.1016/j.scienta.2017.12.041

Ahanger, M.A., Morad-Talab, N., Abd-Allah, E.F., Ahmad, P. & Hajiboland, R., 2016, 'Plant growth under drought stress: Significance of mineral nutrients', *Water Stress and Crop Plants: A Sustainable Approach* 2–2, 649–668. https://doi.org/10.1002/9781119054450.ch37

Ahmed, H.G.M.D., Sajjad, M., Li, M., Azmat, M.A., Rizwan, M., Maqsood, R.H. et al., 2019, 'Selection criteria for drought-tolerant bread wheat genotypes at seedling stage', *Sustainability (Switzerland)* 11(9), 2584. https://doi.org/10.3390/su11092584

Ambuko, J., Mosenda, E., Chemining'wa, G. & Owino, W., 2020, 'Effect of water stress on growth and yield components of selected spider plant accessions', *Journal of Medicinally Active Plants* 9(2), 81. https://doi.org/10.7275/r7cg-3s40

Etminan, A., Pour-Aboughadareh, A., Mohammadi, R., Shooshtari, L., Yousefiazarkhanian, M., & Moradkhani, H., 2019, 'Determining the best drought tolerance indices using artificial neural network (ANN): Insight into application of intelligent agriculture in agronomy and plant breeding', *Cereal Research Communications* 47(1), 170–181. https://doi.org/10.1556/0806.46.2018.057

Fallon, B. & Cavender-Bares, J., 2018, 'Leaf-level trade-offs between drought avoidance and desiccation recovery drive elevation stratification in arid oaks', *Ecosphere* 9(3), e02149. https://doi.org/10.1002/ECS2.2149

Fernandez, G.C.J., 1992, 'Effective selection criteria for assessing plant stress tolerance', in C.G. Kuo (ed.), *Adaptation of food crops to temperature and water stress*, pp. 257–270, Asian Vegetable Research and Development Center (AVRDC), Shanhua, Taiwan.

Gedam, P.A., Thangasamy, A., Shirsat, D.V., Ghosh, S., Bhagat, K.P., Sogam, O.A. et al., 2021, 'Screening of onion (Allium cepa L.) genotypes for drought tolerance using physiological and yield based indices through multivariate analysis', *Frontiers in Plant Science* 12, 600371. https://doi.org/10.3389/fpls.2021.600371

Ghodke, P.H., Ramakrishnan, S., Shirsat, D.V., Vani, G.K. & Arora, A., 2019, 'Morphological characterization of wheat genotypes for stay green and physiological traits by multivariate analysis under drought stress', *Plant Physiology Reports* 24(3), 305–315. https://doi.org/10.1007/s40502-019-00458-8

Gonye, E., Kujeke, G.T., Edziwa, X., Ncube, A., Masekesa, R.T., Icishahayo, D. et al., 2017, 'Field performance of spider plant (Cleome Gynandra L) under different agronomic practices', *African Journal of Food, Agriculture, Nutrition and Development* 17(3), 12179–12197. https://doi.org/10.18697/ajfand.79.15985

Hu, F., Zhang, Y. & Guo, J., 2023, 'Effects of drought stress on photosynthetic physiological characteristics, leaf microstructure, and related gene expression of yellow horn', *Plant Signaling and Behavior* 18(1). https://doi.org/10.1080/15592324.2023.2215025

Islam, M., Karim, R., Hosain Oliver, M., Urmi, T.A., Hossain, A. & Haque, M.M., 2018, 'Impacts of trace element addition on Lentil (Lens culinaris L.) agronomy', *Agronomy* 8(7), 100. https://doi.org/10.3390/AGRONOMY8070100

Ivić, M., Grljušić, S., Popović, B., Andrić, L.A., Plavšin, I., Dvojković, K.D. et al., 2021, 'Screening of wheat genotypes for nitrogen deficiency tolerance using stress screening indices', Agronomy 11(8), 1544. https://doi.org/10.3390/agronomy11081544

Jamalluddin, N., Massawe, F.J., Mayes, S., Ho, W.K., Singh, A. & Symonds, R.C., 2021, *Physiological screening for drought tolerance traits in vegetable Amaranth (Amaranthus tricolor) Germplasm*, MDPI AG, Basel, Switzerland.

Junker, A., Muraya, M.M., Weigelt-Fischer, K., Arana-Ceballos, F., Klukas, C., Melchinger, A.E. et al., 2015, 'Optimizing experimental procedures for quantitative evaluation of crop plant performance in high throughput phenotyping systems', *Frontiers in Plant Science* 5, 770. https://doi.org/10.3389/fpls.2014.00770

Khan, F.U. & Mohammad, F., 2016, 'Application of stress selection indices for assessment of nitrogen tolerance in wheat (Triticum aestivum L.)', *The Journal of Animal & Plant Sciences* 26(1), 201.

Li, G., Hu, S., Zhao, X., Kumar, S., Li, Y., Yang, J. et al., 2021, 'Mechanisms of the morphological plasticity induced by phytohormones and the environment in plants', *International Journal of Molecular Sciences 2021* 22(2), 765. https://doi.org/10.3390/ijms22020765

Liang, G., Liu, J., Zhang, J. & Guo, J., 2020, 'Effects of drought stress on photosynthetic and physiological parameters of tomato', *Journal of the American Society for Horticultural Science* 145(1), 12–17. https://doi.org/10.21273/JASHS04725-19

Madumane, K., Sewelo, L.T., Nkane, M.N., Batlang, U. & Malambane, G., 2024, 'Morphological, physiological, and molecular stomatal responses in local watermelon landraces as drought tolerance mechanisms', *Horticulturae 2024* 10(2), 123. https://doi.org/10.3390/HORTICULTURAE10020123

Mai, W., Ali, R., Azeem, A., Mai, W. & Ali, R., 2023, 'Modeling plant height and biomass production of cluster bean and Sesbania across diverse irrigation qualities in Pakistan's Thar Desert', *Water* 16(1), 9. https://doi.org/10.3390/W16010009

Maseko, I., Ncube, B., Mabhaudhi, T., Tesfay, S., Chimonyo, V.G.P., Araya, H.T. et al., 2019, 'Moisture stress on physiology and yield of some indigenous leafy vegetables under field conditions', *South African Journal of Botany* 126, 85–91. https://doi.org/10.1016/j.sajb.2019.07.018

Mosenda, E., Chemining'wa1, G., Ambuko, J. & Owino, W., 2020, 'Assessment of agronomic traits of selected spider plant (Cleome gynandra L.) accessions', *Journal of Medicinally Active Plants* 9(4), 222.

Moyo, M. & Aremu, A.O., 2020, 'Nutritional, phytochemical and diverse health-promoting qualities of *Cleome gynandra*',*Critical Reviews in Food Science and Nutrition* 62(13), 3535–3552. https://doi.org/10.1080/10408398.2020.1867055

Munene, A.K., 2017, *Genetic Characterization and nutritional analysis of Eastern and South African Cleome Gynandra (spider plant) accessions*, University of Nairobi, Nairobi, Kenya.

Naik, Y.D., Sharma, V.K., Aski, M.S., Rangari, S.K., Kumar, R., Dikshit, H.K. et al., 2024, 'Phenotypic profiling of lentil (*Lens culinaris* Medikus) accessions enabled identification of promising lines for use in breeding for high yield, early flowering and desirable traits', *Plant Genetic Resources: Characterization and Utilization* 22(2), 69–77. https://doi.org/10.1017/S1479262124000042

Nakanwagi, M.J., Sseremba, G., Kabod, N.P., Masanza, M. & Kizito, E.B., 2020, 'Identification of growth stage-specific watering thresholds for drought screening in Solanum aethiopicum Shum', *Scientific Reports* 10(1), 1–11. https://doi.org/10.1038/s41598-020-58035-1

Nemeskéri, E. & Helyes, L., 2019, 'Physiological responses of selected vegetable crop species to water stress', *Agronomy* 9(8), 447. https://doi.org/10.3390/AGRONOMY9080447

Ochieng, D.B., Owaga, E.E. & Njoroge, D.M., 2018, 'Effect of selected processing methods on the nutritional and anti-nutritional properties of spider plant (GynandropsisGynandra)', *Journal of Agricultural and Food Chemistry* 8(1), 1–9.

Onyango, C., Onwonga, R. & Kimenju, J., 2016, 'Assessment of spider plant (Cleome gynandra L.) germplasm for agronomic traits in vegetable and seed production: A green house study', *American Journal of Experimental Agriculture* 10(1), 1–10. https://doi.org/10.9734/AJEA/2016/20209

Proulx, R.L., 2021, 'On the general relationship between plant height and aboveground biomass of vegetation stands in contrasted ecosystems', *PLoS One* 16(5), e0252080. https://doi.org/10.1371/JOURNAL.PONE.0252080

Razi, K. & Muneer, S., 2021, 'Drought stress-induced physiological mechanisms, signaling pathways and molecular response of chloroplasts in common vegetable crops', *Critical Reviews in Biotechnology* 41(5), 669–691. https://doi.org/10.1080/07388551.2021.1874280

Sarker, U. & Oba, S., 2018, 'Catalase, superoxide dismutase and ascorbate-glutathione cycle enzymes confer drought tolerance of Amaranthus tricolor', *Scientific Reports* 8(1), 1–12. https://doi.org/10.1038/s41598-018-34944-0

Sharma, R., Chaudhary, L., Kumar, M., Yadav, R., Devi, U., Amit et al., 2022, 'Phenotypic diversity analysis of lens culinaris Medik. Accessions for selection of superior genotypes', *Sustainability (Switzerland)* 14(10), 5982. https://doi.org/10.3390/su14105982

Vashi, H.D., Patel, P.P. & Bardhan, K., 2020, 'Growth and physiological responses of vegetable crops to water deficit stress', *Journal of Experimental Agriculture International* 42(5), 91–101. https://doi.org/10.9734/jeai/2020/v42i530523

Wakhisi, C.W., Michael, G.M. & Mwangi, E., 2020, 'Mineral and phytochemical composition of Cleome Gynandra methanolic extract', *Advanced Journal of Graduate Research* 8(1), 18–26. https://doi.org/10.21467/ajgr.8.1.18-26

Wu, X., Yuan, J., Luo, A., Chen, Y. & Fan, Y., 2016, 'Drought stress and re-watering increase secondary metabolites and enzyme activity in dendrobium moniliforme', *Industrial Crops and Products* 94, 385–393. https://doi.org/10.1016/J.INDCROP.2016.08.041