CHILEAN JOURNAL of AGRICULTURAL RESEARCH
RESEARCH ARTICLE

Physiological, biochemical and morphological responses of diverse tomato genotypes to early drought stress

Shormin Choudhury[1], Sarwar Hossain[1], Nazrul Islam[1], Rezwan Sarker[1], Md Arif Hussain[2], Fatmah A. Safhi[3*], Areej S. Jalal[3], Nora M. Al Aboud[4], Mohammed O. Alshaharni[5], and Md Sazzad Hossain[6*]

[1]Sher-e-Bangla Agricultural University, Department of Horticulture, Dhaka, Bangladesh.
[2]Sher-e-Bangla Agricultural University, Department of Biochemistry and Molecular Biology, Dhaka, Bangladesh.
[3]Princess Nourah bint Abdulrahman University, College of Science, Department of Biology, Riyadh 11671, Saudi Arabia.
[4]Umm Al-Qura University, Faculty of Science, Department of Biology, Makkah 24372, Saudi Arabia.
[5]King Khalid University, College of Science, Biology Department, Abha 61321, Saudi Arabia.
[6]Sylhet Agricultural University, Department of Agronomy and Haor Agriculture, Sylhet, Bangladesh.
[*]Corresponding author (faalsafhi@pnu.edu.sa, sazzadmh.aha@sau.ac.bd)
Received: 24 August 2025; Accepted: 17 November 2025, doi:10.4067/S0718-58392026000100102

ABSTRACT

Drought stress is a major environmental constraint that significantly affects tomato (*Solanum lycopersicum* L.) productivity, particularly during early stages of plant development. This study evaluated the physiological, biochemical, and morphological responses of 19 tomato genotypes under early drought stress to identify drought-tolerant cultivars. Seedlings were subjected to drought stress by withholding irrigation for 14 d at 35 d after sowing. Across genotypes, drought caused significant reductions in chlorophyll *a* by 28%-46%, chlorophyll *b* by 25%-41%, relative water content (RWC) by 22%-39%, shoot biomass by 30%-55%, and root biomass by 27%-49% compared to non-stressed control plants. Conversely, reducing sugars and phenolic content increased by up to 32% and 47%, respectively, reflecting osmotic adjustment and antioxidant activation. Significant genotypic variation was observed; tolerant cultivars such as BARI-F1-5, BARI-15, BARI-11, and Pathorkuch maintained higher RWC (> 60%), chlorophyll levels more effectively (≥ 70% of control), and stronger root-shoot development (root length up to 24 cm, shoot dry weight up to 1.5 g). In contrast, sensitive genotypes including 'Roma-VF', 'BARI-2', and 'BARI-21' showed significant reductions with chlorophyll content declining below 50% of non-stressed control and RWC reducing to 45%. Multivariate analyses (hierarchical clustering, heatmap, principal component analysis) grouped the genotypes into tolerant, intermediate, and highly sensitive classes. The results indicate that integrating physiological (chlorophyll, RWC), biochemical (sugars, phenols), and morphological (root-shoot growth) parameters provides an effective strategy for screening drought-tolerant tomato germplasm. The identified tolerant genotypes represent valuable genetic resources for breeding programs aimed to enhance tomato resilience in water-limited environments.

Key words: Early-stage drought screening, genotypic variation, osmotic adjustment, phenolic compounds, photosynthetic pigments, physiological response to drought, shoot and root biomass, *Solanum lycopersicum*, tomato physiology.

INTRODUCTION

Drought is the most damaging environmental constraint, causing significant yield losses (Sedhom et al., 2024). Globally, drought-prone areas encompass a substantial portion of arable land and occur across nearly all climate zones (Elagib et al., 2024). Furthermore, climate change is projected to exacerbate this issue by increasing the frequency and intensity of droughts, particularly in currently arid regions (Tegegne et al., 2025). Drought

impacts nearly every stage of plant growth and development, leading to a drastic reduction in photosynthesis, floral anomalies, and losses in both yield and quality (Mannan et al., 2022). Concurrently, the global population is estimated to rise, posing a significant threat to global food security. Developing cultivars with enhanced drought tolerance represents the most efficient and cost-effective strategy to meet the growing demand for agricultural production in future climate scenarios (Gaballah et al., 2024). However, the limited availability of resistance sources has hindered substantial progress in breeding drought-tolerant crops (Morsi et al., 2023).

Tomato (*Solanum lycopersicum* L.) is a widely grown vegetable crop and serves as a valuable model plant in biological research (Liu et al., 2022). Water scarcity resulting from drought periods can severely impact tomato production, potentially causing significant yield reductions. Identifying tolerant cultivars from a large pool of genotypes based solely on yield per plant can be challenging and often inefficient. Most tomato cultivars exhibit sensitivity to drought stress at various developmental stages, with seed germination and early seedling growth being particularly vulnerable. Drought stress during the seedling stage can lead to poor crop establishment and a reduction in flower and fruit production (Yadav et al., 2025).

Drought is a complex abiotic stress that affects the morphological, physiological, and biochemical processes of plants (Abd-El-Aty et al., 2024). Physiological responses to drought include an increased respiration rate, altered plant development, and changes in mineral distribution (Desoky et al., 2023). Notably, drought stress inhibits plant growth by reducing the rate of photosynthesis and limiting shoot growth through the inhibition of cell division and cell elongation in the elongation zone. Water stress also leads to a decrease in the relative water content of plants (Desoky et al., 2020). Furthermore, water stress triggers the excessive formation of reactive oxygen species (ROS), which can cause detrimental effects on cellular structures and metabolic processes (Mousa et al., 2024). To regulate osmotic potential under abiotic stresses like drought, plants accumulate various metabolites, including proline, inorganic ions, and sugars (Mansour et al., 2023). Sugars also play crucial roles in regulating development, photosynthesis, carbohydrate and lipid metabolism, osmotic homeostasis, and gene expression in response to abiotic stresses (Selem et al., 2022).

While numerous breeding programs aim to develop stress-tolerant varieties, progress has been impeded by inadequate screening techniques and a scarcity of genotypes exhibiting distinct responses to well-defined environmental stresses (Awaad et al., 2023). Therefore, the evaluation and identification of drought-tolerant genotypes are critical for all drought tolerance studies (Mansour et al., 2021a). Developing drought-tolerant varieties necessitates diverse genetic resources, reliable traits, accurate phenotyping methods, and consideration of appropriate growth stages when drought stress occurs (Kamara et al., 2022). Physiological screening approaches and genotypic variation are essential to identify drought-resilient cultivars (Zannat et al., 2023). In particular, early-stage drought stress screening provides rapid and accurate assessment tools critical for breeding programs (Çiğ et al., 2024; Yadav et al., 2025). Hence, the present study aimed to evaluate the physiological, biochemical, and morphological responses of diverse tomato (*Solanum lycopersicum* L.) genotypes under early-stage drought stress. This study sought to identify key traits and genotypic variation associated with drought tolerance to facilitate the selection and breeding of drought-resilient tomato cultivars. We hypothesized that subjecting different tomato cultivars to drought stress would investigate their adaptation mechanisms. For efficient phenotyping, simple and rapid screening protocols are needed to identify key traits of drought-tolerant germplasm and develop improved stress-adapted genotypes.

MATERIALS AND METHODS

Growing conditions and treatments

This study was conducted in a shed house at Sher-e-Bangla Agricultural University, Dhaka, Bangladesh, using 19 tomato (*Solanum lycopersicum* L.) cultivars. Seeds were sourced from the Bangladesh Agricultural Research Institute (BARI) and local suppliers in Siddique Bazar, Dhaka, as presented in Table 1. Characteristics of the 19 tomato genotypes used in this study are provided in Table 2. The seeds were sown in polyvinyl chloride (PVC) tanks measuring 1.2 × 0.6 × 0.6 m, each filled with standardized soil mixture supplemented with a commercial fertilizer (% W/V of N:P:K 8.3:1.9:7.6, Thrive, Yates, Sydney, New South Wales, Australia) at a rate of 2 g per tank. Twenty-five days after sowing (DAS), seedlings were transplanted into pots, five seedlings per pot, each containing the same soil mixture. The soil nutrient composition was analyzed by the Soil Research and Development Institution, Dhaka, and the results are presented in Table 3. Each treatment was replicated three

times. Two experimental treatments were applied: A non-stress control, where plants were irrigated daily, and a drought stress condition, in which irrigation was withheld for 14 d starting at 35 DAS (vegetative stage). Morphological, physiological, and biochemical parameters were recorded at the end of this drought period.

Photosynthetic pigments

Photosynthetic pigment concentrations were determined using the method described by Moran and Porath (1980). Briefly, 0.2 g leaf tissue was rapidly frozen in liquid nitrogen and then ground to a fine powder. The powdered tissue was homogenized in 1 mL 100% *N*,*N*-dimethylformamide (DMF). The homogenate was centrifuged at 10 000 × g for 10 min to collect the supernatant. The remaining pellet was resuspended in 1 mL DMF, and the centrifugation step was repeated. The resulting supernatant was combined with the first. This extraction process was repeated once more with 1 mL DMF, and the final supernatant was collected. The absorbance of the combined supernatant was measured at 663 and 645 nm using a spectrophotometer (Genesys 10S UV-Vis, Thermo Fisher Scientific, Waltham, Massachusetts, USA), with 100% DMF serving as the blank.

Total phenolic content

Total phenolic content was determined using the method described by Singleton (1999). Fresh leaves (250 mg) were homogenized with 85% methanol. The resulting homogenate was centrifuged at 3000 g for 15 min at 10 °C, and the supernatant was collected. Subsequently, 2 mL Folin-Ciocalteu reagent was added to 2 mL supernatant. Following this, 2 mL 7.5% sodium carbonate solution were added to each test tube. After incubation for 30-45 min, the absorbance was measured at 725 nm against a reagent blank. A standard curve generated with gallic acid was used to determine the concentration of total phenols in the unknown samples.

Table 1. Name, source and germplasm type of 19 tomato genotypes used in the present study. PGRC: Plant Genetic Resource Centre; BARI: Bangladesh Agricultural Research Institute.

Genotype	Source	Germplasm type
BARI-2	PGRC, BARI	Variety
BARI-8	PGRC, BARI	Variety
BARI-11	PGRC, BARI	Variety
BARI-14	PGRC, BARI	Variety
BARI-15	PGRC, BARI	Variety
BARI-16	PGRC, BARI	Variety
BARI-19	PGRC, BARI	Variety
BARI-20	PGRC, BARI	Variety
BARI-21	PGRC, BARI	Variety
BARI-F1-4	PGRC, BARI	Hybrid
BARI-F1-5	PGRC, BARI	Hybrid
BARI-F1-7	PGRC, BARI	Hybrid
BARI-F1-8	PGRC, BARI	Hybrid
AvTo-1228	PGRC, BARI	Line
AvTo-1229	PGRC, BARI	Line
AvTo-1318	PGRC, BARI	Line
Honey-Bee	Local market	Hybrid
Pathorkuch	Local market	Hybrid
Roma-VF	Local market	Hybrid

Table 2. Characteristics of the tomato genotypes evaluated in the study.

Genotype	Characteristics
BARI-2	A widely grown variety with medium-sized, bright red fruits. It is heat-tolerant and performs well in the Rabi season. Plants show moderate disease resistance.
BARI-8	Produces round, firm fruits with good shelf life. High-yielding and tolerant to leaf curl virus. Suitable for both homestead and commercial cultivation.
BARI-11	Known for large uniform fruits and high productivity. Exhibits tolerance to bacterial wilt. Performs well under moderately high temperatures.
BARI-14	A high-yielding hybrid-like variety with attractive glossy fruits. Resistant to Tomato Yellow Leaf Curl Virus (TYLCV). Popular for its excellent storage ability.
BARI-15	Medium-to-large fruits with good market appeal. Plants have strong vigor and give stable yield under stress. Moderately resistant to common fungal diseases.
BARI-16	High-yield variety producing firm deep-red fruits. Tolerant to heat and leaf curl complex. Suitable for extended-season production.
BARI-19	A relatively new variety with high fruit set and uniform shape. Good tolerance to bacterial wilt. Fruits have strong firmness and long shelf life.
BARI-20	Produces blocky, high-quality salad-type tomatoes. Very good tolerance to TYLCV and late blight. High yield potential in both open field and protected cultivation.
BARI-21	Hybrid-type performance with vigorous growth and early maturity. Fruits are medium-sized, deep red, and firm. Shows high tolerance to disease and transport stress.
BARI-F1-4	A hybrid with excellent fruit uniformity and very high yield. Good resistance to leaf curl virus. Suitable for intensive commercial cultivation.
BARI-F1-5	Produces large firm fruits with attractive shape. Strong tolerance to heat and foliar diseases. Good transportability and shelf stability.
BARI-F1-7	A high-performing hybrid with long shelf-life fruits. Plants are highly vigorous and resistant to major viral diseases. Good for off-season production.
BARI-F1-8	Hybrid variety producing smooth, glossy red fruits. Very good tolerance to TYLCV and early blight. High fruiting even under stress.
AvTo-1228	Research line with good fruit firmness and moderate disease tolerance. Shows stable yield under field stress. Medium-sized round fruits.
AvTo-1229	Performs well in warm climates with good number of fruits per cluster. Fruits are moderately firm and uniform. Shows tolerance to leaf curl conditions.
AvTo-1318	High-yielding genotype commonly used in breeding programs. Fruits are round, smooth, and moderately firm. Good tolerance to heat and humidity.
Honey-Bee	A small-fruited variety known for sweetness and flavor. Early maturing and highly productive. Popular for fresh salads and home gardening.
Pathorkuch	Local type with thick-fleshed, firm fruits. Very good keeping quality and stress tolerance. Suitable for long-distance marketing.
Roma-VF	A classic determinate variety producing oblong "Roma" type fruits. Resistant to Verticillium and Fusarium wilts (VF).

Table 3. Physical and chemical characteristics of the experimental soil. Source: Soil Resources Development Institute (SRDI), Dhaka, Bangladesh.

Characteristics	Value
Particle size analysis	
% Sand	27
% Silt	43
% Clay	30
Textural class	Silty clay loam
pH	5.6
Organic C, %	0.45
Organic matter, %	0.78
Total N, %	0.03
Available P, mg kg^{-1} soil	20.0
Exchangeable K, me 100 g^{-1} soil	0.1
Available S, mg kg^{-1} soil	45.0

Reducing sugar content

Reducing sugar content was determined using a modified phenol-sulfuric acid method, adapted from DuBois et al. (1956) with adjustments to the assay volume and wavelength. Briefly, 0.2 g fresh leaf tissue was homogenized in deionized water, and the resulting extract was filtered. A 2 mL aliquot of the filtrate was mixed with 0.4 mL 5% phenol solution. Subsequently, 2 mL 98% sulfuric acid was rapidly added to the mixture. The reaction mixture was allowed to stand for 10 min at room temperature, followed by incubation in a 30 °C water bath for 20 min to allow for color development. Absorbance was then measured at 540 nm using a spectrophotometer, with deionized water used as a blank. Reducing sugar content was expressed as milligrams per gram of fresh weight (mg g^{-1} FW).

Relative water content measurement

Relative water content (RWC) was determined following the method described by Smart and Bingham (1974). For each biological replicate, three leaves were pooled, and their fresh weight (FW) was recorded. Subsequently, these leaves were fully immersed in distilled water for 12 h at room temperature to achieve full turgidity. After immersion, the turgid leaves were quickly and carefully blotted with absorbent paper to remove any surface water, and their turgid weight (TW) was then measured. Finally, the leaf samples were dried in a forced-air oven at 65 °C for 24 h to obtain their dry weight (DW). The RWC was calculated using the following formula: RWC% = ((FW − DW)/(TW − DW)) × 100.

Determination of shoot and root growth

To determine shoot and root length, five plants were randomly selected from each treatment and replicate 2 wk after imposition of drought stress. The roots were carefully washed with tap water to remove any adhering substrates. The longest root length (cm $plant^{-1}$) was measured from the soil surface to the tip of the longest root. Five plants (both above and below ground portions) were randomly sampled from each treatment replicate 2 wk after the imposition of drought stress. Fresh weight was recorded, and then samples were oven-dried at 65 °C for 72 h to determine dry weight.

Data analysis

All statistical analyses were performed using R software (version 4.2.1; R Foundation for Statistical Computing, Vienna, Austria). The ANOVA was employed to detect significant differences among genotypes, followed by comparisons using the least significant difference (LSD) test at $p \leq 0.01$. Additionally, multivariate analyses, including hierarchical clustering and principal component analysis, were conducted to classify genotypes based on performance metrics and to identify key traits contributing to genotypic variation.

RESULTS

Photosynthetic pigment

Nineteen tomato genotypes were evaluated for their physiological and biochemical responses under both normal and early drought stress conditions. Drought stress significantly reduced chlorophyll *a* and *b* contents across all genotypes. The highest chlorophyll *a* under drought was recorded in 'BARI-F1-8', 'BARI-F1-8', 'BARI-14', and 'BARI-F1-5' (Figure 1A). These genotypes maintained better photosynthetic function under stress. Moreover, 'BARI-F1-7', 'BARI-F1-4', 'BARI-11', 'Pathorkuch', 'BARI-15', 'Roma-VF', 'AvTo-1228', and 'BARI-20' displayed moderate chlorophyll *a* content under drought stress. In contrast, 'BARI-16', 'AvTo-1318', 'BARI-8', and 'BARI-21' recorded the lowest values of chlorophyll *a* content. Regarding chlorophyll *b*, 'BARI-F1-8', 'BARI-11', 'BARI-15', and 'BARI-14' showed resilience with the highest drought-induced value (Figure 1B). Furthermore, 'Pathorkuch', 'BARI-F1-5', 'BARI-20', 'BARI-F1-7', 'AvTo-1318', and 'BARI-F1-4' recorded moderate chlorophyll *b* content. While 'BARI-21', 'BARI-8', and 'BARI-16' recorded the lowest values under drought, indicating their higher susceptibility.

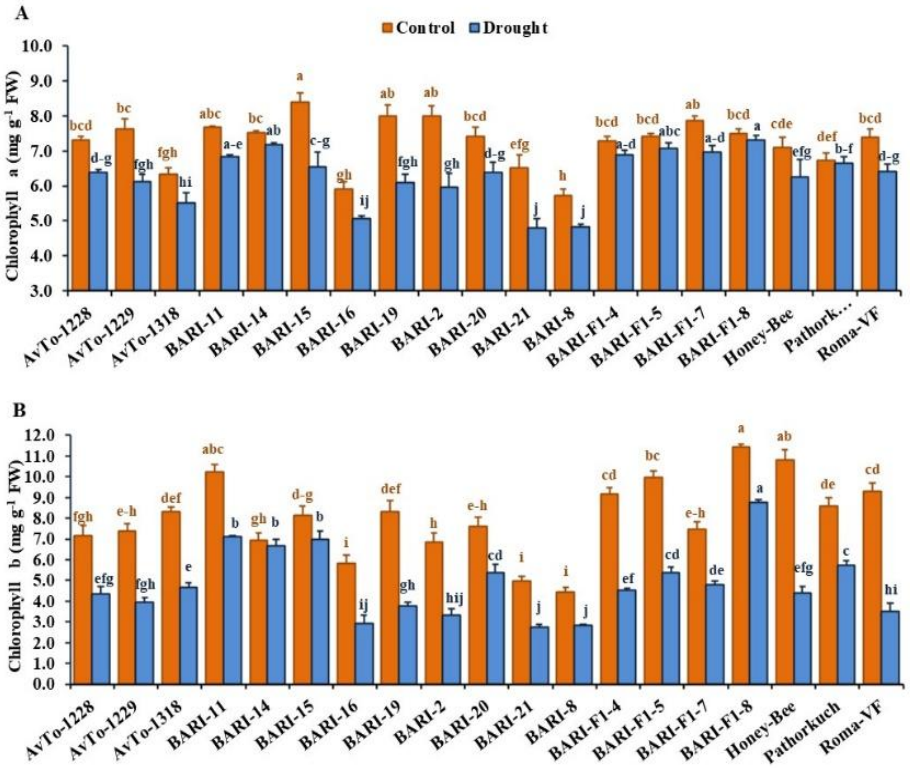

Figure 1. Comparative performance of the evaluated 19 tomato genotypes under control and drought stress conditions: Chlorophyll *a* (A) and chlorophyll *b* content (B). Error bars represent the standard error. Columns marked with different letters (within the same irrigation treatment and color) indicate significant differences according to the LSD test ($p \leq 0.01$).

Cellular hydration and osmolyte accumulation

Relative water content (RWC) declined significantly across genotypes under drought, revealing differences in water retention capacity. The most resilient genotypes, 'BARI-14', 'Pathorkuch', 'AvTo-1318', 'BARI-F1-5', 'BARI-15', 'BARI-F1-8', and 'BARI-11' retained over 60% RWC under drought (Figure 2A). Moderate water retention was observed in 'AvTo-1229', 'BARI-21', 'Honey-Bee', 'AvTo-1228', and 'BARI-16' (~ 56%-59%). The lowest RWC values were recorded in 'BARI-F1-7', 'BARI-19', and 'BARI-8', indicating poor hydration maintenance. Reducing sugar levels, a proxy for carbohydrate metabolism and osmotic adjustment, declined in most genotypes under drought (Figure 2B). The genotypes 'BARI-15', 'BARI-11', and 'BARI-F1-5' maintained high sugar content under stress, showing stable carbohydrate metabolism. The genotypes 'Pathorkuch', 'AvTo-1318', 'BARI-F1-4', 'BARI-8', 'BARI-F1-8', and 'BARI-14' recorded moderate values. The lowest reducing sugar under drought was recorded by 'BARI-20', 'BARI-F1-7', and 'AvTo-1229'. Phenolic content increased under drought in the assessed genotypes, reflecting activation of antioxidant defenses. The genotypes 'BARI-15', 'BARI-F1-7', and 'BARI-20' exhibited the highest phenol content under drought. Moderate phenol accumulation was observed in 'Pathorkuch', 'BARI-11', 'AvTo-1228', 'BARI-8', 'Honey-Bee', 'BARI-F1-5', and 'Roma-VF' (Figure 2C). Genotypes 'BARI-F1-4', 'BARI-16', and 'BARI-19' had the lowest values.

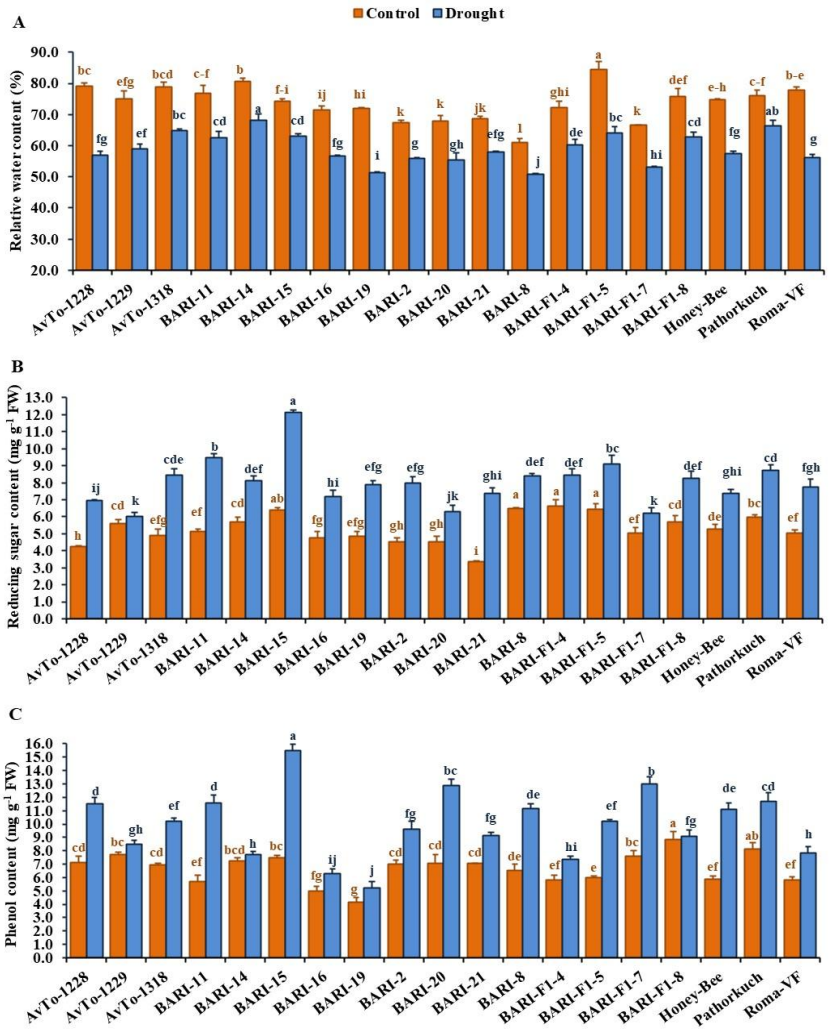

Figure 2. Comparative performance of the evaluated 19 tomato genotypes under control and drought stress conditions: Relative water content (A), reducing sugar content (B), and phenol content (C). Error bars represent the standard error. Columns marked with different letters (within the same irrigation treatment and color) indicate significant differences according to the LSD test ($p \leq 0.01$).

Root growth

Drought stress markedly diminished root elongation across genotypes, revealing significant inter-genotypic variability. Root length was most enhanced in 'Pathorkuch', 'AvTo-1318', 'BARI-20', 'BARI-2', 'BARI-8', and 'BARI-F1-5', demonstrating deep rooting potential. 'BARI-16', 'BARI-15', 'BARI-F1-8', 'BARI-F1-4', 'BARI-21', and 'AvTo-1229' recorded moderate root length. Conversely, 'AvTo-1228', 'BARI-2', 'BARI-19', 'Roma-VF', and 'Honey-Bee' recorded the shortest roots, reflecting poor adaptation (Figure 3A). Root biomass trends under drought showed a considerable reduction compared to well-watered conditions. 'Pathorkuch', 'AvTo-1228', 'Roma-VF', and 'BARI-8' had the highest root fresh weight under drought, indicating robust root development (Figure 3B). 'BARI-F1-7', 'BARI-11', 'BARI-F1-5', 'BARI-15', 'AvTo-1229', and 'BARI-2' exhibited moderate performance. Otherwise, 'BARI-20', 'BARI-19', and 'BARI-16' recorded very low root fresh weights, indicating poor root system resilience. For root dry weight, 'Pathorkuch', 'BARI-15', 'AvTo-1229', 'BARI-11', and 'AvTo-1228' displayed the highest values under drought stress. 'BARI-8', 'BARI-F1-5', 'AvTo-1318', 'Roma-VF', 'BARI-2', and 'BARI-F1-7' had moderate performance. While 'BARI-20', 'BARI-21', 'BARI-F1-8', 'BARI-14', and 'BARI-16' displayed the lowest root dry weight (Figure 3C).

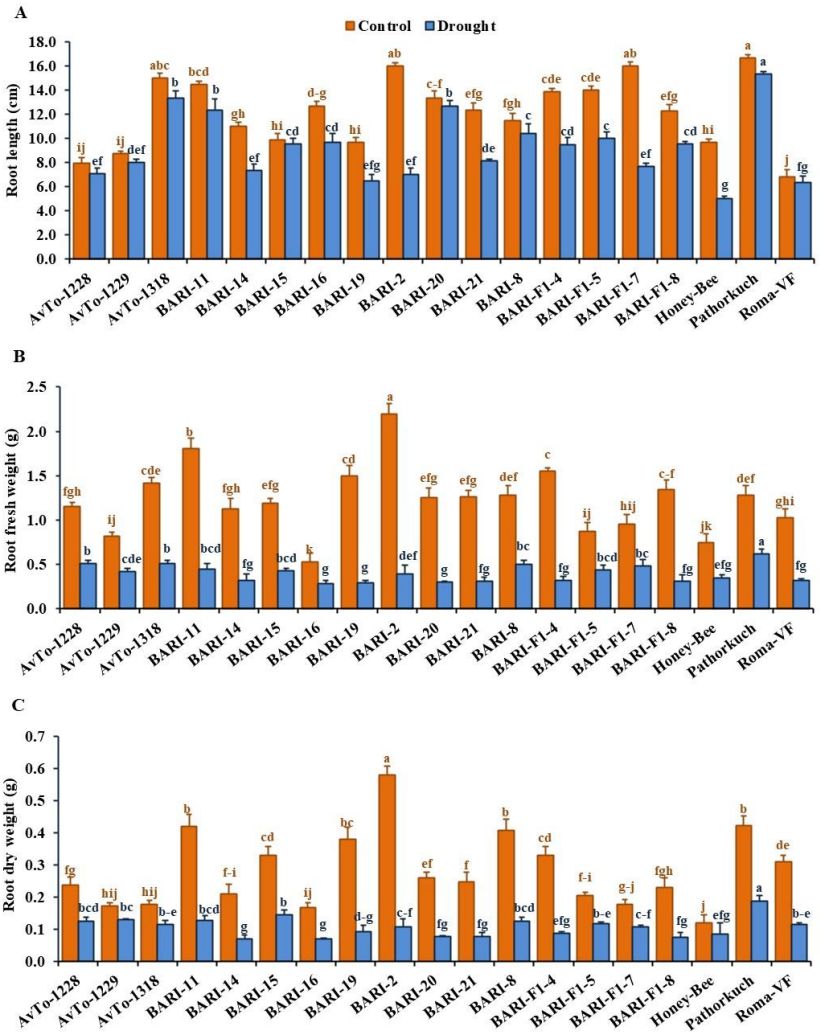

Figure 3. Comparative performance of the evaluated 19 tomato genotypes under control and drought stress conditions: Root length (A), root fresh weight (B), and root dry weight (C). Error bars represent the standard error. Columns marked with different letters (within the same irrigation treatment and color) indicate significant differences according to the LSD test ($p \leq 0.01$).

Shoot growth

Drought stress significantly reduced shoot elongation, with significant genotypic differences. Under drought, 'BARI-11', 'BARI-F1-4', 'AvTo-1318', and 'BARI-15' maintained the highest shoot length. The genotypes 'AvTo-1228', 'Honey-Bee', 'BARI-F1-8', 'BARI-F1-7', and 'AvTo-1229' exhibited moderate shoot length (Figure 4A). While the genotypes 'BARI-8', 'BARI-2', 'BARI-16', 'BARI-21', and 'Roma-VF' exhibited severely stunted shoot growth. Shoot biomass was adversely affected under drought, with certain genotypes maintaining relatively high values. Under drought, 'BARI-F1-4', 'AvTo-1318', 'BARI-15', and 'AvTo-1229' maintained the highest shoot length (Figure 4B). The genotypes 'BARI-11', 'BARI-14', 'BARI-F1-8', 'Pathorkuch', 'BARI-F1-5', and 'BARI-8' exhibited moderate shoot fresh weight. Otherwise, the genotypes 'BARI-2', 'Honey-Bee', 'BARI-20', and 'Roma-VF' exhibited severely stunted shoot growth. For shoot dry weight, 'AvTo-1318', 'BARI-15', and 'BARI-F1-4' recorded the highest shoot dry weight (Figure 4C). The genotypes 'AvTo-1228', 'BARI-14', 'AvTo-1229', 'BARI-F1-5', 'Pathorkuch', 'BARI-F1-8', and 'BARI-11' displayed moderate performance. While 'BARI-21', 'BARI-2', 'BARI-20', 'Roma-VF', and 'BARI-F1-7' had the lowest fresh weights, showing drought-induced biomass decline.

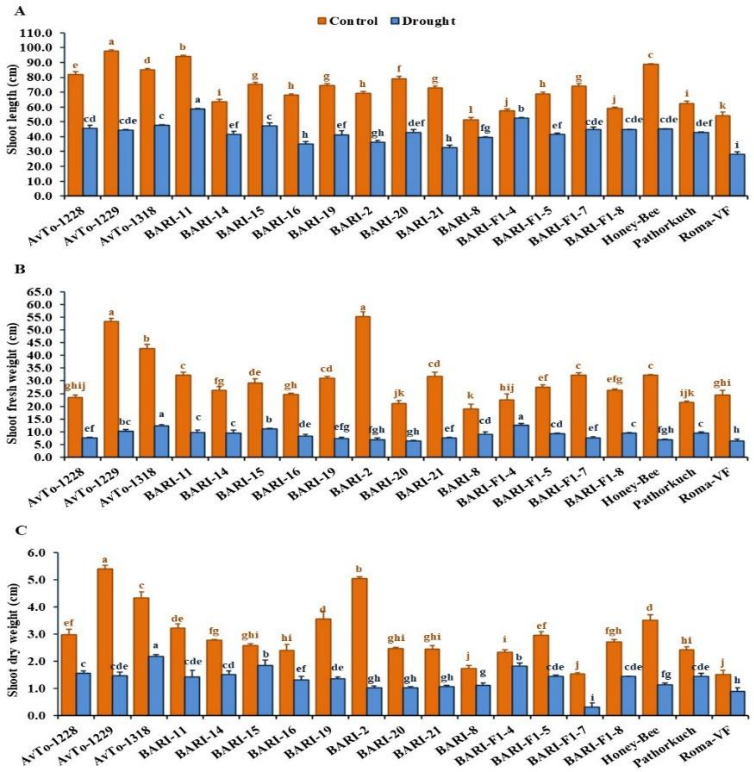

Figure 4. Comparative performance of the evaluated 19 tomato genotypes under control and drought stress conditions: Shoot length (A), shoot fresh weight (B), and shoot dry weight (C). Error bars represent the standard error. Columns marked with different letters (within the same irrigation treatment and color) indicate significant differences according to the LSD test ($p \leq 0.01$)

Classification of genotypic drought responses

The hierarchical cluster analysis (Figure 5) grouped the 19 evaluated tomato genotypes into four major clusters based on their overall performance in physiological parameters (chlorophyll *a* and *b* content, RWC, reducing sugar, and phenol accumulation) as well as root and shoot growth characteristics (length and biomass) under drought stress. Cluster A included 'Pathorkuch', 'BARI-F1-5', 'BARI-15', and 'BARI-11'. Genotypes in this group exhibited high RWC, elevated reducing sugar levels, and increased phenol accumulation, indicating strong osmotic adjustment and enhanced antioxidant capacity under early drought stress conditions. Moreover, these genotypes maintained shoot and root development, with relatively high dry weights and lengths under stress. Therefore, this group represents drought-resilient genotypes that combine both physiological and morphological mechanisms for drought avoidance. Cluster B comprised 'BARI-14', 'BARI-F1-8', 'AvTo-1318', and 'BARI-F1-4'. These genotypes showed high chlorophyll *a* and *b* content under drought conditions, along with moderate to high shoot length and biomass. Their ability to maintain reasonable levels of sugars and phenolics suggests effective physiological adjustment. This group represents moderately drought-tolerant genotypes with consistent shoot performance. Cluster C consisted of 'BARI-F1-7', 'BARI-20', 'BARI-8', 'AvTo-1229', and 'AvTo-1228'. These genotypes displayed variable responses, with certain traits showing moderate tolerance and others being adversely affected by drought. This cluster represents genotypes with a sensitive level of drought tolerance, reflecting diverse physiological and morphological responses to water stress. Cluster D included 'BARI-16', 'BARI-21', 'BARI-19', 'Honey-Bee', 'BARI-2', and 'Roma-VF'. These genotypes were identified as highly drought-sensitive, exhibiting low chlorophyll content, poor RWC, and minimal root and shoot development. Their significantly reduced biomass, low sugar levels, and weak phenolic responses under stress indicate poor physiological adaptation. This cluster represents highly sensitive genotypes that may serve as sensitive controls or contrasting parents in breeding programs aimed at improving drought tolerance.

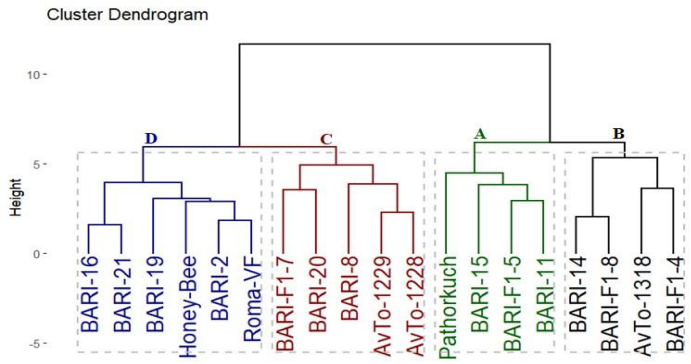

Figure 5. Dendrogram illustrating the distances among assessed tomato genotypes based on physiological, biochemical parameters and root-shoot growth responses under early drought stress. The genotypes were classified into four groups based on the evaluated parameters. A: Drought-tolerant genotypes (four genotypes), B: Moderately drought-tolerant genotypes (four genotypes), C: Drought-sensitive genotypes (five genotypes), and D: highly drought-sensitive genotypes (six genotypes).

Furthermore, the heatmap with hierarchical clustering analysis (Figure 6) illustrates the differential response patterns of 19 tomato genotypes to early drought stress across physiological and morphological traits. The genotypes were clustered based on standardized scores, revealing two primary clusters that distinguish drought-tolerant from drought-sensitive genotypes. Genotypes such as 'BARI-11', 'BARI-F1-5', 'BARI-15', 'Pathorkuch', and 'AvTo-1318' formed a cluster characterized by predominantly positive scores (blue color), indicating superior performance in maintaining high chlorophyll levels, shoot length, RWC, sugar and phenol accumulation, and root-shoot biomass under drought stress. These traits are indicative of strong osmotic adjustment, antioxidant defense, and sustained growth, marking these genotypes as drought resilient. A group of intermediate genotypes, including 'BARI-F1-8', 'BARI-14', 'BARI-F1-4', 'AvTo-1228', and 'AvTo-1229' exhibited moderate trait performance, suggesting partial tolerance and stability under stress. In contrast, the cluster consisting of 'BARI-20', 'BARI-16', 'BARI-21', 'Honey-Bee', 'BARI-19', 'BARI-2', and 'Roma-VF' displayed mostly negative scores (red color), reflecting reduced chlorophyll content, compromised water retention, lower sugar and phenol levels, and significant reductions in root and shoot biomass. These patterns signify a high susceptibility to drought. Notably, traits such as RWC and sugar content were most effective in differentiating tolerant genotypes due to their role in osmotic regulation, while phenol content reflected antioxidant capacity.

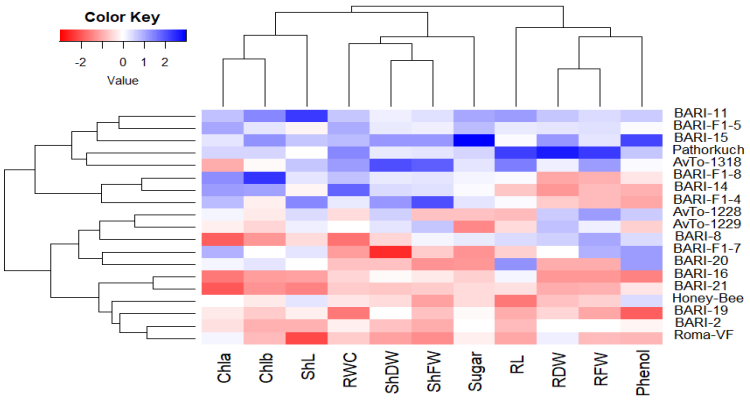

Figure 6. Heatmap and hierarchical clustering of tomato genotypes based on physiological, biochemical, and growth traits under drought stress. Chla: Chlorophyll *a*; Chlb: chlorophyll *b*; ShL: shoot length; RWC: relative water content; ShDW: shoot dry weight; ShFW: shoot fresh weight; Sugar: reducing sugar content; RL: root length; RDW: root dry weight; RFW: root fresh weight; Phenol: phenol content.

Principal component analysis (PCA)

The PCA biplot (Figure 7) illustrates the multivariate relationships among the 19 tomato genotypes and the traits studied under early drought stress. The first two principal components (PC1 and PC2) explained cumulative 63.88% of the total variation, with PC1 accounting for 42.3% and PC2 contributing 21.58%. The distribution of genotypes across the biplot reveals clear variability in trait performance under drought conditions. Genotypes positioned in the right quadrants of PC1, such as 'Pathorkuch', 'BARI-15', 'BARI-11', 'BARI-F1-5', and 'AvTo-1318', were closely aligned with vectors representing positive traits, including chlorophyll *a*, chlorophyll *b*, RWC, shoot length, reducing sugar, phenol content, and root-shoot biomass traits (root length, root dry weight, root fresh weight). This alignment indicates that these traits make strong positive contributions to overall drought resilience. Conversely, the genotypes 'Roma-VF', 'Honey-Bee', 'BARI-2', 'BARI-21', 'BARI-16', 'BARI-19', and 'BARI-8' were located on the left side of PC1 and away from the trait vectors, signifying lower performance in most physiological and growth parameters. These genotypes were negatively correlated with the main contributing traits of PC1, highlighting their sensitivity to drought stress. Intermediate genotypes such as 'AvTo-1229', 'AvTo-1228', and 'BARI-F1-7' clustered near the origin, suggesting variable responses to stress, depending on the trait. Among all traits, RWC, chlorophyll content, and phenol levels exhibited strong vector lengths, indicating their importance in defining the genotypic variability under drought stress.

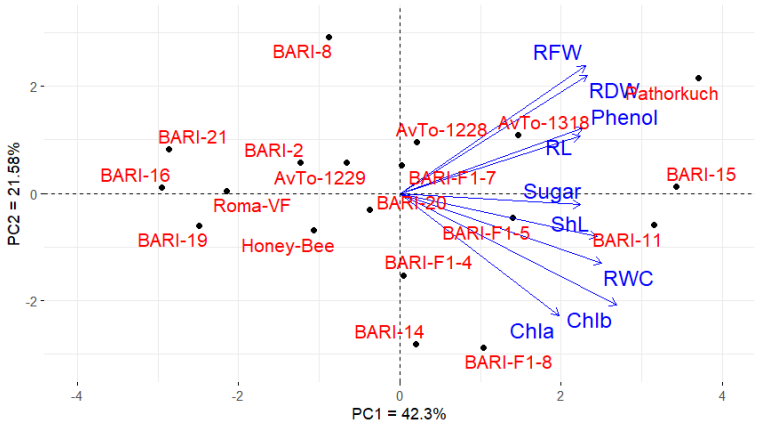

Figure 7. Biplot of principal component analysis revealing trait associations and genotypic variation under early drought stress conditions. Chla: Chlorophyll *a*; Chlb: chlorophyll *b*; ShL: shoot length; RWC: relative water content; ShDW: shoot dry weight; ShFW: shoot fresh weight; Sugar: reducing sugar content; RL: root length; RDW: root dry weight; RFW: root fresh weight; Phenol: phenol content.

DISCUSSION

Drought stress remains one of the most critical abiotic factors limiting tomato productivity, particularly during the early vegetative stages when seedlings are highly sensitive to water deficits. In the present study, 19 tomato genotypes were evaluated under early drought stress to identify the physiological, biochemical, and morphological traits contributing to drought tolerance. Chlorophyll content is widely recognized as an essential indicator of photosynthetic performance and plant vitality under drought stress (Abd El-hady et al., 2022). Drought stress significantly reduced chlorophyll *a* and *b* levels in most genotypes, reflecting impaired photosynthesis due to chloroplast degradation and oxidative damage. However, drought-tolerant genotypes such as 'BARI-F1-8', 'BARI-14', 'BARI-11', and 'BARI-F1-5' maintained relatively higher chlorophyll levels, suggesting that these genotypes possess better protective mechanisms to preserve chloroplast integrity and sustain photosynthetic efficiency under water-deficient conditions. This result is consistent with studies of Patanè et al. (2021) and Kumar et al. (2022), who indicated that chlorophyll retention under drought is positively

correlated with yield stability and stress adaptation in tomatoes and other crops. Relative water content (RWC) is a reliable indicator of the plant hydration status and ability to tolerate water deficit (Desoky et al., 2021a; 2021b). In the present study, genotypes such as 'Pathorkuch', 'BARI-F1-5', 'AvTo-1318', 'BARI-15', and 'BARI-11' exhibited higher RWC under drought, indicating efficient water conservation and cell turgor maintenance. Additionally, the accumulation of reducing sugars played a key role in osmotic adjustment. Genotypes 'BARI-15', 'BARI-11', and 'BARI-F1-5' maintained elevated sugar levels under drought, aiding in osmotic balance, stabilizing cellular membranes, and protecting cellular proteins from dehydration. Conversely, sensitive genotypes such as 'BARI-20', 'AvTo-1229', and 'BARI-F1-7' had low sugar content under stress, suggesting a limited capacity for osmotic adjustment. Similar results were reported by Iqbal et al. (2020) and Ozturk et al. (2021). Drought stress often induces the overproduction of reactive oxygen species (ROS), necessitating an effective antioxidant defense mechanism (Sachdev et al., 2021; Rao et al., 2025). Phenolic compounds are important secondary metabolites involved in ROS scavenging. In this study, 'BARI-15', 'BARI-F1-7', and 'BARI-20' exhibited high phenol content under drought, indicating an active antioxidant response. Moderate phenol accumulation in genotypes like 'Pathorkuch', 'BARI-11', and 'AvTo-1228' further supports their relative stress tolerance. In contrast, 'BARI-19', 'BARI-16', and 'BARI-F1-4' showed low phenolic content, implying a limited antioxidative response and higher susceptibility to oxidative damage under drought conditions.

The development and maintenance of root and shoot systems under drought are critical for survival and resource acquisition (Ezzat et al., 2024). Root traits such as length and biomass contribute to deeper water extraction and better anchorage. Genotypes including 'Pathorkuch', 'AvTo-1318', 'BARI-8', and 'BARI-F1-5' exhibited enhanced root elongation and biomass, indicating superior adaptation through root system architecture. These traits are essential for accessing moisture from deeper soil layers during drought (Ranjan et al., 2022). Shoot traits also showed considerable variation. Genotypes like 'BARI-15', 'BARI-F1-4', and 'AvTo-1318' maintained greater shoot length and biomass under stress, signifying their ability to sustain vegetative growth. The preservation of shoot biomass in these genotypes may be attributed to more efficient water use, reduced transpiration, and stronger sink strength that supports resource allocation (Murtaza et al., 2024). In contrast, 'BARI-2', 'Roma-VF', and 'Honey-Bee' suffered severe reductions in shoot length and dry weight, reinforcing their classification as drought-sensitive.

Multivariate analyses, including hierarchical clustering, heatmap visualization, and principal component analysis, provided classification of genotypes based on integrated trait performance (Salem et al., 2020; Swailam et al., 2021; Omar et al., 2022). The hierarchical clustering identified four major groups: Tolerant (Cluster A), moderately tolerant (Cluster B), sensitive (Cluster C), and highly sensitive (Cluster D). Genotypes in Cluster A ('Pathorkuch', 'BARI-F1-5', 'BARI-15', and 'BARI-11') showed consistently high trait values, particularly for RWC, photosynthetic pigments, sugars, phenols, and root-shoot biomass, indicating their potential as elite drought-tolerant germplasm. The heatmap analysis reinforced these clusters by showing strong positive scores (blue color) for resilient genotypes and negative scores (red color) for sensitive ones. Traits like RWC, sugar, and phenolic content were effective in distinguishing between groups. The PCA further confirmed these patterns, with the first two principal components capturing 63.88% of the total variation. The alignment of tolerant genotypes with critical trait vectors such as Chla, Chlb, RWC, sugar, phenol, and biomass parameters indicate the multifactorial nature of drought tolerance. The genotypes 'BARI-F1-5', 'BARI-15', 'BARI-11', and 'Pathorkuch' offer valuable traits that can be introgressed into commercial cultivars. These genotypes survive drought and maintain key growth and defense functions, making them ideal candidates for marker-assisted selection or hybrid development. The identified genotypes exhibited superior trait combinations across physiological, biochemical, and morphological levels, provide significant promise for tomato breeding programs (Tüzel et al., 2025). Additionally, the positive association detected among RWC, photosynthetic pigments (Chla and Chlb), sugar, phenol, and biomass parameters indicates their pivotal roles in plant adaptation to water deficit. These findings align with Mansour et al. (2021b), Desoky et al. (2021a; 2021b), and Song et al. (2024), who emphasized multifaceted responses at the physiological levels, including the regulation of osmolyte accumulation and photosynthetic efficiency under drought conditions. By linking applied statistical analyses to functional drought tolerance mechanisms and agronomic relevance, this study contributes to a deeper understanding of genotype-specific adaptive strategies and informs the development of stress-resilient cultivars suitable for sustainable agriculture.

CONCLUSIONS

This study evaluated the physiological, biochemical, and morphological responses of 19 tomato genotypes to early-stage drought stress. The findings revealed significant genotypic variability in response to water deficit, indicating the differential expression of key traits such as chlorophyll content, relative water content, reducing sugar and phenol accumulation, and root-shoot growth characteristics. Drought stress adversely affected all measured parameters across genotypes; however, several genotypes demonstrated superior adaptive responses. The genotypes 'BARI-F1-5', 'BARI-15', 'BARI-11', and 'Pathorkuch' exhibited drought resilience, maintaining higher chlorophyll levels, better hydration status, enhanced osmolyte and phenol content, and robust root and shoot biomass under stress conditions. These traits contributed to their consistent classification as drought-tolerant across multivariate clustering, heatmap, and PCA analyses. In contrast, genotypes 'Roma-VF', 'BARI-2', 'Honey-Bee', and 'BARI-21' showed sensitivity to early drought stress, with reductions across all parameters, making them useful as sensitive controls in breeding studies. The integrative approach adopted in this study, by combining physiological, biochemical, and morphological assessments with advanced statistical analyses, proved effective in distinguishing tolerant and sensitive genotypes. The identified drought-resilient genotypes serve as valuable genetic resources for tomato improvement programs targeting water-limited environments

Author contributions

Conceptualization: S.C., S.H., N.I., R.S., M.A.H., F.A.S., A.S.J., N.M.A., M.O.A., M.S.H. Methodology: S.C., S.H., N.I., R.S., M.A.H., M.S.H. Software: F.A.S., A.S.J., N.M.A., M.O.A., M.S.H. Validation: S.C., S.H., N.I., R.S., M.A.H., M.S.H. Formal analysis: F.A.S., A.S.J., N.M.A., M.O.A. Investigation: S.C., S.H., N.I., R.S., M.A.H., M.S.H. Resources: F.A.S., A.S.J., N.M.A., M.O.A., M.S.H. Data curation: S.C., S.H., N.I., R.S., M.A.H., F.A.S., A.S.J., N.M.A., M.O.A., M.S.H. Writing-original draft: S.C., S.H., N.I., R.S., M.A.H. Writing-review and editing: F.A.S., A.S.J., N.M.A., M.O.A., M.S.H. Visualization: S.C., S.H., N.I., R.S., M.A.H., M.S.H. Supervision: N.I., R.S., M.A.H., M.S.H. Funding acquisition: F.A.S., A.S.J., N.M.A., M.O.A., M.S.H. All co-authors reviewed the final version and approved the manuscript before submission.

Acknowledgements

The authors are grateful to the University Grants Commission of Bangladesh for the support provided to conduct this work. The authors extend their appreciation to the Deanship of Research and Graduate Studies at King Khalid University for funding this work through Large Research Project under grant number RGP2/351/46. Additionally, this research was funded by Princess Nourah bint Abdulrahman University Researchers Supporting Project number (PNURSP2026R366), Princess Nourah bint Abdulrahman University, Riyadh, Saudi Arabia.

References

Abd-El-Aty, M.S., Kamara, M.M., Elgamal, W.H., Mesbah, M.I., Abomarzoka, E.A., Alwutayd, K.M., et al. 2024. Exogenous application of nano-silicon, potassium sulfate, or proline enhances physiological parameters, antioxidant enzyme activities, and agronomic traits of diverse rice genotypes under water deficit conditions. Heliyon 10(5):e26077.

Abd El-hady, M.A., Abd-Elkrem, Y.M., Rady, M.O., Mansour, E., El-Tarabily, K.A., AbuQamar, S.F., et al. 2022. Impact on plant productivity under low-fertility sandy soil in arid environment by revitalization of lentil roots. Frontiers in Plant Science 13:937073.

Awaad, H.A., Alzohairy, A.M., Morsy, A.M., Moustafa, E.S., Mansour, E. 2023. Genetic analysis of cadmium tolerance and exploration of its inheritance nature in bread wheat (*Triticum aestivum* L.) Indian Journal of Genetics and Plant Breeding 83(01):41-51.

Çiğ, F., Erman, M., Sabagh, A.E., Ceritoglu, M., Soysal, S., Uçar, Ö., et al. 2024. Screening of lentil genotypes during germination and early growth stages under PEG-induced drought stress. Chilean Journal of Agricultural Research 84:326-337.

Desoky, E.S.M., Alharbi, K., Rady, M.M., Elnahal, A.S., Selem, E., Arnaout, S.M., et al. 2023. Physiological, biochemical, anatomical, and agronomic responses of sesame to exogenously applied polyamines under different irrigation regimes. Agronomy 13(3):875.

Desoky, E.S.M., Mansour, E., Ali, M.M., Yasin, M.A., Abdul-Hamid, M.I., Rady, M.M., et al. 2021a. Exogenously used 24-epibrassinolide promotes drought tolerance in maize hybrids by improving plant and water productivity in an arid environment. Plants 10(2):354.

Desoky, E.S.M., Mansour, E., El-Sobky, E.S.E., Abdul-Hamid, M.I., Taha, T.F., Elakkad, H.A., et al. 2021b. Physio-biochemical and agronomic responses of faba beans to exogenously applied nano-silicon under drought stress conditions. Frontiers in Plant Science 12:637783.

Desoky, E.-S.M., Mansour, E., Yasin, M.A.T., El-Sobky, E.-S.E.A., Rady, M.M. 2020. Improvement of drought tolerance in five different cultivars of *Vicia faba* with foliar application of ascorbic acid or silicon. Spanish Journal of Agricultural Research 18(2):e0802.

DuBois, M., Gilles, K.A., Hamilton, J.K., Rebers, P.A., Smith, F. 1956. Colorimetric method for determination of sugars and related substances. Analytical Chemistry 28(3):350-356.

Elagib, N.A., Ali, M.M., Musa, A.A. 2024. Intensifying droughts render more Sahel drylands unsuitable for cultivation. Science of the Total Environment 954:176390.

Ezzat, M.A., Alotaibi, N.M., Soliman, S.S., Sultan, M., Kamara, M.M., Abd El-Moneim, D., et al. 2024. Molecular and agro-morphological diversity assessment of some bread wheat genotypes and their crosses for drought tolerance. PeerJ 12:e18104.

Gaballah, M.M., Ghazy, M.I., Abd El Salam, K.M., Abou El-Soud, G.M., Marei, A.M., Alomran, M.M., et al. 2024. Assessing productivity and quality potential of promising newly developed rice lines under water deficit and well-watered conditions. Pakistan Journal of Botany 56(6):2107-2116.

Iqbal, A., Dong, Q., Wang, X., Gui, H., Zhang, H., Zhang, X., et al. 2020. High nitrogen enhance drought tolerance in cotton through antioxidant enzymatic activities, nitrogen metabolism and osmotic adjustment. Plants 9(2):178.

Kamara, M.M., Rehan, M., Mohamed, A.M., El Mantawy, R.F., Kheir, A.M., Abd El-Moneim, D., et al. 2022. Genetic potential and inheritance patterns of physiological, agronomic and quality traits in bread wheat under normal and water deficit conditions. Plants 11(7):952.

Kumar, R., Harikrishna, Barman, D., Ghimire, O.P., Gurumurthy, S., Singh, P.K., et al. 2022. Stay-green trait serves as yield stability attribute under combined heat and drought stress in wheat (*Triticum aestivum* L.) Plant Growth Regulation 96(1):67-78.

Liu, W., Liu, K., Chen, D., Zhang, Z., Li, B., El-Mogy, M.M., et al. 2022. *Solanum lycopersicum*, a model plant for the studies in developmental biology, stress biology and food science. Foods 11(16):2402.

Mannan, M.A., Tithi, M.A., Islam, M.R., Al Mamun, M.A., Mia, S., Rahman, M.Z., et al. 2022. Soil and foliar applications of zinc sulfate and iron sulfate alleviate the destructive impacts of drought stress in wheat. Cereal Research Communications 50:1279-1289.

Mansour, E., Desoky, E.-S.M., Ali, M.M.A., Abdul-Hamid, M.I., Ullah, H., Attia, A., et al. 2021a. Identifying drought-tolerant genotypes of faba bean and their agro-physiological responses to different water regimes in an arid Mediterranean environment. Agricultural Water Management 247:106754.

Mansour, E., El-Sobky, E.S.E., Abdul-Hamid, M.I., Abdallah, E., Zedan, A.M., Serag, A.M., et al. 2023. Enhancing drought tolerance and water productivity of diverse maize hybrids (*Zea mays*) using exogenously applied biostimulants under varying irrigation levels. Agronomy 13(5):1320.

Mansour, E., Mahgoub, H.A., Mahgoub, S.A., El-Sobky, E.S.E., Abdul-Hamid, M.I., Kamara, M.M., et al. 2021b. Enhancement of drought tolerance in diverse *Vicia faba* cultivars by inoculation with plant growth-promoting rhizobacteria under newly reclaimed soil conditions. Scientific Reports 11(1):24142.

Moran, R., Porath, D. 1980. Chlorophyll determination in intact tissues using *N*,*N*-dimethylformamide. Plant Physiology 65(3):478-479.

Morsi, N.A., Hashem, O.S., El-Hady, M.A.A., Abd-Elkrem, Y.M., El-temsah, M.E., Galal, E.G., et al. 2023. Assessing drought tolerance of newly developed tissue-cultured canola genotypes under varying irrigation regimes. Agronomy 13(3):836.

Mousa, A.M., Ali, A.M.G., Omar, A.E., Alharbi, K., Abd El-Moneim, D., Mansour, E., et al. 2024. Physiological, agronomic, and grain quality responses of diverse rice genotypes to various irrigation regimes under aerobic cultivation conditions. Life 14(3):370.

Murtaza, G., Usman, M., Iqbal, J., Tahir, M.N., Elshikh, M.S., Alkahtani, J., et al. 2024. The impact of biochar addition on morpho-physiological characteristics, yield and water use efficiency of tomato plants under drought and salinity stress. BMC Plant Biology 24(1):356.

Omar, M., Rabie, H.A., Mowafi, S.A., Othman, H.T., El-Moneim, D.A., Alharbi, K., et al. 2022. Multivariate analysis of agronomic traits in newly developed maize hybrids grown under different agro-environments. Plants 11(9):1187.

Ozturk, M., Turkyilmaz Unal, B., García-Caparrós, P., Khursheed, A., Gul, A., Hasanuzzaman, M. 2021. Osmoregulation and its actions during the drought stress in plants. Physiologia Plantarum 172(2):1321-1335.

Patanè, C., Siah, S., Pellegrino, A., Cosentino, S.L., Siracusa, L. 2021. Fruit yield, polyphenols, and carotenoids in long shelf-life tomatoes in response to drought stress and rewatering. Agronomy 11(10):1943.

Ranjan, A., Sinha, R., Singla-Pareek, S.L., Pareek, A., Singh, A.K. 2022. Shaping the root system architecture in plants for adaptation to drought stress. Physiologia Plantarum 174(2):e13651.

Rao, M.J., Duan, M., Zhou, C., Jiao, J., Cheng, P., Yang, L., et al. 2025. Antioxidant defense system in plants: Reactive oxygen species production, signaling, and scavenging during abiotic stress-induced oxidative damage. Horticulturae 11(5):477.

Sachdev, S., Ansari, S.A., Ansari, M.I., Fujita, M., Hasanuzzaman, M. 2021. Abiotic stress and reactive oxygen species: Generation, signaling, and defense mechanisms. Antioxidants 10(2):277.

Salem, T.S.G., Rabie, H.A., Mowafy, S.A.E., Eissa, A.E.M., Mansour, E. 2020. Combining ability and genetic components of Egyptian cotton for earliness, yield, and fiber quality traits. SABRAO Journal of Breeding & Genetics 52(4):369-389.
Sedhom, Y.S., Rabie, H.A., Awaad, H.A., Alomran, M.M., ALshamrani, S.M., Mansour, E., et al. 2024. Genetic potential of newly developed maize hybrids under different water-availability conditions in an arid environment. Life 14(4):453.
Selem, E., Hassan, A.A., Awad, M.F., Mansour, E., Desoky, E.S.M. 2022. Impact of exogenously sprayed antioxidants on physio-biochemical, agronomic, and quality parameters of potato in salt-affected soil. Plants 11(2):210.
Singleton, V. 1999. Analysis of total phenols and other oxidation substrates and antioxidants by means of Folin-Ciocalteu reagent. Methods in Enzymology 299:152-178.
Smart, R.E., Bingham, G.E. 1974. Rapid estimates of relative water content. Plant Physiology 53(2):258-260.
Song, J., Xin, L., Gao, F., Liu, H., Wang, X. 2024. Effects of foliar selenium application on oxidative damage and photosynthetic properties of greenhouse tomato under drought stress. Plants 13:302.
Swailam, M.A., Mowafy, S.A.E., El-Naggar, N.Z.A., Mansour, E. 2021. Agronomic responses of diverse bread wheat genotypes to phosphorus levels and nitrogen forms in a semiarid environment. SABRAO Journal of Breeding & Genetics 53(4):592-608.
Tegegne, G., Alemayehu, S., Dejene, S.W., Gebre, L., Zeleke, T.T., Tesfaye, L., et al. 2025. Next-generation drought intensity-duration-frequency curves for early warning systems in Ethiopia's pastoral region. Climate 13(2):31.
Tüzel, Y., Kayıkçıoğlu, H.H., Durdu, T., Harouna, O.S., Tunalı, U., Öztekin, G.B., et al. 2025. Enhancing tomato drought resilience with organic amendments and local landraces. Scientific Reports 15(1):1-22.
Yadav, P.K., Bhujel, P., Bhandari, N., Sharma, S., Sharma, A. 2025. Screening tomato genotypes for early-stage drought tolerance using polyethylene glycol-induced osmotic stress. BMC Plant Biology 25(1):1476.
Zannat, A., Hussain, M.A., Abdullah, A.H.M., Hossain, M.I., Saifullah, M., Safhi, F.A., et al. 2023. Exploring genotypic variability and interrelationships among growth, yield, and quality characteristics in diverse tomato genotypes. Heliyon 9(8):e18958.