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Identification of Drought-Tolerant Okra (Abelmoschus esculentus) Genotypes using Multivariate Analysis

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ABSTRACT

Okra (*Abelmoschus esculentus*), a nutritionally valuable crop, is highly susceptible to drought stress, which significantly impacts its yield and quality, necessitating research into mitigation strategies. During the 2021-2022 growing season, a field experiment was conducted at the Seed and Plant Improvement Institute in Karaj, Iran, to assess the effects of water stress on quantitative and qualitative traits of 15 okra genotypes (G1-G15). A split-plot design in a randomized complete block (RCBD) with three replications was employed, comparing two irrigation regimes: optimal (5 d interval) and severe stress (10 d interval). Water stress significantly affected various plant traits, as evidenced by the high coefficients of variation, indicating genetic diversity in stress responses. Under non-stress conditions, genotypes G1, G2, G7, and G10 showed fruit yields of approximately 14.87, 19.09, 16.61, and 16.54 t ha^{-1}, respectively. However, severe water stress resulted in substantial yield reductions in these genotypes (approximately 67.3, 48.9, 28.83, and 27.08%, respectively). Conversely, genotypes G9 and G11 showed relatively lower yield reductions, with G9 maintaining a yield of approximately 7.39 t ha^{-1} under water stress (1.62% reduction) and G11 yielding around 7.99 t ha^{-1} (2.0% reduction), suggesting drought tolerance. Genotype G10 demonstrated notable performance under water stress, yielding 12.06 t ha–1 with a 27.0% reduction. Under non-stress conditions, fruit and biological yields were positively correlated with vegetative growth indices and fruit traits, but these correlations weakened under water stress. Principal component analysis (PCA) highlighted variations in trait associations and their contributions to variability between the two water regimes. Cluster analysis revealed distinct genotypic groupings under both irrigation conditions. Under non-stressed conditions, cluster 1 (G1, G7) exhibited high productivity with fruit yield of 15.745 t ha^{-1}, biological yield of 82.50 t ha^{-1}, and 100 seeds per plant. Under water stress, cluster 2 (G2, G5, G7, G10, G11, G13) showed superior performance in yield-related traits. Genotypes G10, G11, and G5 exhibited superior tolerance to water stress, highlighting their potential for breeding programs aimed at enhancing drought resilience in okra. These findings emphasize the crucial influence of water stress on okra production and the importance of genotypic selection for improved crop performance under drought conditions.

Introduction

Water stress, a significant form of abiotic stress, has increasingly emerged as one of the foremost challenges confronting farmers globally. This form of stress inflicts considerable damage on agricultural productivity and leads to a reduction in the area under cultivation (Roy et al., 2025). The effects of

water scarcity extend beyond mere yield losses, contributing to diminished crop quality and heightened vulnerability to pests and diseases (Barzegar et al., 2016; Xu et al., 2024). Moreover, drought conditions exacerbate soil erosion, reduce biodiversity, and contribute to increased greenhouse gas emissions. With climate change projected to elevate both the frequency and intensity of drought events, the development of drought-resistant crops becomes essential for securing future food supplies (Roy et al., 2025).

Okra (*Abelmoschus esculentus*), a member of the Malvaceae family, stands out as a vital vegetable in tropical and subtropical climates, particularly in southern Iran, and enjoys significant popularity in global markets (Fattahi et al., 2023; Kwok et al., 2025). Native to Africa, okra is highly valued for its nutritional content, which includes proteins, essential amino acids, minerals, fibers, and carbohydrates (Maliha et al., 2022).

By 2050, the global population is anticipated to increase from 7 billion to approximately 9 billion, necessitating a 60-110% increase in food production to meet the demands of this growing population (Godoy et al., 2021). To fulfill these food requirements, it is crucial to develop drought-resistant plants and their suitable varieties (Towolawi et al., 2024)

Okra is one of the plants that produces a deep main root and also has dense surface roots at shallow depths of the soil. Therefore, it can tolerate drought stress to some extent, and at the same time, water consumption by this plant is high (Farhan and Sugirtharan, 2023). Hence, to achieve optimal performance in okra, it is necessary to provide sufficient water during the growth period (Patra et al., 2023). The impact of water shortage on the okra plant varies depending on the severity of stress, duration of stress, type of variety, stage of crop growth, and the extent to which a plant can withstand water stress is determined by its ability to physiologically recover and survive (Asante et al., 2024; Udpuay et al., 2024). Depending on the type of variety, water shortage can prevent fruit formation in okra, in addition to delaying flowering and causing a sharp drop in yield (Asante et al., 2024).

Water stress leads to a decrease in dry matter production, leaf area index, plant height, fruit count per plant, biological yield, and fruit yield in okra (Ayub et al., 2021; Wakchaure et al., 2023). In addition, water shortage can cause changes in protein content (decrease) and sugar content (increase) in the okra plant (Younis et al., 2024). Eskandari and Alizadeh-Amraie (2017) reported that increasing irrigation intervals reduced dry matter accumulation, leaf area index, plant height, fruit number per plant, biological yield, and fruit yield in okra. Specifically, when irrigation intervals were extended from 70 mm to 160 mm cumulative evaporation, fruit yield declined by 31%, indicating a direct and proportional relationship between irrigation frequency and yield loss. A study reported that in okra, water stress leads to a reduction in photosynthetic pigments, including chlorophyll, and an increase in the activity of antioxidant enzymes such as catalase and peroxidase (Shaki et al., 2014).

Despite its nutritional value and status as a staple crop in tropical and subtropical regions, okra is increasingly threatened by water scarcity due to climate change and growing population demands (Uwiringiyimana et al., 2024; Maliha et al., 2022). Identifying drought-tolerant genotypes is crucial for ensuring food security, maintaining crop productivity, and preserving okra's nutritional quality under water-limited conditions. Understanding genotypic responses to water stress can inform breeding programs aimed at developing resilient cultivars, benefiting farmers in arid and semi-arid regions. However, comprehensive studies evaluating diverse okra genotypes under both non-stressed and water-stressed conditions remain limited. Therefore, this study aims to assess the performance of various okra genotypes under these conditions, providing a foundation for enhancing drought tolerance and sustainable production.

Materials and Methods

Plant materials and experimental design

A field experiment was conducted during the 2021-2022 growing season at the research farm of the Seed and Plant Improvement Institute in Karaj, Iran (coordinates: 50°54' E, 35°55' N; elevation: 1312.5 m.a.s.l.). The experiment employed a split-plot design within a randomized complete block framework, with three replications. It investigated the effects of varying water stress levels, from no stress to severe stress, on 15 okra genotypes (Table 1). Karaj, characterized by a semi-arid climate, experiences hot and dry summers, cold and humid winters, and an average annual precipitation of approximately 239.5 mm. Table 2 presents the physicochemical characteristics of the soil in the experimental field, as well as the mean monthly precipitation and temperature data.

Water stress included optimal irrigation (every 5 d) and severe water stress (every 10 d), based on okra's physiological thresholds, Karaj's climatic conditions, and established research benchmarks, ensuring minimal and severe stress conditions, respectively. The required chemical fertilizers were used based on the soil test results and recommendations from the Soil and Water Research Department. According to the soil test findings, 100 kg ha^{-1} of triple superphosphate and 100 kg ha^{-1} of potassium sulfate were added to the soil during the fall as part of the land preparation process. Furthermore, to meet nitrogen requirements, 150 kg

ha^{-1} of urea was applied, with one-third applied before planting and the remaining two-thirds applied during the stem elongation and flowering stages. Seeds were sown manually in mid-June at a depth of 2 cm. The spacing between the seeds in the rows was 30 cm, while the spacing between the rows was 60 cm. Each plot consisted of four rows, each measuring 2 m in length, with a 60 cm gap between the rows, covering a total area of 5 m^2. To prevent moisture leakage, a distance of 6 m was maintained between experimental plots. All treatments were irrigated by flooding. It is important to note that to achieve optimal plant density, thinning was conducted at the six-leaf stage. Prior to planting, the seeds were treated with benomyl fungicide at a ratio of 2 g 1000 g^{-1} to prevent soil-borne diseases. Throughout the growth period, weeds were manually controlled several times.

Table 1. List of evaluated okra (*Abelmoschus esculentus*) genotypes with corresponding codes, sample numbers, and geographic origin in this study.

Code	Genotype	Region
G1	38	Zabol
G2	Vikima	-
G3	43	Azerbaijan
G4	48	Azerbaijan
G5	49	Lorestan
G6	52	Sistan
G7	53	Sistan
G8	63	Sistan
G9	74	Khuzestan
G10	83	Khorasan
G11	105	Lorestan
G12	111	Kurdistan
G13	161	Sistan
G14	Arzuman	-
G15	156	Khuzestan

Table 2. Physicochemical properties of soil (0–30 cm depth) at the experimental site prior to planting.

Soil depth (cm)	Organic carbon (%)	pH	Salinity (dS m^{-1})	Phosphorus (mg kg^{-1})	Potassium (mg kg^{-1})
0-30	0.47	8.5	1.26	5.29	228

Table 3. Average monthly temperature and rainfall recorded during the plant growth period at the experimental site.

Month	Rainfall (mm)	Temperature (°C)
April	103	12.23
May	25.6	20.62
June	0	25.21
July	0.7	27.15
August	0	24.09
September	0	21.65
October	17.2	14.5

Measurement of phenological and morphological traits

The study documented key phenological traits, specifically the initiation dates for flowering and fruiting milestones: flowering initiation, 50% flowering, 100% flowering, fruiting initiation, and 50% fruiting. To assess fruit growth, measurements were taken over a 4 d period in early September. Additionally, the time from planting to the emergence of the first flower and fruit was meticulously recorded. Morphological traits, including stem height, stem diameter, and petiole diameter, were evaluated in three selected plants subjected to both water stress and non-stress conditions during the mid-growth phase in late September. Measurements involved the assessment of stem height as well as the diameter and length of selected leaves, utilizing calipers and rulers for accuracy. To monitor plant development over time, one complete plant (excluding roots) was harvested every 20 d, dried, and weighed to determine biomass. Leaf area was also measured to facilitate the calculation of the leaf area index. This systematic approach allowed for a comprehensive analysis of plant responses to varying environmental conditions.

Measurement of fruit characteristics

These measurements were conducted at specific growth stages to track development and quality. Fruits were harvested ten times at 2 d intervals. The yields of six randomly selected plants were harvested separately and transferred to the laboratory for the evaluation of fruit weight per ha, fruit yield, fruit diameter, number of fruits, fruit length, and number of seeds per fruit. The 1000-seed weight was determined by weighing four samples of 250 seeds each using a balance. At harvest, an area of 2.5 m^2, considering border effects, was harvested to determine the seed yield. At the end of the growing season in November, to minimize edge effects, the two outer rows and half a meter from both ends of each plot were excluded. From the remaining area, six plants were randomly selected and harvested from each plot. Key traits such as plant height and biological yield were then carefully measured to assess the performance of each genotype under the given conditions.

Extraction of mucilage

Mucilage extraction was performed according to the protocol defined by Farooq et al. (2013). 2 g of each ground okra sample were accurately weighed and mixed with 50 mL of distilled water. The solution was continuously stirred at 60 °C for 4 h to facilitate mucilage dissolution. After stirring, the solution was filtered and stored at 4-6 °C for 30 min to allow further separation. Subsequently, 30 mL acetone was added to induce mucilage precipitation. The mixture was filtered a second time to isolate the precipitated mucilage. The collected mucilage the mucilage was placed in an oven set to a temperature range of 35-45 °C and left to dry for 24 h. Afterward, the dried mucilage was weighed and recorded for further analysis.

Determination of moisture content

The fresh weight of okra pods was recorded immediately after harvest, followed by a second weighing post-drying to determine dry matter. These measurements allowed for the calculation of moisture content and dry matter percentage, providing insights into the pods' water retention and nutritional composition (Syaiful et al., 2025).

Determination of soluble and insoluble sugar content

The phenol-sulfuric acid method was employed to determine the soluble sugar content, using glucose as the reference standard (Dubois et al., 1956). The soluble sugar content of okra pods was expressed as mg of sugar per gram of dry okra pods, calculated using the following equation:

$$Y = 465.46x - 111.41\ (R2 = 0.9783)$$

Equation 1

Insoluble sugars were measured by drying the plant tissue residues at 50 °C for 2 h. Afterward, 4.5 mL of distilled water and 6 mL of 52% perchloric acid were introduced to the dried residues, and the samples were stored in a cold room overnight. Then, the samples underwent centrifugation at 3000 rpm for a duration of 10 min. The supernatant was then extracted and diluted with distilled water to reach a total volume of 30 mL. A 1 mL aliquot of the solution was placed in a vial, then 0.5 mL of 5% phenol and 2.5 mL of 98% sulfuric acid were added. The samples were allowed to develop color for 45 min under a fume hood, and the absorbance was recorded at 485 nm with a spectrophotometer.

Measurement of fiber content

The fiber content was assessed using the ISIRI 3394 procedure. A sample weighing 2 g was combined with 200 mL of sulfuric acid in a 1-liter Erlenmeyer flask and brought to a boil for 30 min. Following filtration, 200 mL of sodium hydroxide was introduced, and the mixture was boiled again for another 30 min. The insoluble residue was then placed in a crucible and rinsed with boiling water and hydrochloric acid. Further washing was done with ethanol and acetone, after which the residue was dried at 103 °C for 2 h, cooled, and weighed. It was subsequently heated at 600 °C for 24 h and weighed again. The crude fiber percentage (W) was determined as follows:

$$W = (\frac{M1 - M2}{M0}) \times 100$$

M0: the sample's weight in g, M1: the weight of the crucible along with the residue post-drying in g, and M2: the weight of the crucible and residue after being heated in g.

Determination of total protein concentration

The Bradford method (Bradford, 1976) was employed to determine the total protein concentration in dry okra pods. To do this, 1 mL of Bradford solution and 0.02 g of plant extract were introduced, and the absorbance was recorded at a wavelength of 595 nm using a spectrophotometer (Cecil. CE9200, England). Bovine serum albumin at four concentrations of 15, 30, 60, and 90 mg L^{-1} was used to create a protein standard curve. The total protein content of okra pods was calculated as mg g^{-1} of dry okra pods, using Equation 2:

$$Y = 1670.1x - 184.61 \ (R2 = 0.9715)$$

Equation 2

Statistical analysis

Prior to analysis, the normality of experimental errors was assessed using the Kolmogorov-Smirnov test, and the equality of variances was evaluated with Levene's test, both conducted in MSTAT-C software version 1.4. Subsequent statistical analyses, including correlation studies, cluster analysis, stepwise regression, and principal component analysis (PCA), were performed using Excel 2018 and Minitab 18, ensuring robust and comprehensive data interpretation.

Results

Genotypic variation

Table 4 presents a comparative analysis of 15 okra genotypes under water stress and non-stress conditions, highlighting the significant impact of water stress on various plant traits while also revealing considerable genetic variation among these genotypes. The high coefficients of variation (CV), particularly under water stress conditions, indicate pronounced genetic differences in stress responses, which are evident in traits such as flowering and fruiting time, vegetative growth (stem height, LAI, stem, and leaf diameter), fruit and seed characteristics (diameter, length, number, weight, yield, 1000-seed weight, and number), and chemical composition (mucilage content, moisture content, soluble and total sugars, fiber content, and protein content). The significant reductions in these parameters suggest an overall decline in plant performance under water-stress conditions. However, some genotypes were able to maintain better performance under water stress, indicating the presence of stress resistance genes in these genotypes.

Figure 1 presents a comparative analysis of fruit yield and its reduction percentage across 15 okra genotypes (G1 to G15) under non-stress and water stress conditions. The results clearly show that water stress significantly reduced fruit yield in all genotypes, as visually demonstrated by the comparison of black bars (water stress) and white bars (non-stress), highlighting the substantial impact of stress on yield performance. However, the extent of the yield reduction varied among the genotypes, as illustrated by the red trend line (reduction percentage). Genotypes G1, G2, G7, and G10 with fruit yields of approximately 14.87, 19.09, 16.61, and 16.54 t ha^{-1} under non-stress conditions, demonstrated high yield potential. However, these genotypes experienced substantial yield reductions under water stress, by approximately 67.3, 48.9, 28.83, and 27.08%, respectively. In contrast, genotypes G9 and G11 showed relatively lower reductions in yield. Genotype G9 maintained a yield of approximately 7.39 t ha^{-1} under water stress, with only a 1.62% reduction, while genotype G11 yielded around 7.99 t ha^{-1} with an approximate 2.0% reduction. These results indicate the drought tolerance potential of the genotypes G9 and G11. The reduction percentage trend (red line) suggests that some genotypes maintained better performance under stress conditions despite having lower absolute yields. These drought-tolerant genotypes, like G9 and G11 may be ideal for breeding initiatives focused on enhancing okra's drought tolerance. Moreover, genotype G6 stands out due to its yield of 6.72 t ha^{-1} under water stress, experiencing a 35.5% reduction in yield, highlighting its notable performance in challenging conditions.

Correlation patterns

Correlation analysis of various traits in okra genotypes under non-stress and water stress conditions revealed significant differences in the relationships among morphological, physiological, and biochemical characteristics. Under non-stress conditions, traits such as fruit yield (27) and biological yield (28) exhibited strong positive correlations with vegetative growth indices, including stem height (7) and leaf area index (LAI, 8–11). This indicates that plant growth directly influences yield enhancement. Additionally, fruit-related characteristics, such as the number (23) and weight (24) of mature fruits, showed significant positive correlations with yield, underscoring their role in plant productivity. Furthermore, biochemical traits, including mucilage content (30) and soluble sugars (32), were significantly correlated with growth and yield traits, suggesting their physiological importance in enhancing plant performance (Table 5).

Table 4. Comparative analysis of agronomic and physiological traits among okra (*Abelmoschus esculentus*) genotypes under non-stress (well-watered) and water stress conditions.

Characteristics	Minimum		Maximum		Mean		SD		Variance		CV	
	NS	WS	NS	WS	NS	WS	NS	WS	NS	WS	NS	WS
Initiation of flowering (d)	46.00	44.00	61.00	62.00	54.71	56.42	3.76	4.82	14.16	23.25	6.88	8.55
Initiation of fruiting (d)	49.00	46.00	63.00	65.00	57.36	58.96	3.84	4.95	14.78	24.50	6.70	8.40
50% flowering (d)	55.00	48.00	71.00	79.00	64.20	67.98	4.44	7.76	19.71	60.20	6.92	11.41
50% fruit set (d)	56.00	50.00	75.00	83.00	66.47	71.07	4.66	8.09	21.75	65.52	7.02	11.39
100% flowering (d)	61.00	55.00	85.00	92.00	73.58	76.16	5.99	8.17	35.93	66.68	8.15	10.72
100% fruit set (d)	62.00	57.00	86.00	95.00	75.38	79.44	6.10	8.54	37.19	72.89	8.09	10.75
Stem height (cm)	101.83	52.33	175.83	108.33	129.16	80.75	15.16	11.85	79.29	52.14	11.74	14.68
LAI (stage 1)	1.60	1.57	1.97	1.71	1.79	1.63	0.08	0.04	0.01	0.00	4.61	2.44
LAI (stage 2)	3.09	2.00	3.70	2.21	3.36	2.12	0.16	0.04	0.02	0.00	4.69	1.93
LAI (stage 3)	3.20	2.12	4.53	3.50	3.83	2.61	0.34	0.27	0.12	0.07	8.91	10.18
LAI (stage 4)	2.01	1.43	2.28	1.71	2.15	1.56	0.07	0.07	0.00	0.00	3.29	4.25
Diameter of the lower third of the stem (mm)	19.09	15.93	26.18	21.64	22.83	18.70	1.40	1.17	1.95	1.37	6.12	6.26
Diameter of the middle third of the stem (mm)	10.89	9.55	17.84	15.70	13.37	12.11	1.66	1.51	2.74	2.28	12.38	12.46
Diameter of the upper third of the stem (mm)	4.39	3.19	7.31	5.87	5.49	4.54	0.75	0.61	0.56	0.37	13.64	13.47
Diameter of the lower third of the leaf (mm)	4.09	2.22	6.36	4.79	5.25	3.60	0.57	0.55	0.33	0.30	10.90	15.27
Diameter of the middle third of the leaf (mm)	3.00	2.03	4.77	3.74	3.88	2.78	0.41	0.36	0.17	0.13	10.49	12.76
Diameter of the upper third of the leaf (mm)	2.07	1.52	3.95	2.90	3.04	2.06	0.46	0.32	0.22	0.10	15.28	15.73
Leaf length (cm)	5.87	4.06	9.67	6.99	7.59	5.39	0.99	0.63	0.98	0.40	13.04	11.74
Number of cavities and grooves	5.00	5.00	9.00	9.00	6.89	6.71	1.25	1.24	1.56	1.53	18.10	18.42
Rate of fruit growth	2.60	2.90	7.00	6.50	4.48	4.05	0.95	1.09	0.90	1.20	21.19	27.02
Diameter of mature fruit (cm)	1.32	1.00	2.67	2.27	2.11	1.81	0.33	0.28	0.11	0.08	15.70	15.39
Length of mature fruit (cm)	12.20	9.53	23.83	19.30	17.90	14.99	2.68	2.26	7.16	5.09	14.95	15.05
Number of mature fruits per plant	7.00	5.00	17.00	10.00	10.51	7.16	2.46	1.31	6.07	1.73	23.45	18.36
Weight of mature fruit (g)	52.33	26.34	167.34	78.23	92.82	52.98	31.74	13.31	107.02	77.40	34.20	25.12
Number of seeds per mature fruit	42.00	31.00	109.00	90.00	84.64	66.82	20.75	17.43	46.43	30.37	24.51	26.08
1000- seed weight (g)	49.00	45.38	82.67	73.67	64.73	59.04	6.96	7.14	48.45	50.92	10.75	12.08

Fruit yield (t ha^{-1})	5.61	3.84	20.71	12.92	11.53	7.87	3.84	2.28	14.72	5.19	33.29	28.96
Biological yield (t ha^{-1})	40.60	15.10	90.50	58.50	70.14	32.59	11.84	9.61	140.19	92.33	16.88	29.49
Harvest index (%)	8.98	11.56	25.85	45.75	16.32	25.64	4.00	8.75	16.00	76.51	24.51	34.11
Mucilage content (%)	0.27	0.22	0.43	0.43	0.33	0.29	0.04	0.04	0.00	0.00	12.72	15.26
Moisture content (%)	80.59	70.58	92.23	86.60	86.45	80.66	2.15	3.42	4.63	11.67	2.49	4.23
Soluble sugars (mg g^{-1})	155.60	99.80	221.30	154.30	177.70	129.38	16.53	17.61	273.37	310.16	9.30	13.61
Total sugars (mg g^{-1})	55.60	68.90	167.60	216.60	88.45	148.34	32.09	52.05	80.10	59.80	36.28	35.09
Fiber content (%)	7.40	6.28	10.20	11.23	8.98	8.24	0.78	1.25	0.61	1.57	8.70	15.20
Protein content (%)	103.50	63.40	230.10	198.60	189.03	122.88	37.69	33.82	120.4	70.44	19.94	27.53

NS: non-stress; WS: water stress.

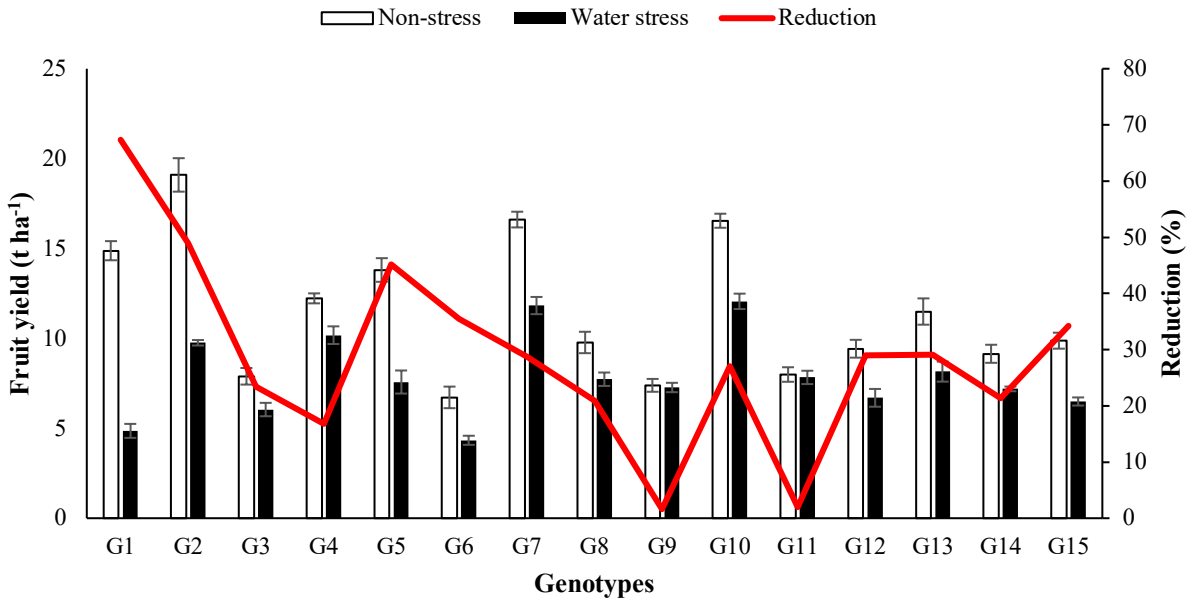

Fig. 1. Comparison of fruit yield (t ha^{-1}) and percentage reduction in yield among 15 okra genotypes (G1-G15) under non-stress (well-watered) and water stress conditions. Bar graphs represent mean fruit yields (± standard error) of each okra genotype grown under non-stress (white bars) and water stress (black bars) conditions. The red line indicates the percentage reduction in yield caused by water stress for each genotype.

Table 5. Correlation matrix of various morphological and yield-related traits in okra genotypes under non-stress (well-watered) conditions.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
2	0.97																																	
3	0.91	0.93																																
4	0.89	0.91	0.98																															
5	0.81	0.81	0.87	0.85																														
6	0.80	0.80	0.88	0.88	0.99																													
7	0.27	0.32	0.34	0.35	0.35	0.33																												
8	0.09	0.05	0.03	0.01	0.10	0.08	0.08																											
9	-0.18	-0.17	-0.12	-0.10	-0.13	-0.12	-0.30	-0.14																										
10	-0.03	0.00	0.03	0.04	0.02	0.03	-0.27	0.16	0.77																									
11	-0.02	-0.02	-0.07	-0.06	0.07	0.06	-0.27	0.22	0.26	0.41																								
12	0.23	0.21	0.29	0.34	0.34	0.38	-0.03	0.10	0.23	0.25	0.23																							
13	0.45	0.45	0.42	0.46	0.38	0.39	0.00	0.04	0.15	0.20	0.12	0.51																						
14	0.42	0.45	0.43	0.45	0.41	0.44	0.09	-0.32	0.24	0.17	0.03	0.52	0.35																					
15	0.12	0.03	0.13	0.13	0.09	0.10	-0.13	0.01	0.20	0.13	0.19	0.21	0.22	-0.02																				
16	0.12	0.13	0.23	0.23	0.23	0.24	0.03	-0.08	0.16	0.20	0.07	0.32	0.19	0.28	0.28																			
17	-0.16	-0.16	-0.05	0.00	-0.03	0.01	-0.01	0.11	0.04	0.04	-0.15	0.52	0.16	0.16	0.24	0.27																		
18	0.14	0.06	0.22	0.23	0.24	0.25	0.07	0.07	0.13	0.03	0.00	0.27	0.32	0.00	0.70	0.20	0.44																	
19	0.25	0.26	0.35	0.36	0.20	0.21	0.14	0.34	-0.09	-0.04	-0.06	0.07	0.09	-0.06	0.32	0.10	0.22	0.41																
20	-0.41	-0.42	-0.46	-0.56	-0.43	-0.53	0.04	-0.19	-0.07	-0.14	-0.21	-0.50	-0.42	-0.28	-0.19	-0.23	-0.27	-0.32	-0.38															
21	0.16	0.14	0.23	0.26	0.17	0.21	-0.12	0.13	0.31	0.32	0.35	0.42	0.37	0.14	0.48	0.22	0.40	0.52	0.38	-0.51														
22	-0.08	-0.15	-0.21	-0.30	-0.09	-0.16	0.10	0.07	-0.28	-0.35	-0.32	-0.43	-0.35	-0.29	-0.22	-0.30	-0.33	-0.24	-0.32	0.61	-0.78													
23	-0.33	-0.39	-0.34	-0.31	-0.28	-0.25	-0.54	-0.30	0.36	0.15	0.11	-0.13	-0.23	-0.04	0.39	0.06	-0.03	0.20	-0.02	-0.08	0.14	-0.07												
24	-0.05	-0.10	0.09	0.13	0.18	0.23	-0.23	-0.23	0.42	0.23	0.19	0.19	0.15	0.16	0.54	0.21	0.12	0.56	0.23	-0.39	0.48	-0.38	0.71											
25	0.18	0.16	0.37	0.42	0.37	0.41	0.28	0.22	0.21	0.12	0.00	0.37	0.32	0.14	0.43	0.27	0.42	0.68	0.53	-0.48	0.60	-0.42	-0.07	0.53										
26	0.32	0.32	0.45	0.41	0.31	0.30	0.15	-0.08	0.14	0.28	-0.16	0.28	0.16	0.33	0.18	0.33	0.32	0.19	0.05	0.09	0.29	-0.18	-0.28	-0.08	0.25									
27	-0.43	-0.49	-0.31	-0.28	-0.24	-0.20	0.04	0.19	0.12	-0.09	-0.05	-0.04	-0.18	-0.28	0.35	0.03	0.34	0.57	0.36	-0.15	0.29	-0.09	0.32	0.52	0.63	-0.24								
28	-0.12	-0.16	-0.01	0.01	0.01	0.07	0.10	0.23	-0.14	-0.06	0.08	0.12	-0.05	-0.21	0.41	0.18	0.38	0.58	0.47	-0.42	0.42	-0.32	0.26	0.46	0.48	-0.12	0.67							
29	-0.49	-0.54	-0.40	-0.37	-0.32	-0.31	-0.02	0.12	0.25	-0.07	-0.11	-0.15	-0.22	-0.26	0.14	-0.10	0.19	0.32	0.14	0.07	0.10	0.08	0.21	0.35	0.49	-0.24	0.84	0.17						
30	-0.13	0.02	0.03	0.05	-0.05	-0.06	0.08	-0.16	-0.12	-0.01	-0.28	-0.15	0.01	0.09	-0.11	0.22	0.07	-0.28	-0.04	0.20	-0.30	-0.04	-0.15	-0.14	-0.05	0.07	-0.22	-0.25	-0.11					
31	-0.01	0.00	0.13	0.20	0.12	0.17	-0.13	-0.04	0.31	0.18	0.11	0.33	0.21	0.11	0.18	0.14	0.24	0.34	0.14	-0.41	0.41	-0.40	0.13	0.41	0.53	0.02	0.39	0.07	0.49	-0.10				
32	-0.02	0.02	0.10	0.09	0.21	0.21	-0.18	-0.06	-0.28	-0.22	-0.22	0.03	-0.11	0.02	-0.14	0.16	0.16	-0.07	-0.19	0.04	-0.44	0.38	-0.05	-0.08	-0.05	0.07	-0.12	-0.17	-0.05	0.40	-0.01			
33	0.11	0.17	0.22	0.20	0.30	0.30	-0.16	-0.03	-0.27	-0.12	-0.16	0.02	-0.07	0.07	-0.17	0.17	0.08	-0.19	-0.20	0.04	-0.45	0.36	-0.13	-0.16	-0.13	0.15	-0.31	-0.25	-0.24	0.48	-0.13	0.96		
34	0.43	0.38	0.27	0.25	0.35	0.32	-0.10	-0.12	0.11	0.09	0.27	0.03	0.40	0.22	-0.11	-0.26	-0.57	-0.17	-0.18	-0.05	-0.11	0.11	0.01	0.07	-0.30	-0.21	-0.43	-0.39	-0.31	-0.30	-0.10	-0.20	-0.13	
35	0.04	0.06	0.05	0.08	0.00	0.02	0.06	0.08	0.26	0.41	0.33	0.12	0.11	0.04	0.26	0.22	0.11	0.18	0.32	-0.34	0.66	-0.68	0.23	0.31	0.15	0.08	0.09	0.48	-0.20	-0.21	-0.01	-0.70	-0.63	-0.04

Coefficients greater than 0.25 and up to 0.44 are statistically significant at the 5% probability level, while those exceeding 0.45 are significant at the 1% probability level. Coefficients below 0.24 are considered non-significant.

-1	-0.9	-0.8	-0.7	-0.6	-0.5	-0.4	-0.3	-0.2	-0.1	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1

High negative correlation — Non-correlation — High positive correlation

Red and blue colors show negative and positive correlation, respectively

1. Initiation of flowering; 2. Initiation of fruiting; 3. 50% flowering; 4. 50% fruit set; 5. 100% flowering; 6. 100% fruit set; 7. Stem height; 8. LAI (stage 1); 9. LAI (stage 2); 10. LAI (stage 3); 11. LAI (stage 4); 12. Diameter of the lower third of the stem; 13. Diameter of the middle third of the stem; 14. Diameter of the upper third of the stem; 15. Diameter of the lower third of the leaf; 16. Diameter of the middle third of the leaf; 17. Diameter of the upper third of the leaf; 18. Leaf length; 19. Number of cavities and grooves; 20. Rate of fruit growth; 21. Diameter of mature fruit; 22. Length of mature fruit; 23. Number of mature fruits; 24. Weight of mature fruit; 25. Number of seeds per mature fruit; 26. 1000-seed weight; 27. Fruit yield; 28. Biological yield; 29. Harvest index; 30. Mucilage content; 31. Moisture content; 32. Soluble sugars; 33. Total sugars; 34. Fiber content; 35. Protein content.

However, under water stress conditions, the correlation patterns changed. Many of the positive correlations observed under non-stress conditions were weakened or even turned negative. Specifically, the correlation between yield (27) and vegetative growth traits, such as stem height (7) and LAI (8–11), decreased, indicating that water stress has an adverse impact on vegetative growth. Moreover, the reduced correlation between yield and fruit characteristics suggests that water stress negatively affects the reproductive stages. Certain biochemical traits such as mucilage content (30) and soluble sugars (32), which were positively correlated with growth and yield under non-stress conditions, showed weaker correlations under water stress, reflecting shifts in plant adaptation mechanisms (Table 6). These findings highlight the potential for selecting drought-tolerant okra genotypes and the need for deeper insights into plant adaptation mechanisms to enhance agricultural productivity under stressful conditions.

Identifying key determinants of okra fruit yield under varying water conditions

The Pareto chart and regression analysis in Figure 2 and Table 7, respectively, examined the factors influencing fruit yield in okra under non-stress conditions. The Pareto chart shows that the number of seeds per fruit (Z), 1000-seed weight (aa), initiation of fruiting (B), and initiation of flowering (A) exerted the most significant effects on fruit yield, in descending order. Consistent with these findings, the regression analysis confirmed a direct and significant relationship between the initiation of flowering, leaf length, and fruit yield, whereas the initiation of fruiting and diameter of the lower and middle thirds of the stem exhibited an inverse and significant correlation. Notably, the number of seeds per fruit and 1000-seed weight emerge as the most potent predictors of fruit yield. The adjusted R-squared value of 89.50% indicated that the regression model accounted for 89.50% of the variance in fruit yield, underscoring the robustness of the model. The findings indicate that okra genotypes with a larger number of seeds per fruit and a higher 1000-seed weight show improved potential for fruit yield.

In a complementary analysis, the factors influencing fruit yield in okra under water stress conditions were investigated. The Pareto chart and regression analysis (Figure 3 and Table 8) revealed that under water stress, 50% fruit set (E), stem height (G), leaf branch 7-1 (K), diameter of the upper third of the stem (O), length of mature fruit (W), and weight of mature fruit (Y) were the primary determinants of fruit yield, in order of decreasing influence. Contrary to the non-stress scenario, the number of seeds per fruit and 1000-seed weight demonstrated minimal effects under water stress. Regression analysis established an inverse and significant relationship between 50% fruit set, leaf branch 7-1, diameter of the upper third of the stem, length of mature fruit, and fruit yield. Conversely, the stem height and weight of mature fruit exhibited a direct and significant correlation with fruit yield. The adjusted R-squared value of 54.06% indicated that the regression model explained 54.06% of the variation in fruit yield, reflecting a moderate model fit. These findings suggest that, under water stress, factors associated with vegetative growth and mature fruit characteristics play a more prominent role in determining fruit yield, with okra genotypes exhibiting greater stem height and heavier fruits demonstrating superior performance under these conditions.

PCA biplot analysis

Figures 4 and 5 present PCA biplots illustrating the relationships between 35 traits (T1-T35) in okra genotypes under non-water and water stress conditions, respectively. Under non-water stress (Fig. 4), the first principal component (PC1) explains 23.3% of the total variance, while the second component (PC2) accounts for 18.6%. Notably, T27 (fruit yield), T23 (number of mature fruits), T24 (weight of mature fruit), and T25 (number of seeds per mature fruit) were closely clustered, indicating strong positive correlations and significant contributions to PC1. In contrast, under water stress conditions (Fig. 5), PC1 explained 28.2% of the variance and PC2 explained 13.4%. Here, T7 (stem height) and T24 (weight of mature fruit) were prominent contributors to PC1, suggesting their importance in explaining variability under water stress. Furthermore, T20 (rate of fruit growth) and T22 (length of mature fruit) were distinct, implying their unique roles in differentiating genotypes under both conditions. These biplots collectively reveal that trait associations and their contributions to variability differ significantly between non-water stress and water stress environments, highlighting the differential responses of okra genotypes to varying water availability.

Table 6. Correlation matrix of various morphological and yield-related traits in okra genotypes under water stress conditions.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
2	0.99																																	
3	0.92	0.9																																
4	0.91	0.9	0.99																															
5	0.85	0.85	0.95	0.95																														
6	0.84	0.84	0.95	0.95	0.99																													
7	0.17	0.12	0.24	0.24	0.13	0.13																												
8	0.12	0.09	0.21	0.22	0.28	0.28	-0.01																											
9	0.09	0.09	0.16	0.19	0.24	0.24	0	0.3																										
10	0.12	0.11	0.08	0.09	0	0.01	0.36	0.13	0.39																									
11	0.27	0.22	0.34	0.34	0.32	0.33	-0.04	0.45	0.06	0.21																								
12	0.09	0.06	0.26	0.25	0.19	0.16	0	0.05	0.19	0.1	0.37																							
13	0.4	0.38	0.54	0.55	0.55	0.55	-0.11	0.29	0.28	0.13	0.55	0.54																						
14	0.54	0.54	0.66	0.65	0.66	0.66	0.07	0.14	0.13	-0.04	0.19	0.27	0.47																					
15	0.29	0.29	0.4	0.41	0.44	0.43	-0.16	0.56	0.29	0.23	0.39	0.4	0.66	0.35																				
16	0.09	0.13	0.04	0.03	0.11	0.06	-0.42	0.12	0.06	-0.15	0.03	0.16	0.27	-0.03	0.29																			
17	0.1	0.11	0.24	0.24	0.22	0.21	-0.17	0.31	0.27	0.19	0.06	0.33	0.34	0.17	0.47	0.39																		
18	0.4	0.41	0.51	0.5	0.53	0.5	-0.21	0.3	0.05	0.09	0.27	0.33	0.58	0.48	0.7	0.38	0.51																	
19	0.31	0.31	0.41	0.41	0.49	0.47	0.01	0.13	0.13	0.02	0.15	0.08	0.41	0.09	0.22	0.08	0.18	0.42																
20	-0.75	-0.77	-0.72	-0.74	-0.75	-0.76	0	-0.23	-0.08	-0.1	-0.34	-0.04	-0.38	-0.31	-0.29	-0.03	-0.09	-0.41	-0.5															
21	0.08	0.11	0.14	0.17	0.24	0.26	0.18	0.16	0.01	0.29	0.15	-0.19	0.11	-0.1	0.14	-0.08	0.01	0.19	0.52	-0.54														
22	-0.39	-0.45	-0.38	-0.4	-0.42	-0.45	-0.06	-0.04	-0.01	-0.41	-0.16	0.07	-0.17	-0.2	-0.26	0.02	-0.1	-0.4	-0.36	0.7	-0.74													
23	-0.32	-0.32	-0.39	-0.39	-0.38	-0.35	-0.04	-0.08	-0.55	-0.19	-0.04	-0.46	-0.37	-0.41	-0.18	-0.22	-0.42	-0.16	-0.07	0.2	0.19	-0.03												
24	0.11	0.11	0.31	0.32	0.41	0.4	0.14	0.17	0.09	0.02	0.07	0.03	0.3	0.19	0.38	-0.09	0.09	0.42	0.57	-0.28	0.48	-0.31	0.26											
25	0.36	0.39	0.51	0.52	0.66	0.66	0	0.41	0.21	0.11	0.3	0.01	0.42	0.38	0.42	0.11	0.27	0.46	0.62	-0.59	0.65	-0.56	-0.05	0.69										
26	-0.1	-0.13	-0.08	-0.09	-0.16	-0.16	0.43	-0.08	0.04	0.39	-0.4	-0.24	-0.15	-0.18	-0.07	-0.08	0.23	-0.12	0.11	0.28	0.08	0.1	0.09	0.26	0.05									
27	-0.28	-0.24	-0.29	-0.28	-0.2	-0.19	0.07	-0.13	-0.15	0.01	-0.19	-0.2	-0.14	-0.44	-0.08	-0.04	-0.13	-0.11	0.32A	-0.1	0.47	-0.34	0.36	0.31	0.22	0.18								
28	0.12	0.15	0.06	0.05	0.02	0.02	0.57	-0.1	-0.01	0.42	-0.1	-0.05	-0.19	0.09	-0.05	-0.23	-0.13	-0.14	-0.07	0.01	0.24	-0.36	0.07	-0.04	0.12	0.24	0.27							
29	-0.25	-0.24	-0.22	-0.2	-0.1	-0.09	-0.45	0.09	-0.05	-0.22	0	-0.16	0.17	-0.35	0.13	0.22	0.11	0.14	0.37	-0.13	0.22	-0.03	0.19	0.33	0.18	0.05	0.56	-0.6						
30	-0.03	-0.08	-0.03	-0.05	-0.07	-0.06	0.23	0.28	0.32	0.46	-0.02	-0.07	0	0.06	0.21	-0.23	0.13	0.04	0.01	0.15	-0.05	0.07	-0.02	0.2	0.07	0.51	-0.19	0.1	-0.08					
31	0.04	0.07	0.12	0.13	0.26	0.25	0.04	0.19	0.04	0.1	0.22	0.02	0.29	-0.06	0.27	0.08	0	0.22	0.55	-0.4	0.7	-0.51	0.14	0.55	0.68	0.03	0.66	0.18	0.44	-0.1				
32	-0.11	-0.08	-0.21	-0.21	-0.14	-0.15	-0.61	0.03	0.03	-0.37	-0.2	-0.06	-0.09	-0.27	-0.08	0.37	0.17	-0.1	-0.1	0.04	-0.39	0.31	-0.12	-0.35	-0.19	-0.22	0.13	-0.46	0.47	-0.28	-0.18			
33	-0.2	-0.22	0.01	-0.01	0.03	0.02	0.02	0.12	0.1	-0.05	0.11	0.06	0.19	0.15	0.27	0.13	0.23	0.18	0	0.43	-0.12	0.29	0.12	0.35	0.11	0.26	-0.36	-0.14	-0.09	0.21	-0.06	-0.41		
34	-0.37	-0.35	-0.49	-0.48	-0.47	-0.45	-0.21	-0.14	-0.1	0.14	0.05	-0.07	-0.1	-0.31	0.1	-0.02	-0.3	-0.03	-0.12	0.27	0.08	-0.11	0.59	0.2	-0.13	0.01	0.28	0.14	0.13	0.24	0.19	-0.21	0.12	
35	0.05	0.06	0.21	0.21	0.3	0.3	0.22	0.12	0.03	0.07	0.09	-0.21	-0.06	0.08	0.08	-0.04	0	0.13	0.32	-0.12	0.51	-0.3	0.31	0.65	0.57	0.2	0.05	0.13	-0.07	0.01	0.36	-0.51	0.58	0.07

Coefficients greater than 0.25 and up to 0.44 are statistically significant at the 5% probability level, while those exceeding 0.45 are significant at the 1% probability level. Coefficients below 0.24 are considered non-significant.

-1	-0.9	-0.8	-0.7	-0.6	-0.5	-0.4	-0.3	-0.2	-0.1	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
High negative correlation										Non-correlation										High positive correlation
Red and blue colors show negative and positive correlation, respectively																				

1. Initiation of flowering; 2. Initiation of fruiting; 3. 50% flowering; 4. 50% fruit set; 5. 100% flowering; 6. 100% fruit set; 7. Stem height; 8. LAI (stage 1); 9. LAI (stage 2); 10. LAI (stage 3); 11. LAI (stage 4); 12. Diameter of the lower third of the stem; 13. Diameter of the middle third of the stem; 14. Diameter of the upper third of the stem; 15. Diameter of the lower third of the leaf; 16. Diameter of the middle third of the leaf; 17. Diameter of the upper third of the leaf; 18. Leaf length; 19. Number of cavities and grooves; 20. Rate of fruit growth; 21. Diameter of mature fruit; 22. Length of mature fruit; 23. Number of mature fruits; 24. Weight of mature fruit; 25. Number of seeds per mature fruit; 26. 1000-seed weight; 27. Fruit yield; 28. Biological yield; 29. Harvest index; 30. Mucilage content; 31. Moisture content; 32. Soluble sugars; 33. Total sugars; 34. Fiber content; 35. Protein content.

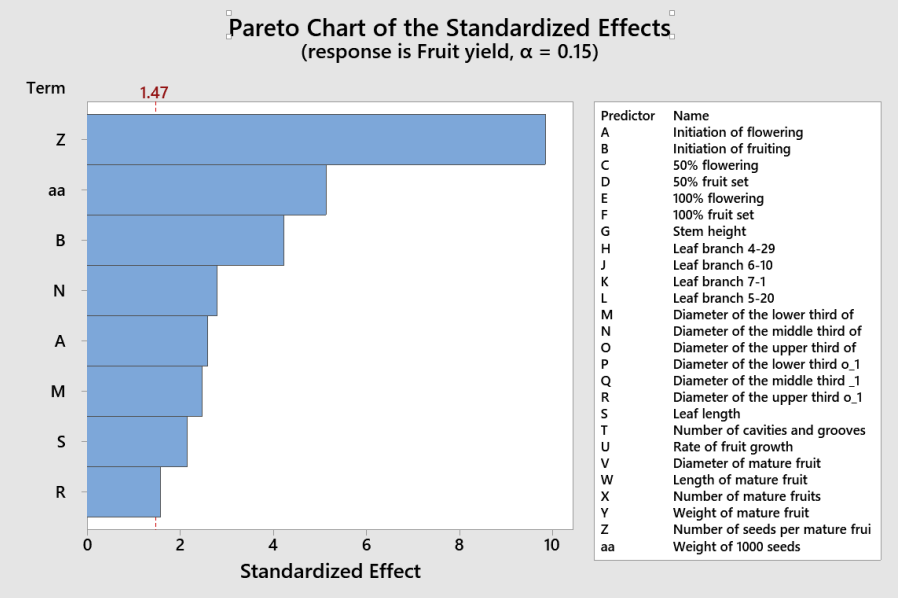

Fig. 2. Pareto chart illustrating the standardized effects of various morphological and yield-related traits (as listed) on fruit yield of okra under non-stress (well-watered) conditions.

Table 7. Results of regression analysis identifying significant factors influencing fruit yield in okra genotypes under non-stress (well-watered) conditions.

Term	Coef	SE Coef	*T* Value	*P* Value
Constant	41.71	4.37	9.55	0.000
Initiation of flowering	0.626	0.241	2.60	0.014
Initiation of fruiting	-0.987	0.233	-4.23	0.000
Diameter of the lower third of	-0.474	0.192	-2.47	0.019
Diameter of the middle third of	-0.421	0.151	-2.79	0.008
Leaf length	0.662	0.308	2.15	0.038
Number of seeds per mature frui	0.1317	0.0134	9.85	0.000
1000-seed weight	-0.1604	0.0312	-5.14	0.000
R-sq(adj) = 89.50%				

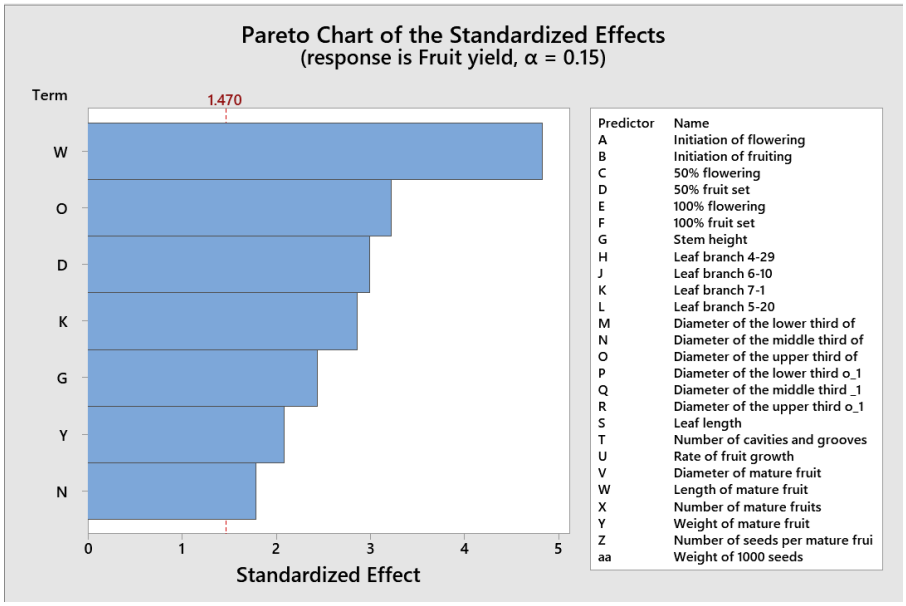

Fig. 3. Pareto chart illustrating the standardized effects of different morphological and yield-related traits (as listed) on fruit yield of okra under water stress conditions.

Table 8. Results of regression analysis identifying significant factors influencing fruit yield in okra genotypes under water stress conditions.

Term	Coef	SE Coef	*T* Value	*P* Value
Constant	32.22	5.06	6.37	0.000
50% fruit set	-0.1421	0.0475	-2.99	0.005
Stem height	0.0600	0.0246	2.44	0.019
LAI (stage 3)	-3.26	1.14	-2.86	0.007
Diameter of the upper third of	-1.670	0.519	-3.22	0.003
Length of mature fruit	-0.657	0.136	-4.82	0.000
Weight of mature fruit	0.0415	0.0199	2.09	0.044
R-sq(adj) = 54.06				

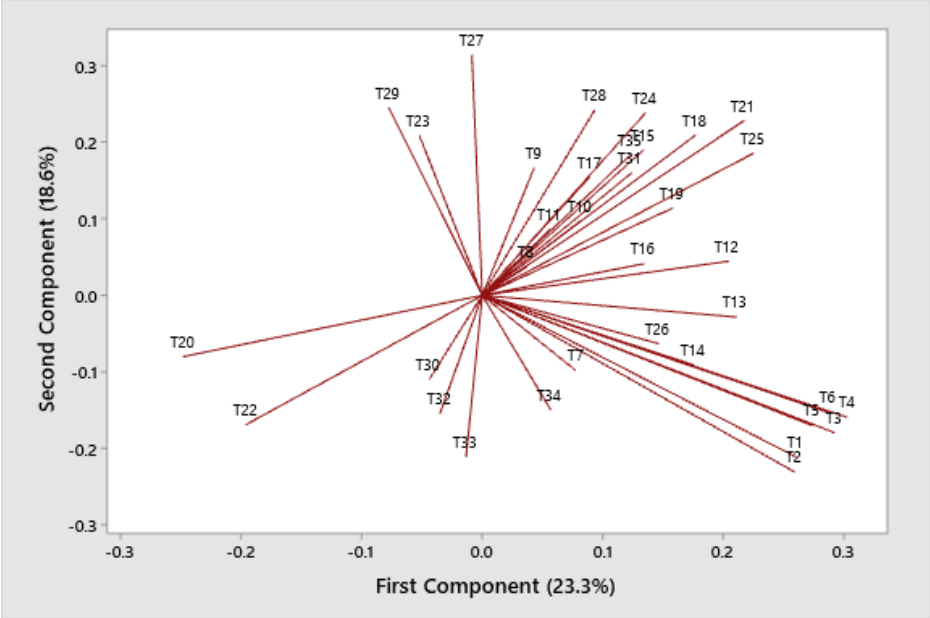

Fig. 4. Biplot of principal component analysis (PCA) showing the distribution of evaluated traits (T1–T35) for okra genotypes under non-stress (well-watered) conditions based on the first and second principal components. T1. Initiation of flowering; T2. Initiation of fruiting; T3. 50% flowering; T4. 50% fruit set; T5. 100% flowering; T6. 100% fruit set; T7. Stem height; T8. LAI (stage 1); T9. LAI (stage 2); T10. LAI (stage 3); T11. LAI (stage 4); T12. Diameter of the lower third of the stem; T13. Diameter of the middle third of the stem; T14. Diameter of the upper third of the stem; T15. Diameter of the lower third of the leaf; T16. Diameter of the middle third of the leaf; T17. Diameter of the upper third of the leaf; T18. Leaf length; T19. Number of cavities and grooves; T20. Rate of fruit growth; T21. Diameter of mature fruit; T22. Length of mature fruit; T23. Number of mature fruits; T24. Weight of mature fruit; T25. Number of seeds per mature fruit; T26. 1000-seed weight; T27. Fruit yield; T28. Biological yield; T29. Harvest index; T30. Mucilage content; T31. Moisture content; T32. Soluble sugars; T33. Total sugars; T34. Fiber content; T35. Protein content.

Cluster analysis

The results of a cluster analysis conducted on the 15 okra genotypes under non-water stress conditions are illustrated in Figure 6 and summarized in Table 9. The dendrogram indicated the formation of three distinct clusters, highlighting the significant phenotypic diversity among the genotypes. Cluster 1, which included genotypes G1 and G7, showed the highest mean values for key traits, such as fruit yield (15.74 t ha^{-1}), biological yield (82.50 t ha^{-1}), and number of seeds per fruit (100.0). In contrast, Cluster 3, consisting of genotypes G6, G12, and G14, had lower mean values for these traits, but excelled in others, including the length of mature fruit (20.41 cm) and total sugars (142.91 mg g^{-1}). Cluster 2, the largest group with 10 genotypes, displayed intermediate mean values across most traits. This analysis underscores the substantial phenotypic variation among okra genotypes, facilitating their classification into three distinct clusters based on trait similarity.

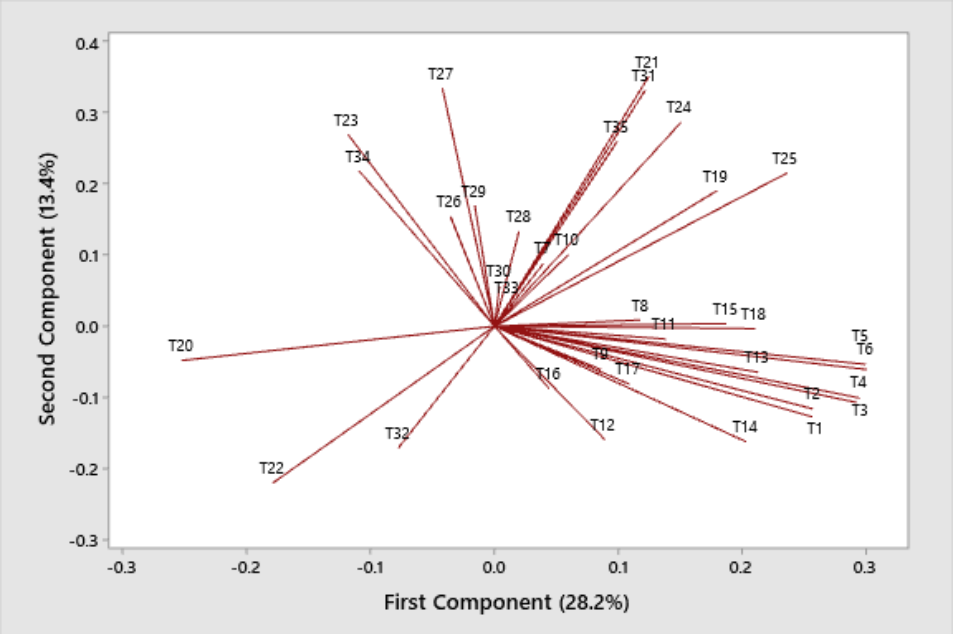

Fig. 5. Biplot of principal component analysis (PCA) showing the distribution of evaluated traits (T1–T35) for okra genotypes under water stress conditions based on the first and second principal components. T1. Initiation of flowering; T2. Initiation of fruiting; T3. 50% flowering; T4. 50% fruit set; T5. 100% flowering; T6. 100% fruit set; T7. Stem height; T8. LAI (stage 1); T9. LAI (stage 2); T10. LAI (stage 3); T11. LAI (stage 4); T12. Diameter of the lower third of the stem; T13. Diameter of the middle third of the stem; T14. Diameter of the upper third of the stem; T15. Diameter of the lower third of the leaf; T16. Diameter of the middle third of the leaf; T17. Diameter of the upper third of the leaf; T18. Leaf length; T19. Number of cavities and grooves; T20. Rate of fruit growth; T21. Diameter of mature fruit; T22. Length of mature fruit; T23. Number of mature fruits; T24. Weight of mature fruit; T25. Number of seeds per mature fruit; T26. 1000-seed weight; T27. Fruit yield; T28. Biological yield; T29. Harvest index; T30. Mucilage content; T31. Moisture content; T32. Soluble sugars; T33. Total sugars; T34. Fiber content; T35. Protein content.

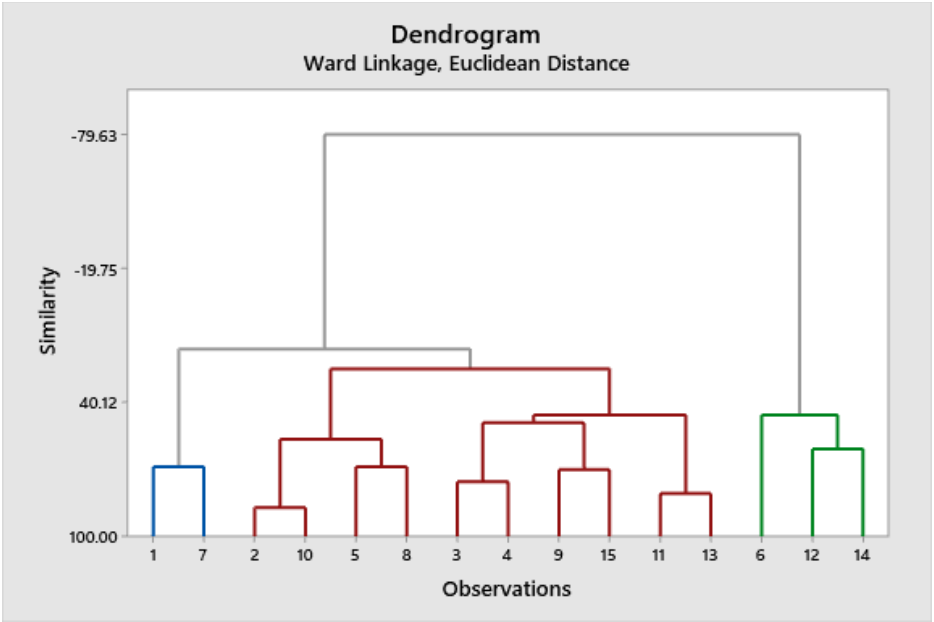

Fig. 6. Dendrogram of hierarchical cluster analysis (Ward's method, Euclidean distance) illustrating genetic relationships among 15 okra genotypes (1-15) under non-stress (well-watered) conditions.

Table 9. Cluster means of evaluated variables for okra genotypes grouped by hierarchical cluster analysis under non-stress (well-watered) conditions.

Variable	Cluster1	Cluster2	Cluster3
Initiation of flowering (d)	53.000	54.567	56.333
Initiation of fruiting (d)	55.167	57.167	59.444
50% flowering (d)	63.500	63.733	66.222
50% fruit set (d)	66.333	65.900	68.444
100% flowering (d)	75.833	72.133	76.889
100% fruit set (d)	78.333	73.833	78.556
Stem height (cm)	122.001	130.964	127.923
LAI (stage 1)	1.723	1.810	1.786
LAI (stage 2)	3.405	3.375	3.264
LAI (stage 3)	3.758	3.893	3.677
LAI (stage 4)	2.182	2.145	2.123
Diameter of the lower third of the stem (mm)	23.833	22.589	22.941
Diameter of the middle third of the stem (mm)	13.618	13.280	13.527
Diameter of the upper third of the stem (mm)	5.815	5.330	5.826
Diameter of the lower third of the leaf (mm)	5.577	5.306	4.864
Diameter of the middle third of the leaf (mm)	4.048	3.842	3.877
Diameter of the upper third of the leaf (mm)	3.242	3.024	2.938
Leaf length (cm)	8.410	7.635	6.890
Number of cavities and grooves	7.000	7.067	6.222
Rate of fruit growth	3.650	4.600	4.622
Diameter of mature fruit (cm)	2.372	2.183	1.693
Length of mature fruit (cm)	15.856	17.553	20.414
Number of mature fruits per plant	14.000	10.233	9.111
Weight of mature fruit (g)	156.381	86.445	71.705
Number of seeds per mature fruit	100.000	84.600	74.556
1000- seed weight (g)	60.323	65.767	64.233
Fruit yield (t ha^{-1})	15.745	11.610	8.431
Biological yield (t ha^{-1})	82.500	70.790	59.744
Harvest index (%)	19.085	16.375	14.280
Mucilage content (%)	0.307	0.326	0.364
Moisture content (%)	88.347	86.275	85.791
Soluble sugars (mg g^{-1})	178.883	169.427	204.511
Total sugars (mg g^{-1})	80.708	73.666	142.911
Fiber content (%)	9.270	8.865	9.184
Protein content (%)	207.000	202.963	130.611
Number of genotypes	2	10	3

Figure 7 and Table 10 depict the outcomes of cluster analysis performed on the same 15 okra genotypes under water stress conditions. Similar to the previous analysis, the dendrogram revealed three distinct clusters, indicating notable phenotypic diversity among genotypes. Cluster 1, containing six genotypes (G1, G15, G9, G8, G14, and G12), exhibited the lowest mean values for crucial traits such as fruit yield (6.70 t ha^{-1}), biological yield (29.26 t ha^{-1}), and weight of mature fruit (55.36 g). Conversely, Cluster 2, also with six genotypes (G2, G5, G7, G10, G11, and G13), demonstrated the highest mean values for these traits, suggesting superior performance under water stress. Cluster 3, which includes three genotypes (G3, G4, and G6), displayed intermediate mean values across most traits. This analysis revealed significant phenotypic variation among okra genotypes, facilitating their classification into three distinct groups based on trait similarity and performance under stress conditions.

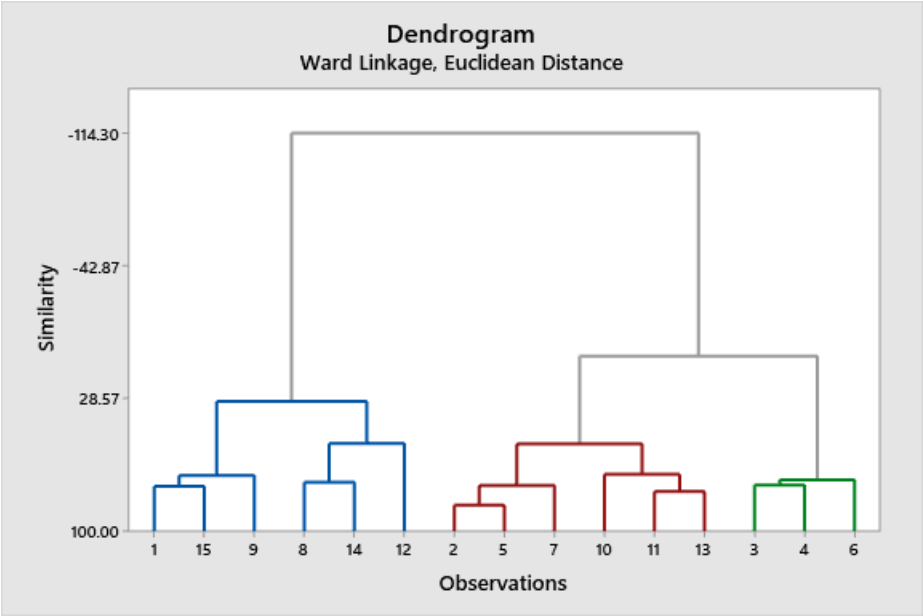

Fig. 7. Dendrogram of hierarchical cluster analysis (Ward's method, Euclidean distance) illustrating genetic relationships among 15 okra genotypes (1-15) under water stress conditions.

Discussion

Genetic diversity and response to water stress

The high coefficients of variation observed under water stress conditions indicate significant genetic diversity among okra genotypes, which is crucial for breeding programs aimed at developing drought-resistant varieties. This genetic diversity is expressed in several important traits, including flowering and fruiting times, vegetative growth, fruit and seed characteristics, and chemical composition. Variations in flowering and fruiting times among the genotypes may indicate different mechanisms of escape or tolerance to water stress. For example, certain genotypes may complete their life cycle before the onset of severe water scarcity, thereby ensuring successful reproduction despite challenging conditions (Silva-Junior et al., 2024). This adaptation is particularly beneficial in arid and semi-arid regions where water availability fluctuates significantly. Furthermore, variations in vegetative growth, such as stem height and leaf area index, reflect differences in the ability of genotypes to sustain growth under drought conditions. Genotypes exhibiting greater vegetative growth may develop more extensive root systems, allowing them to access deeper water supplies. This characteristic not only supports overall plant health during periods of water stress but also enhances the ability of these plants to compete for resources in their natural environment. Additionally, the variations observed in fruit and seed characteristics, including size and weight, are indicative of how different genotypes allocate resources for reproduction. Genotypes that produce larger and heavier fruits and seeds may allocate more resources to reproductive efforts, which can be crucial for ensuring the continuation of the species under adverse environmental conditions (Khadivi et al., 2025).

Genotypes with larger fruits and seeds may maintain higher yields under water stress conditions. Variations in chemical composition, such as mucilage, soluble sugars, and proteins, indicate differences in plant adaptation mechanisms to water stress. The study by Tran et al. (2025) demonstrated that intermittent water supply under drought conditions significantly improved peanut growth, yield, and nutritional content compared to continuous drought stress, highlighting its potential as an effective irrigation strategy for sustainable production. Mucilage can help retain moisture in plant tissues, whereas soluble sugars can assist in the osmotic regulation and maintenance of cell turgor (Clifford et al., 2002). Significant reductions in various parameters indicated a negative impact of water stress on plant performance. This reduction may be due to disruptions in physiological and biochemical processes caused by water scarcity. However, genotypes G9 and G11, which showed less yield reduction under water stress, showed potential drought resistance. These genotypes may possess genes related to drought tolerance that allow them to maintain a better performance under water scarcity conditions. Under water stress conditions, the plasma membrane constitutes one of the earliest components of the plant to suffer damage. The stability of the cellular membrane is significantly correlated with the plant's tolerance to various stressors, including those affecting photosynthesis, serving as a vital

indicator of stress resilience (Dastneshan et al., 2022). In instances of drought stress, the integrity of the cell wall is compromised, leading to the leakage of cellular fluids into the intercellular spaces, which consequently increases the electrical conductivity of the solution. Thus, a greater extent of cell damage correlates with a lower resistance to dehydration (Afshari et al., 2022). Consequently, this genetic diversity provides suitable opportunities for selecting drought-resistant genotypes for breeding programs. It appears that increased irrigation intervals or reduced watering led to a decrease in water and nutrient uptake by the plant, resulting in reduced biomass production, which is associated with the leaf area index of okra under water scarcity conditions. Many researchers believe that a reduction in cell turgor is the first and most sensitive response to water deficiency, leading to decreased plant growth (Boussora et al., 2024; Shukla et al., 2025). Other studies have reported a reduction in okra fruit yield under drought stress (Ali et al., 2023; Wang et al., 2025). Notably, the fruit yield of certain genotypes under low irrigation conditions was significantly higher than that of other genotypes grown under optimal irrigation. For example, genotype G10 under low irrigation conditions outperformed genotypes G11, G12, G13, G14, G15, G8, G9, G6, and G3, which were cultivated under non-stress conditions. Some studies have reported that the fruit yield of okra increases under drought stress, which may be related to its ability to survive and tolerate water scarcity through various osmolytes (Adejumo et al., 2019). These mechanisms might contribute to the adaptability and enhanced fruit yield of okra under challenging conditions. Under non-stressed conditions, the number of seeds per fruit and 1000-seed weight are the key factors influencing fruit yield, indicating that genotypes with more and heavier seeds have a higher yield potential. However, under water stress, stem height, mature fruit weight, and 50% fruiting are important for yield (Chaturvedi et al., 2019). This finding highlights that under water-stressed conditions, traits like vegetative growth and fruit characteristics become crucial. Taller plants tend to produce heavier fruits and fruit earlier, which is essential for yield under stress. This shift in yield-determining factors is likely due to plants reallocating resources, prioritizing survival and maintaining growth over investing in fruit and seed production. The steady decline in seed protein levels during drought conditions is likely a result of decreased nitrate uptake. Additionally, limited nitrogen availability may arise from imbalances in intracellular ion concentrations, which obstruct plant capacity to take in nitrogen ions for transport to the leaves (Farooq et al., 2015; Shadmehri and Abbasdokht, 2024).

Trait correlation patterns

Under non-stress conditions, a pronounced positive correlation exists between fruit yield and various factors such as vegetative growth, fruit characteristics, and biochemical composition. These correlations underscore the significant influence of plant growth on yield improvements; specifically, plants exhibiting enhanced vegetative growth tend to produce higher yields. Furthermore, those that yield larger and heavier fruits are associated with higher overall production. Additionally, plants synthesizing greater amounts of biochemical compounds, including mucilage and soluble sugars, demonstrate increased yields. However, these correlations change under water stress conditions. The relationship between yield and vegetative growth becomes noticeably weaker, indicative of the detrimental effects of water scarcity on plant growth. This suggests that under drought conditions, diminished plant growth results in lower fruit yields (Wakchaure et al., 2023). Furthermore, the correlation between yield and fruit characteristics likewise declines, emphasizing the negative consequences of reduced water availability during the reproductive phases. In such scenarios, plants tend to produce fruits that are both smaller and lighter, leading to a further decrease in yield (Unlukara and Cemek, 2019). Moreover, alterations in the correlations involving biochemical compositions, such as mucilage and soluble sugars, in relation to growth and yield, point to a transformation in the plant's adaptive strategies under water stress conditions (Zaferanieh and Mahdavi, 2021). This implies that, in an attempt to cope with the challenges posed by water scarcity, plants may increase the production of specific biochemical compounds to enhance their resilience. Such adaptations play a crucial role in determining their ability to survive and thrive despite diminished water availability, ultimately affecting their yield potential in the challenging conditions of drought.

PCA analysis and clustering

PCA revealed distinct differences in trait relationships and their contributions to overall variation between non-stressed and water-stressed conditions, indicating varied responses to water regimes among okra genotypes. Clustering analysis further highlighted significant phenotypic diversity, a valuable resource for selecting promising genotypes in breeding programs. Water stress significantly affects okra performance and traits; however, existing genetic diversity offers opportunities for selecting drought-resistant genotypes. Under non-water stress, Cluster 1 (genotypes G1 and G7) showed high productivity in fruit yield and seed number, whereas Cluster 3 (genotypes G6, G12, and G14) excelled in mature fruit length and total sugars. Conversely, under water

stress, Cluster 1 displayed the lowest mean values for yield traits, indicating vulnerability, while Cluster 2 maintained superior performance, suggesting enhanced drought resistance. This adaptability underscores the crucial need for breeding strategies to both enhance yield under optimal conditions and improve resilience to water stress.

PCA biplot analysis provides valuable insights into the phenotypic relationships among the 35 traits of okra genotypes and their interactions under varying water conditions. Under non-water stress conditions, traits such as fruit yield, number of mature fruits, and seed count formed a strong cluster, indicating a clear correlation that suggests these traits collectively influence yield potential. This emphasizes the significance of implementing breeding strategies that focus on these key traits to enhance yield performance in optimal conditions. Conversely, during water stress, there was a noticeable shift in influential traits. Specifically, traits like stem height and mature fruit weight highlighted significant adaptive mechanisms among genotypes. This indicates that the importance of certain traits changes under stress, necessitating a dual approach in breeding programs that account for both non-stress and stress scenarios. Cluster analysis further supports these findings by demonstrating distinct groupings based on trait performance, which highlights the genetic diversity within okra genotypes. This diversity offers potential for targeted selection in breeding initiatives aimed at improving drought resistance. The contrasting performances of genotypes across different clusters stress the need for a deeper understanding of specific trait contributions in both stress and non-stress environments.

Conclusion

The comparative analysis of okra genotypes revealed substantial differences in their performance under varying water conditions, offering insights into both productivity potential and drought resilience. Under non-stress conditions, genotypes such as G1, G2, G7, and G10 demonstrated high yield potential. However, under stress, these genotypes showed a stark reduction in yield, highlighting the impact of water scarcity on otherwise high-performing genotypes. In contrast, genotypes G9 and G11 stood out for their robustness under water stress, maintaining yields with minimal reductions. These genotypes exhibited traits indicative of drought tolerance and adaptability, making them valuable for breeding programs targeting resilience in water-limited environments. Furthermore, genotype G6 also performed notably, underscoring its potential for cultivation under challenging conditions. PCA and cluster analyses confirmed significant phenotypic diversity among the genotypes, allowing their classification based on performance and traits. For breeding programs targeting okra productivity, genotypes G1, G2, G7, and G10 are ideal under well-watered conditions due to their high yield potential, while G9 and G11 are recommended for water-stressed environments because of their superior drought tolerance and minimal yield reduction.

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Author Contributions

MN, FG, GRBK, HS, and HRF designed the study and performed data analysis. MN, FG, and HS conducted the experiments and collected the data. MN, GRBK, and HRF wrote the manuscript, and FG supervised the project. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest

The authors indicate no conflict of interest in this work.

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