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Assessing Tomato Genotypes for Organic Hydroponic Production in Stressful Environmental Conditions

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Abstract. **Identifying tomato genotypes that can thrive and produce abundantly under arid climatic conditions and addressing the growing food demand caused by population growth are pressing concerns for food security. This research aimed to assess the growth, physiological, phenological, fruit yield, and postharvest quality of tomato genotypes cultivated in an organic hydroponic system in Qatar, where abiotic stress conditions prevail. Ten different tomato genotypes were carefully evaluated, and comprehensive data regarding their growth and development were collected and analyzed. The performance of these tomato genotypes across all traits related to yield and quality showed significant variations. Notably, the ‘Velocity’ and ‘Sigma’ genotypes consistently exhibited robust vegetative growth and improved phenological characteristics compared with the other tomato cultivars. Specifically, ‘Velocity’ and ‘Sigma’ displayed increased leaf assimilation rates (35% and 32%), stomatal conductance (14% and 11%), and reduced transpiration loss (50% and 44%) compared with ‘SV4129TH’. These genotypes also showed lower electrolyte leakage (32% and 28%) and maintained higher intercellular CO_2 concentrations. Furthermore, ‘Velocity’ exhibited an accelerated flowering pattern, with the first flowering occurring 4 days sooner and 50% flowering occurring 5 days sooner than that of ‘SV4129TH’. ‘Velocity’ also demonstrated superior fruit set (14%), pollen viability (24%), and fewer incidences of flower drops (36%) compared with ‘SV4129TH’. Notably, ‘Velocity’ outperformed ‘SV4129TH’ in terms of marketable fruit yields, with a 32% higher yield. In addition to its impressive yield, ‘Velocity’ exhibited superior postharvest quality, including firmness, Brix level, acidity, and color. Therefore, overall, ‘Velocity’ and ‘Sigma’ emerged as promising genotypes with strong abiotic stress tolerance capabilities. The correlation analysis of these traits provided valuable insights into the selection and breeding of genotypes that can withstand abiotic stress conditions, laying the foundation for effective comparisons and selections of genotypes suitable for organic hydroponic cultivation in stressful environments.**

Tomato has a wide range of adaptability to diverse environmental conditions and can thrive even in hot and humid climatic conditions (Wahid et al. 2007). However, the detrimental effects of abiotic stress on tomato physiology significantly hamper productivity (Fahad et al. 2017; Keatinge et al. 2014). The intensity and nature of abiotic stresses vary depending on the growing season and environmental conditions (Ro et al. 2021). In Qatar, where high temperatures are commonplace, heat stress severely constrains crop productivity, necessitating substantial imports of produce. The impetus for food security research in the region stems from the increasing demand caused by population growth (van Dijk et al. 2021) and, in some instances, geopolitical factors (QNFSS 2020). The vegetable supply plays a pivotal role in food security, with tomatoes being one of the most valuable fresh market commodities. Qatar’s agricultural sector has expanded significantly because of population growth, heightened food demand, and rapid economic growth. Hence, efficient management strategies are imperative to achieve food security in Qatar.

The average maximum outdoor temperature in Qatar exceeds 35 °C, particularly during the October tomato growing season (Weather Atlas 2023). The Intergovernmental Panel on Climate Change warns that global warming will elevate temperatures by 1.5 °C in Asia by 2050 (Intergovernmental Panel on Climate Change 2022), posing a grave threat to crop production. Research indicates that high temperatures severely impact plant physiological attributes (Rajametov et al. 2021). The combined effects of temperature and relative humidity play a crucial role in the response of tomatoes to heat stress (Peet et al. 2003). Heat and drought stress jointly suppress tomato CO_2 assimilation rates, leading to disruptions in the leaf photosynthetic apparatus (Haupt-Herting and Fock 2000) and the onset of photo-oxidative stress through excessive reactive oxygen species production (Li et al. 2015). This process damages proteins, chlorophylls, membrane lipids, and nucleic acids, resulting in reduced photosystem II efficiency and water status. Elevated air temperatures further increase leaf temperature, transpiration, and stomatal conductance fluctuations, thereby disrupting the electron transport chain and photosynthesis (Moore et al. 2021). Moreover, heat stress can reduce tomato pollen viability, cause anther deformities (Muller and Rieu 2016), and lead to blossom-end rot in tomato fruits (Saure 2014). However, sensitivity to water and heat stress varies among tomato cultivars despite the preference of tomato plants for temperatures between 25 and 30 °C for growth and development (Arena et al. 2020; Francesca et al. 2020; Zhou et al. 2020). Some tomato genotypes, such as LA2854, LA1478, and LA0417, have been identified as thermotolerant because they maintain higher pollen viability under heat stress conditions (Paupiere et al. 2017). Evidence of a negative link between pollen viability and the successful formation of fruits has been identified when plants are subjected to high temperatures (Pham et al. 2020; Rutley et al. 2021), ultimately causing a decrease in fruit production and consequently leading to reduced tomato yields (Ayenan et al. 2019; Driedonks et al. 2016). On the contrary, Ayenan et al. (2021) and Miller et al. (2021) reported that tomato genotypes could maintain high levels of pollen viability under heat stress but fail to set fruit, leading to low or no correlation between pollen viability and fruit set or yield under heat stress.

Results demonstrate that a complex interplay among crop genotypes, environmental conditions, and management strategies can profoundly influence crop physiology, leading to significant yield variations (Potgieter et al. 2021). Therefore, selecting the most suitable crop genotypes and optimal management practices is crucial for achieving high yields and mitigating the growing food demand (Aldubai et al. 2022). In greenhouse conditions, a substantial proportion of tomato yields (37%–98%) is lost because of extreme heat stress (24–43 °C) (Ro et al. 2021). Similarly, heat stress (36 °C) restricts fruit number,

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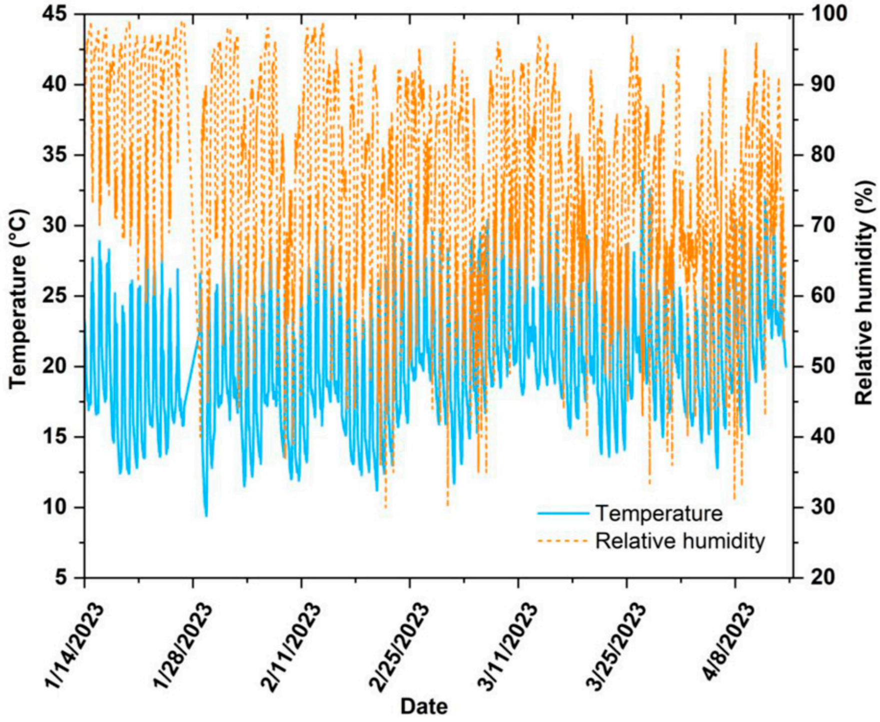

Fig. 1. Real-time air temperature and relative humidity inside the greenhouse.

weight, and per-plant yield across all tested tomato genotypes (Vijayakumar et al. 2021). The phenotypic characteristics of tomatoes under severe heat stress (40 °C) vary among genotypes and climatic conditions, but they consistently reduce overall yield and yield components (Sherzod et al. 2020).

Research has confirmed that tomato genotypes possess the capacity to compensate for temperature fluctuations (de Koning 1990) and could play a pivotal role in mitigating heat stress (Zhou et al. 2017). Identifying genotypes tolerant to high temperatures offers the potential to cultivate and manage tomatoes under greenhouse conditions while maintaining high yields and fruit quality. In Qatar, tomatoes are grown both in open fields and greenhouses. Greenhouse production is particularly advantageous in adverse climatic conditions because it often results in higher yields compared with open-field cultivation (Shamshiri et al. 2018). Controlled environment vegetable production is increasingly popular because of its advantages, including reduced risk of pests and diseases, and the ability to manage abiotic stresses. The influence of genotypes on high-temperature tolerance in open field conditions is complex because it involves multiple factors (Sharma et al. 2014). An ideal genotype possesses several positive traits, such as high yield, consistency in yield, and performance stability under varying environmental conditions year after year (Kalloo 1998). Cultivar selection in hydroponic production systems is a critical management decision that directly impacts tomato growers' profitability. However, knowledge of the performance of indeterminate tomato cultivars in organically grown hydroponic systems under Qatari conditions, or similar climates, remains limited. Therefore, this study was undertaken to evaluate the growth, physiology, and yield responses of tomato genotypes to abiotic stress environments and organic hydroponic systems.

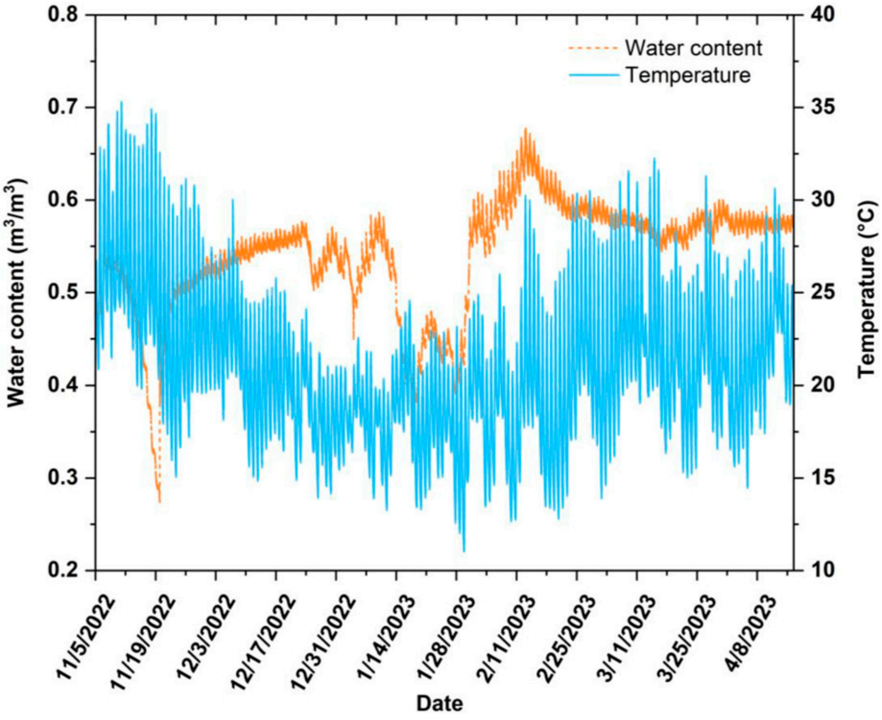

Fig. 2. Real-time growing media temperature and water content at a depth of 2 cm.

Materials and Methods

Plant material and growth conditions. Ten cultivars of organic tomato seeds were used during this study, including two open-pollinated and eight hybrid cultivars. 'Cherokee Purple' and 'Brandywine' are open-pollinated. 'New Girl F1', 'BHN-589 F1' (BHN), 'Sakura F1' (SK) (Johnny's Selected Seeds; Fairfield, ME, USA), 'Velocity F1', 'Sigma F1' (Semillas Fito; Barcelona, Spain), 'SV4129TH', 'Shourouq F1' (Seminis®; Bayer Pty. Ltd.; Johannesburg, South Africa), and 'Salimah F1' (H.M. Clause SAS, Portes-Les-Valence, France) are hybrid cultivars. The organic tomato seeds were initially sown in polystyrene 50-cell trays (dimensions: 4.8 × 3.8 × 5.8 cm, with an 80 cm^3 cell volume; XQ50; Wilson Garden Co. Ltd., Zhengzhou, China) filled with a growth medium comprising 90% cocopeat and 10% compost (LivePlant Biotec; Hortalan Group, Almeria, Spain). These trays were irrigated and incubated in an insulated cold room at 24 °C and 80% relative humidity for 72 h. Subsequently, the trays were moved to a propagation unit, where the seedlings were allowed to grow for 35 d before transplanting into the greenhouse. During this period, the trays received regular fertilization every 3 d using organic nitrogen (N), phosphorus (P), and potassium (K) fertilizers (N20–P10–K30) at a concentration of 200 mg·L^{-1} of N, along with trace elements [iron (Fe), zinc (Zn), bromine (Br), molybdenum (Mb), copper (Cu), manganese (Mn)] at a concentration of 10 mg·L^{-1} (Yara; Hortalan Group, Madrid, Spain) commencing 24 d after seedling emergence.

The experimental design adopted was a complete randomized block design, with the various tomato genotypes being replicated four times and each replication consisting of a minimum of 12 plants. The plants were grown at a density of 3.5 plants/m^2 in a large commercial hydroponic system that uses a grow bag (1.0 × 0.2 × 0.1 m) gutter filled

Table 1. Effect of genotypes on seedling growth and root characteristics of tomato.

						Root length (cm)			
Genotypes	Ht (cm)	Stem diam (cm)	Leaf number	Leaf area (cm^2)	Root diam (mm)	Fine (0–0.45 mm)	Medium (0.45–1.50 mm)	Large (1.5–2.5 mm)	Total
Cherokee Purple	11.3 cd	0.31 a	4.7 a	16.1 a	0.47 a	243.4 b	49.5 ab	8.1 b	301.0 b
New Girl	9.3 d	0.23 bc	2.5 b	7.2 bc	0.36 c	162.7 e	30.7 c	6.0 c	199.4 de
BHN-589	10.0 d	0.29 ab	3.3 ab	8.4 abc	0.35 c	140.6 h	27.4 c	5.5 c	173.5 e
Brandywine	14.0 bc	0.30 a	3.6 ab	14.9 ab	0.42 b	237.1 b	44.9 b	7.8 b	289.8 b
Sakura	10.3 d	0.32 a	3.3 ab	9.9 abc	0.34 c	152.5 fg	28.1 c	5.9 c	186.5 e
SV4129TH	9.1 d	0.18 c	2.3 b	6.5 c	0.33 c	155.8 ef	29.2 c	5.6 c	190.6 e
Salimah	9.2 d	0.26 ab	2.6 b	8.3 abc	0.40 b	175.1 d	35.7 c	6.1 c	216.9 d
Shourouq	9.6 d	0.26 ab	3.2 ab	9.4 abc	0.37 c	145.6 gh	29.9 c	5.7 c	181.2 e
Velocity	16.0 ab	0.33 a	3.3 ab	9.9 abc	0.45 a	281.5 a	54.2 a	11.9 a	347.6 a
Sigma	17.6 a	0.32 a	3.3 ab	10.6 abc	0.40 b	200.8 c	50.8 ab	9.5 ab	261.1 c
Significance	**	**	*	*	*	**	**	*	**

All pairwise comparisons were performed using Tukey's honestly significant difference test at $P < 0.05$. Columns with dissimilar letters are statistically different, whereas columns sharing the same letter are statistically similar. *$P < 0.05$; **$P < 0.01$.

with a cocopeat (90%) and compost (10%) mix (Kirulapone; Polydime, Colombo, Sri Lanka) located at AGRICO Organic Farm in Al-Khore, Qatar (lat. 25°41′ N; long. 51°30′ E). The grow bags were positioned on a metal bench with a 1.2 m center-to-center distance, and the blank space between them was 0.2 m; a drip tube hose was inserted for each plant to provide irrigation and nutrients. Continuous monitoring of greenhouse air temperature (°C) and relative humidity (%) was conducted throughout the experiments using an Ambient weather monitoring system (WS80BN; Chandler, AZ, USA) (Fig. 1). Additionally, data loggers were used to record growing media temperatures (°C) and water content ($m^3 \cdot m^{-3}$) at a depth of 2 cm (HOBO® MX2307; ONSET®, Bourne, MA, USA) (Fig. 2). The plants were irrigated daily between 8:00 AM and 4:00 PM through a drip irrigation system with an emitter flow rate of 0.3 L per hour. Weekly fertilization with N20–P10–K30 fertilizer (200 $mg \cdot L^{-1}$ of N) was maintained and continued until 25 Mar 2023.

Seedlings growth and root traits measurements. Various growth and root attributes of tomato seedlings were assessed, encompassing parameters such as stem diameter, plant height, leaf number, leaf area, the presence of fine, medium, and larger roots, and the total roots. Manual leaf counting was used to determine the number of leaves per plant. Plant height was measured in centimeters using a scale, whereas stem diameter was measured using a digital slide caliper (Digi-max™ slide caliper Z503576; Merck Korea, Gangnam, Seoul, Korea). Leaf area was calculated using ImageJ software (version 1.53e; Madison, WI, USA), as recommended by Martin et al. (2020). Additionally, root characteristics were analyzed using WinRHIZO™ 2021 (Regent Instrument Inc.; Sainte Foy, Quebec, Canada) before the transplanting phase.

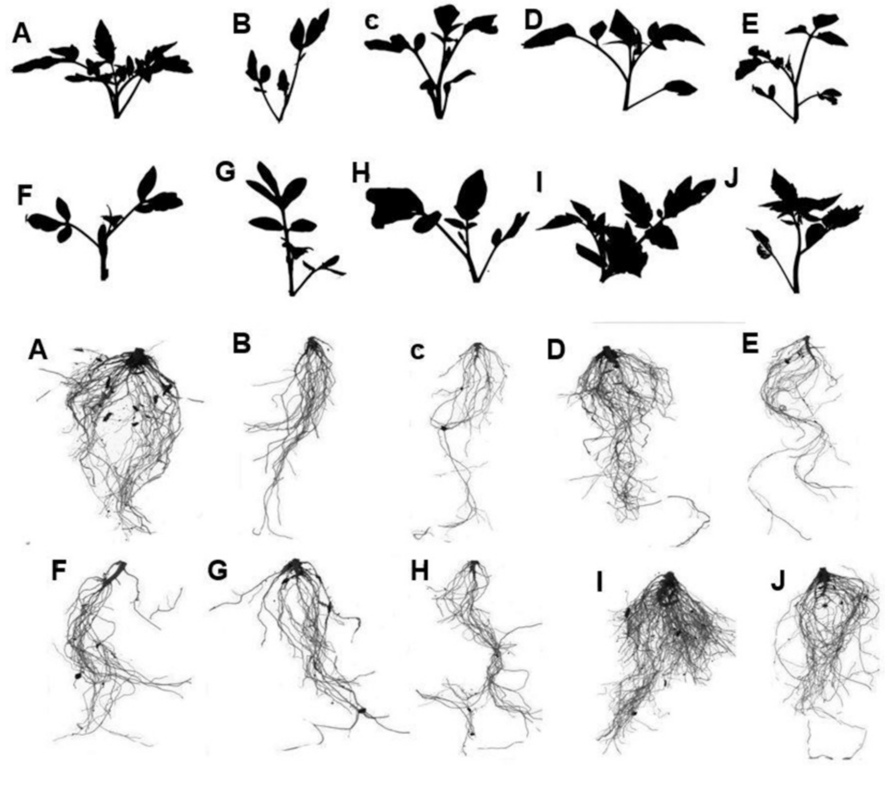

Fig. 3. Shoot and root architecture of 10 tomato genotypes. (**A**) 'Cherokee Purple'. (**B**) 'New Girl'. (**C**) 'BHN-589'. (**D**) 'Brandywine'. (**E**) 'Sakura'. (**F**) 'SV4129TH'. (**G**) 'Salimah'. (**H**) 'Shourouq'. (**I**) 'Velocity'. (**J**) 'Sigma' (from left to right in the row).

Growth and physiological measurements. Commencing 30 d after planting, the canopy area (cm^2) was measured weekly by capturing images from the top of the plants using a Nikon AF-S DX Nikkor camera (D5500 DSLR; Bangkok, Thailand). Image analysis was performed using ImageJ software (version 1.53e) following the methodology outlined by Martin et al. (2020). Chlorophyll levels [soil plant analysis development (SPAD) values] were recorded using a portable chlorophyll meter (SPAD-502 Plus; Konica Minolta, Tokyo, Japan) on the third fully expanded leaf from the top. Gas exchange data, including transpiration rate (E), assimilation rate (A), intercellular CO_2, and stomatal conductance to water vapor, were measured on the same leaf using a portable photosynthesis system (LI-6800; LI-COR Inc., Lincoln, NE, USA) between 10:00 AM and 1:00 PM, with a flow rate of 500 $\mu mol \cdot m^{-2} \cdot s^{-1}$, reference CO_2 concentration of 400 $\mu mol \cdot m^{-2} \cdot s^{-1}$, fan speed set at 10,000 rpm, fluorometer set point at 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$, and an aperture size of 6 cm^2. These gas exchange measurements were conducted starting 30 d after planting and continued for 15 d. Electrolyte leakage was calculated following the method described by Mukherjee et al. (2023) and Dash et al. (2023) with the following formula:

Electrolyte leakage (%) $= \frac{E1}{E2} \times 100$, where E1 was recorded using a conductivity meter (Cond 6+ conductivity meter; Oakton Instruments, Bunker Court, Vernon Hills, IL, USA) after six leaf discs had been placed in deionized water for 20 h. Subsequently, the leaf samples were boiled for 15 min, cooled, and E2 readings were recorded.

Phenological measurements. The flowering aspects, including days to first flowering and 50% flowering, were monitored by recording the number of days from planting to the emergence of the first flowers and the point at which 50% of the flowers had bloomed in each experimental unit. To assess flower drop and fruit set performance in

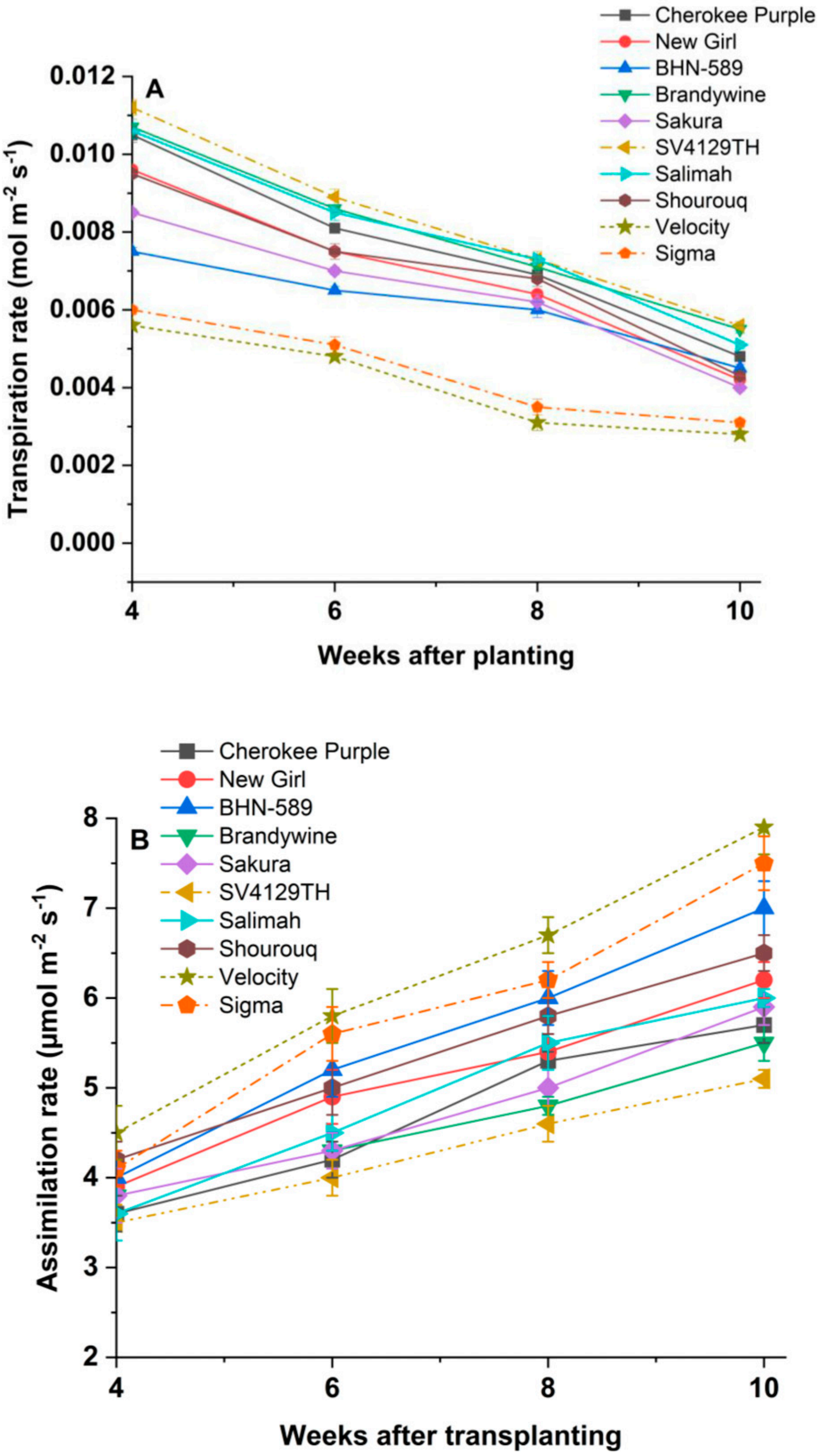

Fig. 4. Effects of tomato genotypes on transpiration rate (**A**), assimilation rate (**B**), intercellular CO_2 (**C**), and stomatal conductance (**D**).

response to abiotic stresses, five mature flower clusters (each containing 5–12 flowers) were tagged in each plot, and information regarding flower drop and fruit set was collected at regular intervals. Pollen viability was determined according to the method outlined by Sulusoglu and Cavusoglu (2014) and Dash et al. (2023) using an iodine potassium iodide (IKI) staining test to assess pollen viability. During this procedure, an IKI solution was prepared by dissolving 1 g of potassium iodide and 0.5 g of iodine in 100 mL of distilled water. Pollen viability was assessed by observing pollen grains 5 minutes after they were placed in the IKI solution. Pollen grains stained dark (dark red or brown) were considered viable, and further examination was conducted using a microscope (DM 2700M; Leica Microsystems Inc., Deerfield, IL, USA).

Yield and postharvest quality assessment. Ripe, marketable fruits were harvested every other day for a total of 38 harvests, commencing on 25 Dec 2022, and concluding on

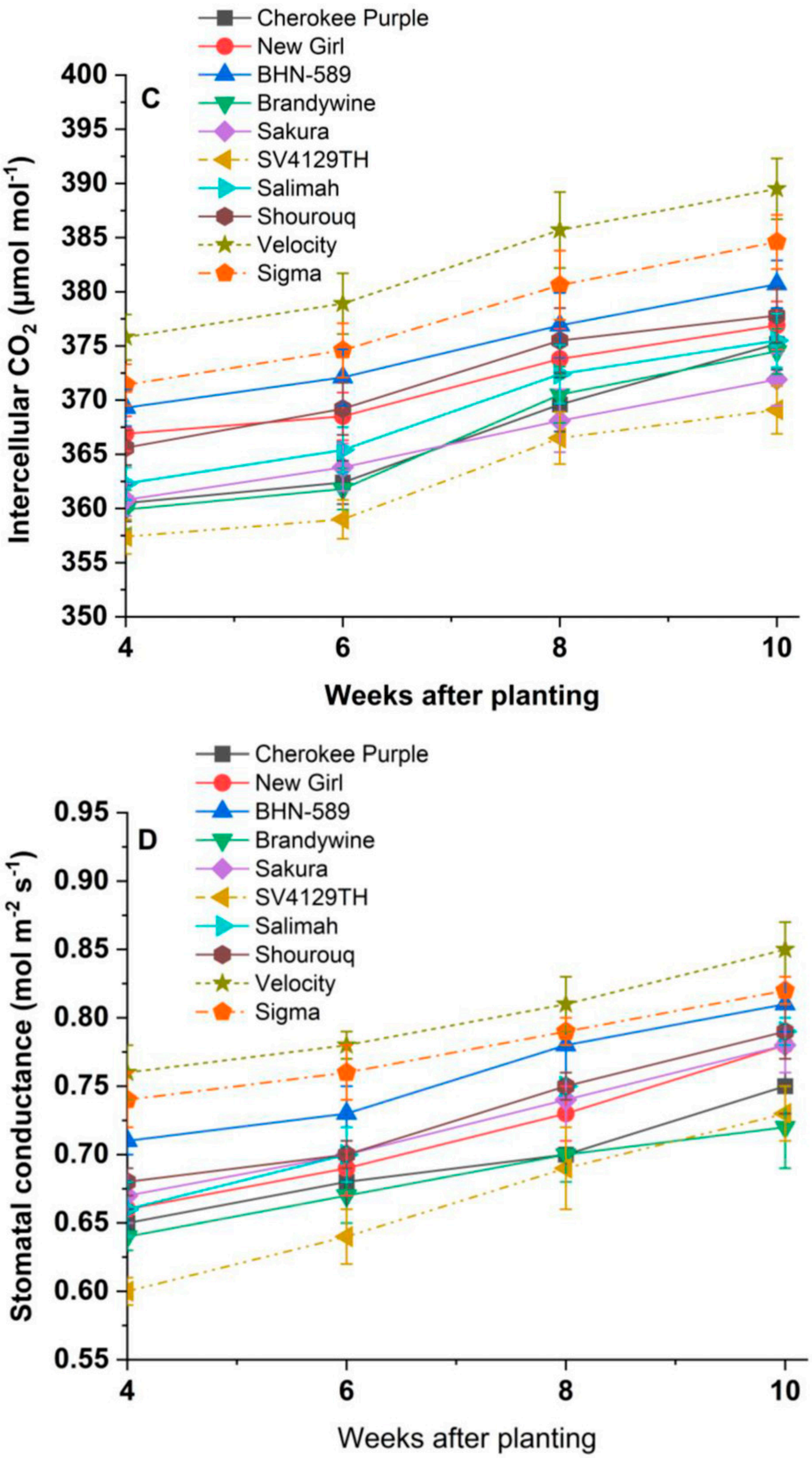

Fig. 4. (Continued)

15 Apr 2023. The cumulative yield was calculated based on these harvests. Various postharvest quality parameters, including fruit weight, firmness, color attributes, titratable acidity (TA), and °Brix, were assessed for the stored fruits. The harvested tomato fruits were promptly stored in the laboratory, specifically the Mechanical Engineering Program at Texas A&M University in Qatar. These fruits were stored under ambient conditions, with a temperature of 23 °C and a relative humidity of 75%, to evaluate their postharvest quality. Fruit firmness was measured using a digital force gauge (Chatillon force measurement; Ametek®; DFS3, Largo, FL, USA) equipped with a 2-mm probe. The force applied was calculated in N/cm^2. Color attributes of the stored fruits, such as L* (lightness), a* (redness/greenness), b* (yellowness/blueness), C* (chroma), and °h (hue angle), were recorded using a portable chromometer (CR 410; Konica Minolta, Inc., Chiyoda City, Tokyo, Japan). The

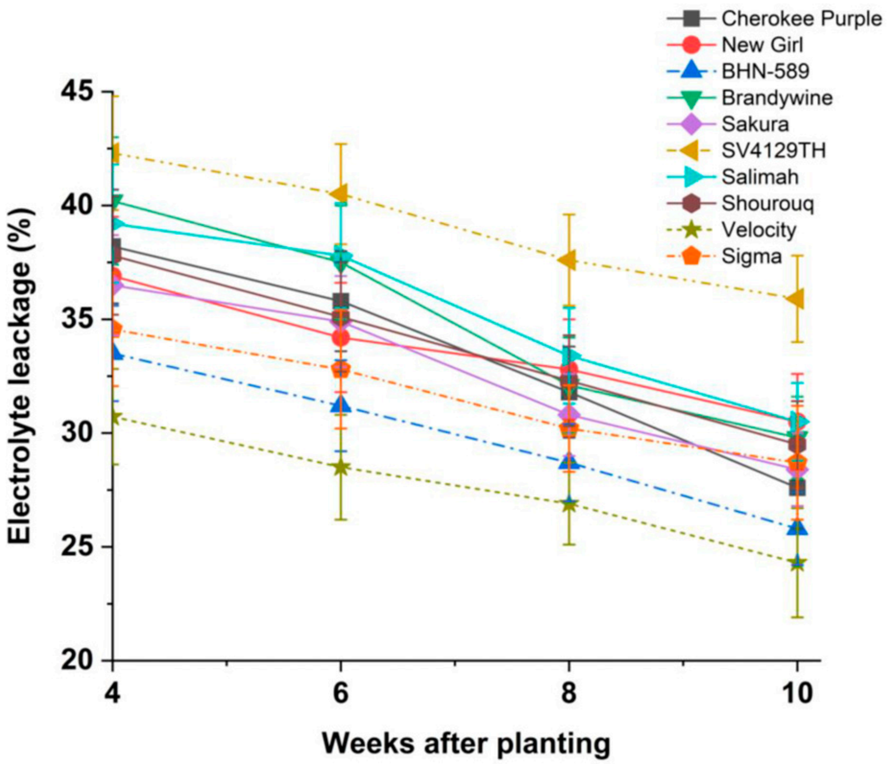

Fig. 5. Effect of tomato genotypes on electrolyte leakage.

percentage of °Brix and acidity in tomato juice following a dilution ratio of 1:50 were determined using a pocket Brix-Acidity meter (PAL-BXIACID3; Atago Co. Ltd.; Shiba-Koen, Minato-ku, Tokyo, Japan).

Statistical analysis. The collected data were analyzed using Origin 2023 (version 9.6.5; OriginLab Corporation, Northampton, MA, USA). Before analysis, the data were validated for homogeneity. To ascertain significant differences among the treatments, pairwise mean comparisons were conducted using Tukey's honestly significant difference test at a significance level of $P \leq 0.05$. Additionally, an analysis of correlation among variables, principal component analysis, and clustering of cultivars were performed to explore relationships between the variables and treatments and to visually represent trends and patterns in the data. A heatmap was generated based on the scale values of each parameter, and the correlation distance was used in the cluster analysis.

Results

Tomato seedlings of various genotypes, such as 'Velocity', 'Sigma', 'Cherokee Purple', 'Brandywine', 'BHN-589', and 'Sakura', grown using the standard containerized system exhibited significantly superior vegetative growth (plant height, stem diameter, number of leaves, leaf area), root growth (fine, medium, and larger roots and total roots), high-quality characteristics, and more robust transplants compared with other genotypes as shown in Table 1 and Fig. 3. The analysis of variance revealed significant genotype effects on canopy area. Notably, there were significant differences ($P < 0.05$) in canopy growth among tomato genotypes (data not shown). Across all measured genotypes, 'Velocity' and 'Sigma' outperformed other tomato genotypes in maintaining canopy growth. For instance, at 11 weeks after transplanting (WAT), 'Velocity' and 'Sigma' exhibited 13% and 10% higher canopy growth, respectively, compared with the 'SV4129TH' tomato genotype. It is worth noting that tomato genotypes did not have a significant impact on the chlorophyll index (SPAD value) during this study (data not shown). However, the leaf transpiration rate (E) was significantly reduced in 'Velocity' and 'Sigma' genotypes compared with other genotypes, as shown in Fig. 4A. Transpiration rates decreased by 50% and 44% in 'Velocity' and 'Sigma' tomato genotypes, respectively, compared with the 'SV4129TH' genotype at 10 WAT. Additionally, the assimilation rate was significantly higher in 'Velocity' and 'Sigma' genotypes compared with other genotypes, as depicted in Fig. 4B. For instance, 'Velocity' and 'Sigma' showed 35% and 32% increases in leaf assimilation rates, respectively, compared with the 'SV4129TH' tomato genotype at 10 WAT. Similarly, some tomato genotypes, such as 'Velocity', 'Sigma', and 'BHN-589', maintained higher intercellular CO_2 concentrations than other genotypes (Fig. 4C). Similarly, stomatal conductance was significantly higher in 'Velocity', 'Sigma', and 'BHN-589' than in other tomato genotypes (Fig. 4D). These three genotypes showed 14%, 11%, and 10% higher stomatal conductance, respectively, compared with the 'SV4129TH' genotype at 10 WAT. Overall, tomato genotypes like 'SV4129TH', 'Brandywine', 'Cherokee Purple', 'New Girl', 'Sakura', 'Salimah', and 'Shourouq' did not significantly impact the measured growth and physiological parameters. In contrast, 'Velocity', 'BHN-589', and 'Sigma' reduced electrolyte leakage by 32%, 28%, and 20%, respectively, compared with the 'SV4129TH' genotype at 10 WAT (Fig. 5). There were significant genotype effects on phenological attributes, such as the days required for the first flower, which differed among the tomato genotypes (Fig. 6A). Flowering occurred earlier by 4 d in 'Velocity' compared with 'SV4129TH'. A similar trend was observed for 50% flowering, with 'SV4129TH' flowering 5 d later than 'Velocity' (Fig. 6B). The 'Velocity' genotype exhibited a 36% decrease in the number of flower drops compared with the 'SV4129TH' genotype (Fig. 6C). Additionally, 'Velocity' exhibited higher fruit set compared with other genotypes (Fig. 6D), with a 14% higher fruit set compared with 'SV4129TH'. Furthermore, 'Velocity' showed higher pollen viability (24%) than 'SV4129TH' (Fig. 7). Marketable fruit yield was significantly influenced by tomato genotypes ($P < 0.01$). The 'Velocity' tomato genotype had a 32% higher marketable fruit yield than the 'SV4129TH' genotype (Fig. 8). Similarly, 'Sigma' and 'BHN-589' tomato genotypes showed 24% higher fruit yields compared with the 'SV4129TH' genotype. In general, fruits collected from different tomato genotypes maintained postharvest quality over a 3-week storage period (Table 2). However, fruit weight decreased significantly among the genotypes during storage. At the end of the storage period, fruits from 'Sigma' and 'Velocity' genotypes experienced a 14% and 13% weight loss, respectively, whereas the 'Sakura' (cherry) genotype had 50% weight loss. Fruit firmness is a crucial indicator of tomato quality during storage. Results showed that the 'Sakura' genotype lost firmness more rapidly by 60% while retaining sweetness, as indicated by a higher Brix value compared with those of other genotypes. Additionally, fruits from the 'Sakura' genotype showed 44% less acidity than fruits from the 'Velocity' genotype, and vice versa. At the end of the storage period, the 'Velocity' tomato genotype exhibited higher surface color, as indicated by a 15% higher lightness (L*) compared with the 'Sakura' genotype. Furthermore, 'Velocity' fruits had higher level of redness (a*), yellowness (b*), higher color purity (chroma value, C*), and maintained a higher level of color tone (hue angle, °h) and firmness value than other genotypes.

The correlogram in Fig. 9 illustrates the correlations among all the growth and development parameters of the 10 tomato cultivars under greenhouse conditions. The leaf area showed significant positive correlations with the SPAD value (r = 0.85), transpiration (r = 0.98), assimilation rate (r = 1.0), intercellular CO_2 concentration (r = 0.98), stomatal conductance (r = 0.97), fruit set (r = 0.88), pollen viability (r = 0.94), and fruit yield (r = 0.98). However, it exhibited significant negative correlations with electrolyte leakage (r = −0.89), days required for the first flower

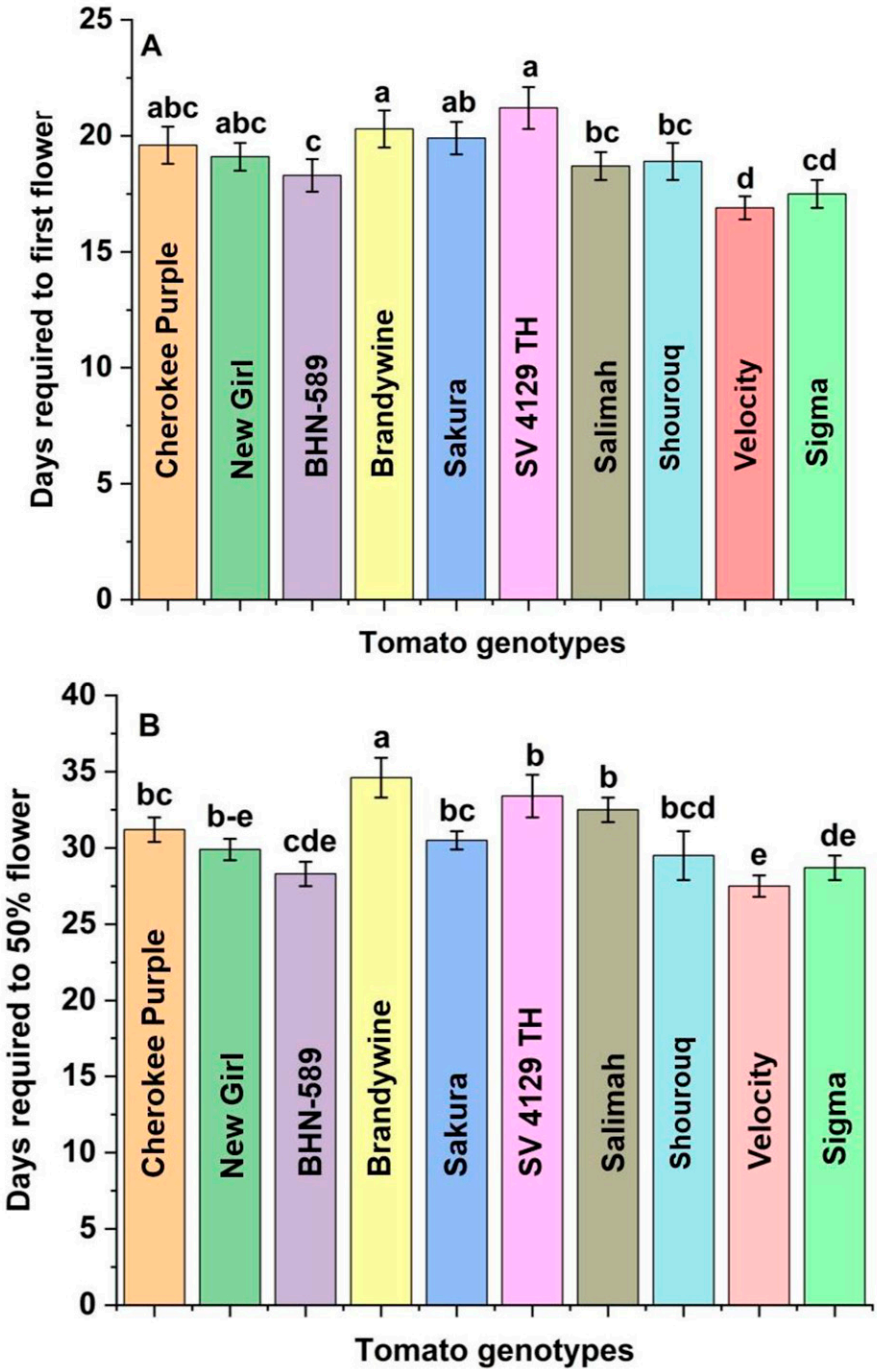

Fig. 6. Effect of tomato genotypes on (**A**) days required to first flower, (**B**) days required to 50% flower, (**C**) flower drop, and (**D**) fruit set.

(r = −0.97), days required for 50% flower (r = −0.87), and flower drop (r = −0.99). The SPAD value (chlorophyll index) was positively correlated with transpiration (r = 0.80), the assimilation rate (r = 0.85), intercellular CO_2 concentration (r = 0.80), stomatal conductance (r = 0.86), fruit set (r = 0.96), pollen viability (r = 0.88), and fruit yield (r = 0.84). Additionally, the transpiration rate showed a significant positive correlation with the assimilation rate (r = 0.98), intercellular CO_2 concentration (r = 1.0), stomatal conductance (r = 0.96), fruit set (r = −0.85), pollen viability (r = 0.93), and fruit yield (r = 0.97). The assimilation rate was positively correlated with intercellular CO_2 concentration (r = 0.98), stomatal conductance (r = 0.97), fruit set (r = 0.88), pollen viability (r = 0.94), and fruit yield (r = 0.98). Stomatal conductance had a significant positive correlation with fruit set (r = 0.92), pollen viability (r = 0.99), and fruit yield (r = 0.95). Electrolyte leakage was positively correlated with days to the first flower (r = 0.85), days to 50% flower (r = 0.84), and flower drop (r = 0.87); however, it showed negative correlations with fruit set (r = −0.88), pollen viability (r = −0.85), and fruit yield (r = −0.92). Fruit yield was significantly and negatively correlated with electrolyte leakage (r = −0.92), days to the first flower (r = −0.93), days to 50% flower (r = −0.87), and flower drop (r = −0.97). Conversely, it exhibited significant positive correlations with leaf area (r = 0.98), SPAD value (r = 0.84), transpiration rate (r = 0.97), assimilation rate (r = 0.98), stomatal conductance (r = 0.95), fruit set (r = 0.87), and pollen viability (r = 0.91).

A principal component analysis (PCA) was conducted for all 22 studied growth, development, and postharvest quality variables to assess the significance of overall variability and identify the main variables contributing to experimental variation. Of all the principal components (PCs), the first two, PC1 and PC2, accounted for 46.8% and 17.4% of the

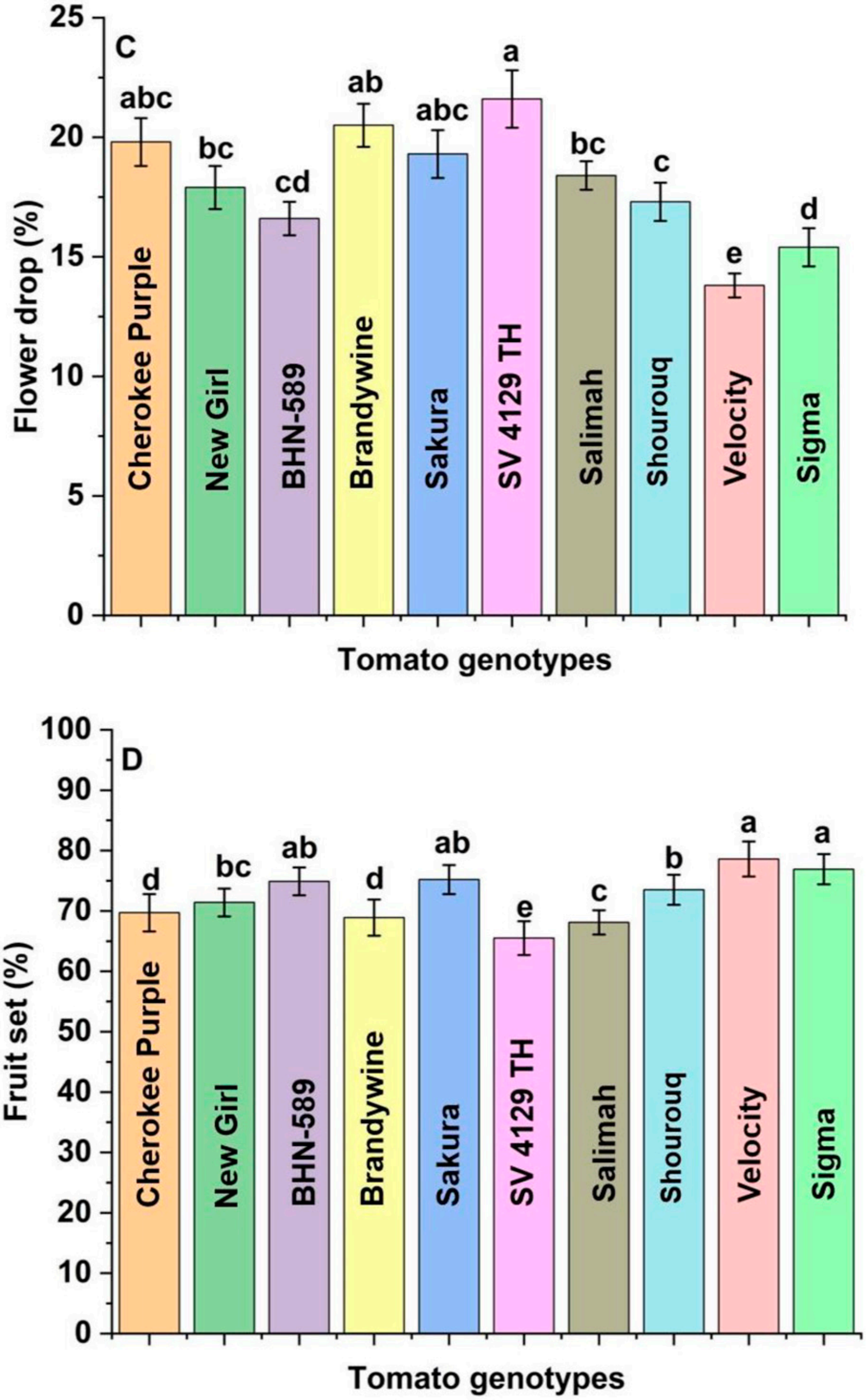

Fig. 6. (Continued)

total explained variability, respectively, (Fig. 10). The biplot is a suitable method of visualizing the results of PCA, depicting the PC scores and loading vectors in a single graph. The biplot illustrated that variables like fruit yield, fruit set, pollen viability, intercellular CO_2 concentration, SPAD value, assimilation rate, stomatal conductance, hue angle, chroma, TA, firmness, a*, L*, and b*, were positively correlated. In contrast, variables like flower drop, days to the first flower, electrolyte leakage, days to 50% flower, transpiration, Brix value, and fruit weight did not appear to be strongly linked. The analysis indicated that all the studied variables had varying effects on understanding experimental variance, either positively or negatively. Additionally, tomato plant physiological and phenological traits had a more pronounced influence on modulating plant growth and development and enhancing fruit yield while maintaining postharvest quality. However, PC2 did not provide as much clarification of the experimental variations. Similarly, a heatmap (Fig. 11) was generated to better illustrate the relationships between variables among different tomato cultivars and to cluster variables based on their responses. The heatmap revealed distinct cluster groups that categorized the cultivars as highly tolerant, sensitive, or moderately tolerant to abiotic stresses. The clusters were clearly distinguished based on variables such as yield, leaf area, assimilation rate, pollen viability, fruit set, flower drop, transpiration, electrolyte leakage, days to the first flower, and days to 50% flowering. The highly abiotic stress-tolerant genotypes group included ‘Velocity’ and ‘Sigma’. These genotypes exhibited tolerance to abiotic stress conditions in organic hydroponic systems in the greenhouse, which was primarily characterized by their high fruit yield and leaf area. The highly abiotic stress-

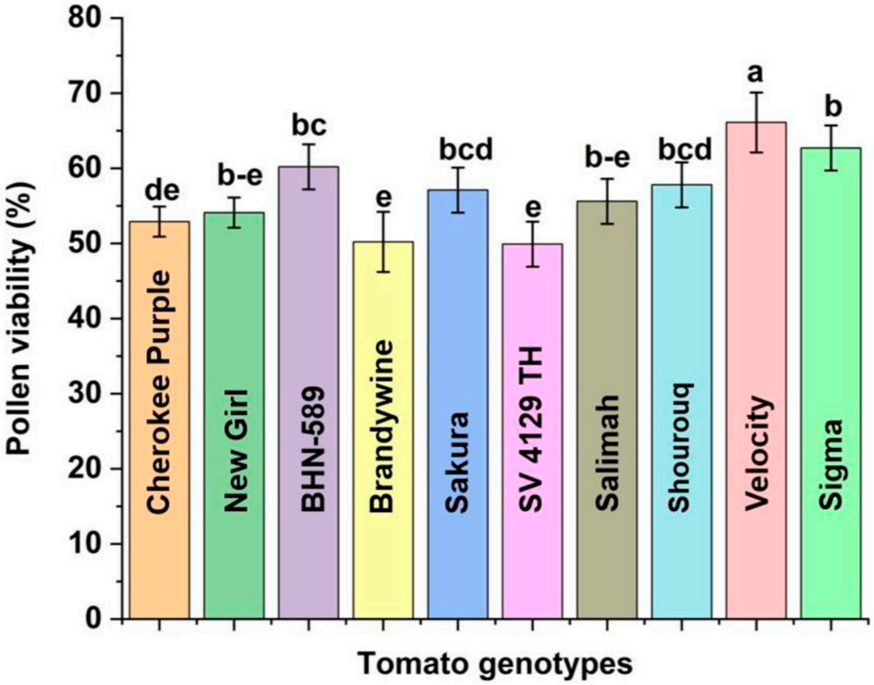

Fig. 7. Effect of tomato genotypes on pollen viability.

tolerant group displayed low transpiration, electrolyte leakage, and flower drop (blue color) and high yield (red color). Conversely, the sensitive group consisted of 'SV4129TH' and 'Brandywine', which exhibited high electrolyte leakage, flower drop, delayed flowering, and low fruit yield.

Discussion

This research provides new evidence of resilient tomato genotypes well-suited for organic hydroponic systems in challenging abiotic stress conditions. Although previous studies have extensively examined the potential and limitations of conventionally and organically cultivated tomatoes in open-field conditions (Hallmann 2012), relatively few efforts have been directed toward assessing tomato production in organic hydroponic systems under abiotic stress conditions. The vigor of tomato seedlings is influenced by their specific cultivars, which is in line with findings for both tomatoes and paprikas (Massimi and Radocz 2022), supporting our research findings. Certain tomato cultivars displayed superior seedling quality traits, likely positively influencing nutrient uptake from the growing media and overall plant growth and development. High-quality seedlings exhibit robust foliage, ample carbohydrate reserves, prolific root growth devoid of nutrient deficiencies, and resistance to diseases and pests (Nkurunziza et al. 2022). The performance of tomato plants is intricately linked to the quality of their seedlings, as noted by Wei et al. (2018). In our study, we observed significant variations among tomato genotypes in terms of growth, physiological attributes, phenological characteristics, yield, and postharvest quality parameters. Our analysis revealed substantial phenotypic variability, particularly in canopy areas, photosynthetic rates, and phenological attributes, among the tested tomato genotypes. This variability presents an opportunity to select new genotypes better suited for organic hydroponic production systems. However, it is essential to recognize that environmental factors play a significant role in influencing trait variation, as reported by Tripodi et al. (2022). This underscores the growing popularity of soilless production systems, such as hydroponics, in tomato cultivation under controlled environments. These systems enable precise and efficient nutrient and irrigation management, resulting in enhanced fruit yields (Urrestarazu 2013). Previous research has also emphasized the consistency of tomato yields in protected environments (Nordey et al. 2017). The selection of suitable cultivars is crucial for achieving economically viable tomato yields across different production systems (Singh et al. 2021). Furthermore, the choice of indeterminate tomato cultivars is common in greenhouse production (Thaxton and Hochmuth 2015), and cultivar selection should align with specific production system requirements, including lifespan considerations (Figas et al. 2018). Variability among cultivars encompasses growth habits, physiological and phenological traits, disease and pest resistance, and other factors. Growers must make informed decisions by considering trade-offs in trait performance when selecting cultivars.

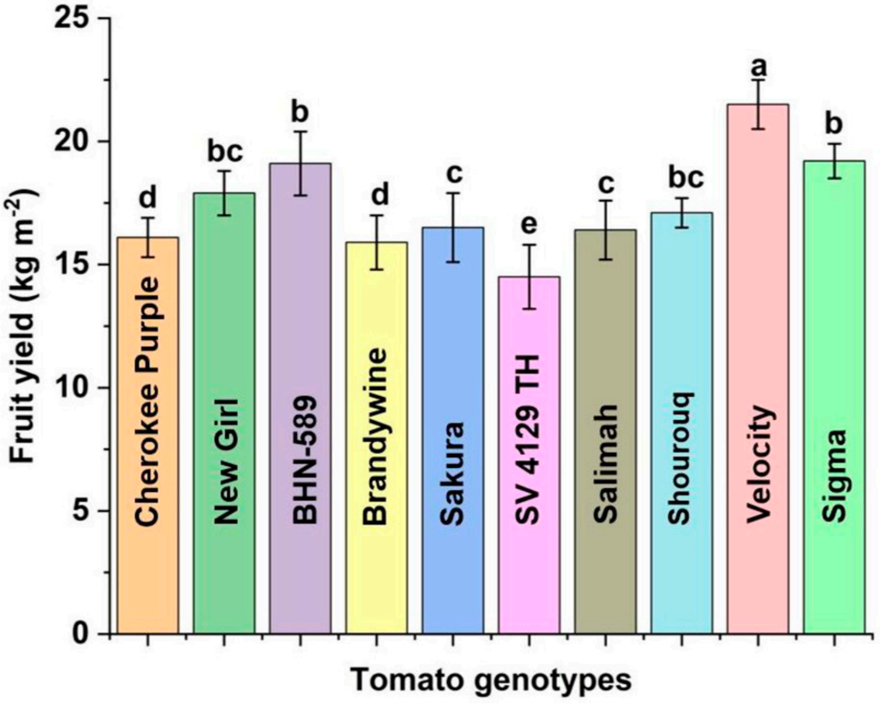

Fig. 8. Effect of tomato genotypes on fruit yield.

It is hypothesized that tomato genotypes resistant to abiotic stress can thrive in challenging environmental conditions by modulating microclimates. Therefore, the selection of appropriate genotypes represents the initial crucial step in tomato production, particularly in organic hydroponic systems facing abiotic stress environments. Under stressful conditions, plants undergo a series of events, including reductions in intercellular CO_2 concentration, stomatal conductance, and transpiration rate. In rice, this reduction resulted in a marked decrease in net photosynthesis (Pereira et al. 2013). Adverse stress conditions trigger the substantial production of reactive oxygen species, leading to severe damage in plants (Soares et al. 2019). The excessive accumulation of reactive oxygen species results in cellular

Table 2. Effect of genotypes on the postharvest quality of tomato.

Cultivars	Fruit wt (g)	Firmness (N)	Acidity (%)	°Brix	L*	a*	b*	C*	°h
	Day 0 of storage								
Cherokee Purple	0.21 ab	5.5 de	1.7 de	4.5 a-d	39.4 bc	11.3 b	14.4 d	18.3 d	51.9 abc
New Girl	0.21 ab	8.5 cd	2.2 bcd	5.6 ab	41.9 ab	19.3 a	27.3 a	33.1 ab	55.7 ab
BHN-589	0.24 ab	9.7 bc	2.0 cde	3.6 cd	42.4 ab	20.8 a	25.5 ab	32.0 ab	52.8 abc
Brandywine	0.32 a	3.9 e	2.3 abc	3.8 bcd	42.3 ab	18.7 a	15.9 d	24.5 c	40.6 d
Sakura	0.02 c	4.0 e	1.5 e	6.2 a	36.6 c	13.7 b	20.9 c	24.9 c	56.9 a
SV4129TH	0.17 b	5.4 de	2.1 bcd	3.2 d	40.9 ab	18.6 a	25.7 ab	32.5 ab	49.4 c
Salimah	0.20 ab	8.5 cd	2.0 cde	3.3 d	41.6 ab	19.0 a	26.1 a	33.9 a	53.7 abc
Shourouq	0.23 ab	11.4 abc	2.1 bcd	3.7 cd	42.1 ab	19.4 a	28.2 a	35.1 a	53.5 abc
Velocity	0.29 ab	12.3 ab	2.8 a	5.4 abc	43.8 a	22.2 a	26.5 a	33.6 a	52.0 abc
Sigma	0.27 ab	13.7 a	2.6 ab	4.9 a-d	42.9 ab	20.9 a	22.8 bc	29.6 b	50.4 bc
Significance	**	**	**	**	**	**	**	**	**
	Day 21 of storage								
Cherokee Purple	0.16 b	3.2 cd	1.6 b	3.6 bcd	34.5 d	18.9 d	13.2 d	23.2 e	34.9 d
New Girl	0.15 b	4.7 bc	2.1 a	3.9 bc	38.9 abc	27.4 ab	26.2 a	37.9 ab	43.8 abc
BHN-589	0.17 b	5.8 ab	1.9 ab	3.4 bcd	39.6 abc	26.3 ab	25.9 a	36.9 ab	44.2 abc
Brandywine	0.24 a	3.1 cd	2.2 a	2.8 de	37.5 c	25.0 bc	20.4 bc	32.3 cd	39.2 cd
Sakura	0.01 c	1.6 d	1.5 b	7.6 a	34.9 d	22.1 cd	18.7 c	29.0 d	40.2 bc
SV4129TH	0.14 b	4.7 bc	2.0 ab	1.9 e	37.8 c	26.4 ab	22.6 abc	35.1 abc	40.1 bc
Salimah	0.16 b	5.1 ab	1.8 ab	3.2 cd	38.2 bc	28.1 ab	24.7 ab	38.8 a	43.6 abc
Shourouq	0.19 a	6.1 ab	2.0 ab	3.5 bcd	39.3 abc	24.4 bc	23.6 ab	34.1 bc	44.1 abc
Velocity	0.25 a	6.3 ab	2.7 a	4.3 b	41.2 a	29.3 a	25.8 a	39.1 a	44.6 ab
Sigma	0.23 a	6.4 a	2.5 a	4.2 bc	40.3 ab	20.1 d	21.8 abc	29.7 d	47.3 a
Significance	*	**	*	**	**	**	**	**	**

All pairwise comparisons were performed using Tukey's honestly significant difference test at $P < 0.05$. Columns with dissimilar letter are statistically different. Columns sharing the same letter are statistically similar. *$P < 0.05$; **$P < 0.01$. a* = redness; b* = yellowness; C* = chroma; °h = hue angle; L* = lightness.

damage by generating lipid peroxides, which break-down various complex compounds such as malondialdehyde and disrupt the normal physiological processes of plants (Wakeel et al. 2020). The findings of our study reveal that different tomato genotypes exhibited varied physiological responses, including transpiration rate, assimilation rate, intercellular CO_2 concentration, and stomatal conductance, supporting the role of abiotic stress mechanisms in tomato plants. During our study, some tomato genotypes exhibited an accelerated flowering time. It is possible that these genotypes mitigated the adverse effects of transplanting shock and established robust root systems early on, allowing for enhanced nutrient uptake from the growing media compared with other genotypes. Abiotic stresses are known to reduce the pollen viability of tomatoes and other crops. Viable pollen serves as a crucial indicator, reflecting the ability of a plant to navigate a series of flowering events encompassing pollination, fertilization, and seed and fruit development (Halo et al. 2023). Heat stress, as described by Borghi and Fernie (2020), adversely affects anthers and pollen, leading to a significant reduction in fruit set. Similarly, Muller and Rieu (2016) demonstrated that high temperatures decrease pollen viability. Extreme heat disrupts several physiological and biochemical processes in plants, resulting in flower drops, poor flower set, and reduced fruit yield (Osei-Bonsu et al. 2022). Alsamir et al. (2021) also noted that extreme high temperatures not only reduce flower and fruit sets but also impact fruit development and maturity. The improved flower and fruit set, lower flower drop, and higher pollen viability observed in certain tomato genotypes during our study suggest that these genotypes effectively alleviated abiotic stresses and continued to exhibit proper growth and development in hydroponic production systems.

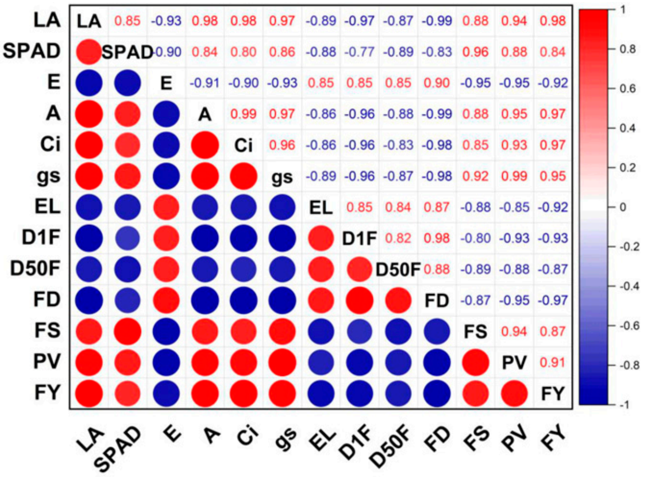

Fig. 9. Correlogram showing the relationship between average values of the variable in greenhouse conditions. The intensity of color and size of the circle increased with an increase in the significance of correlation. Dark blue denotes a high negative correlation, whereas dark red represents a high positive correlation. The cell value denotes correlation coefficient values.

The outcomes of our study revealed that the 'Velocity' tomato genotype consistently delivered significantly higher yields, followed by 'Sigma' and 'BHN-589', surpassing the performance of other tomato cultivars. Additionally, the 'Sakura' cherry tomato cultivar exhibited commendable performance during our study, aligning with the findings of Pickens et al. (2020), who highly recommended 'Sakura' for its remarkable yield potential in greenhouse conditions. Our study further corroborates the superior yield of 'Sakura' compared with the 'SV4129TH' beef tomato cultivar. The reduced yield and diminished fruit setting observed in certain genotypes under heat stress conditions can be attributed to lower fruit numbers, potentially stemming from compromised pollen viability. This observation aligns with similar findings in tomatoes (Ro et al. 2021) and other crops (Djanaguirman et al. 2013). Although our assessment encompassed various aspects of tomato growth, yield, and postharvest performance, it is imperative to conduct further evaluations of these tomato genotypes and consider additional traits such as cell membrane stability. Additionally, exploring molecular traits related to mutations (Ayenan et al. 2019) could uncover valuable genes with potential applications in breeding programs (Shaheen et al. 2016). The enhancement of tomato genotypes

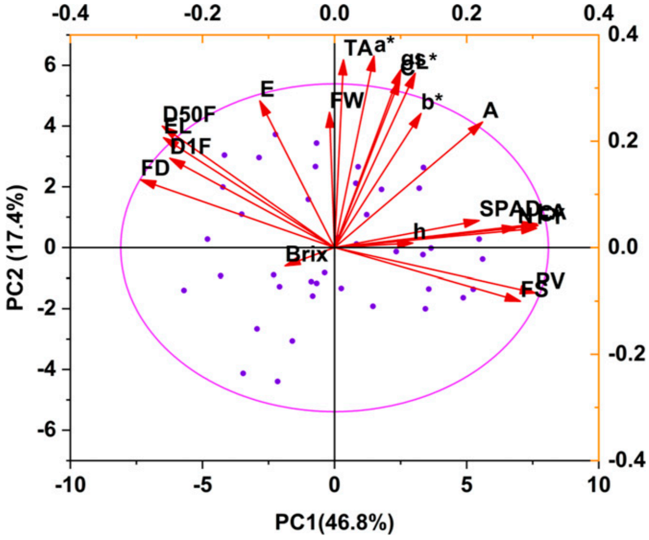

Fig. 10. Principal component analysis (PCA) biplot [principal component 1 (PC1) vs. principal component 2 (PC2)] visualizing the correlations among the growth, physiological, phenological, yield, and postharvest quality parameters affected by the tomato cultivars under abiotic stress environments.

and the implementation of suitable management techniques should be integral considerations to augment tomato yield within the context of organic hydroponic systems facing abiotic stress environments.

The tomato genotypes exerted a significant influence on the quality of stored fruits. Among the various quality indicators, fruit firmness emerges as a key parameter, surpassing even acid and sugar contents. Firmness plays a pivotal role in determining the freshness and juiciness of stored fruits, as emphasized by Jantra et al. (2018). The impact of tomato genotypes on fruit firmness aligns with findings reported by Kandel et al. (2020). However, variations in Brix levels may be attributed to genetic disparities among the tested tomato genotypes, as noted by Hossain et al. (2017). In general, tomatoes with higher total soluble solids (TSS) concentrations are deemed more flavorful. It is worth considering that TSS concentrations are intricately linked to fruit water content. Hence, it is plausible that tomatoes cultivated under controlled environments in hydroponic systems exhibit elevated water content and, consequently, lower TSS concentrations. This hypothesis was supported by the inverse correlation between water potential and fruit TSS, as elucidated by Kubota et al. (2012). An essential attribute contributing to postharvest quality is the pigmentation of flesh, particularly its red coloration. Lycopene, the most abundant carotenoid in ripe tomatoes, predominantly accounts for the vibrant red hue (Davila-Avina et al. 2011). During our study, all genotypes exhibited the highest intensity of red coloration toward the conclusion of the storage period. However, it is noteworthy that ‘Cherokee purple’ and ‘Brandywine’ displayed distinctive color variations. Consequently, the identification and selection of suitable tomato genotypes boasting superior fruit quality characteristics are pivotal considerations in the context of organically grown hydroponics within controlled environments. Such choices hold the potential to yield increased profits for growers.

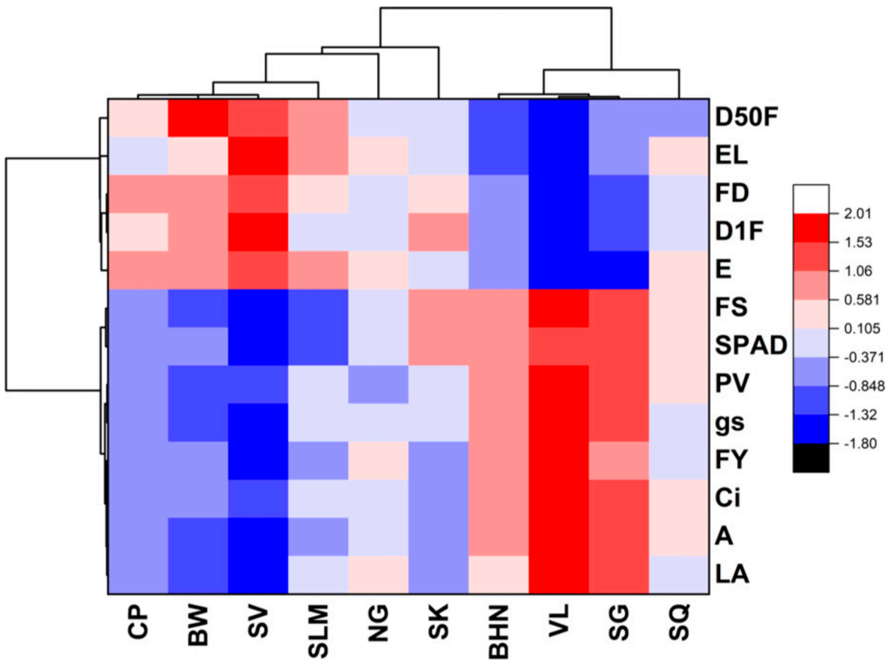

Fig. 11. Heatmap and clustering of cultivars based on the scaled values of the measured variables attained under greenhouse conditions. Each column represents a cultivar, and each row indicates a measured parameter. Treatment cultivars are clustered based on their measured variables, and variable groups are clustered based on their correlation. The variables that are clustered together have a high positive correlation. Cells with red and blue colors have high and low relative appearances, respectively.

The correlogram, PCA, heatmap, and cluster analysis have effectively illuminated the primary variables influencing tomato growth and yield traits. The heatmap and dendrogram have provided additional support to the PCA by organizing the measured variables into distinct clusters based on their similarity indices. Notably, certain variables such as flower drop, transpiration rate, electrolyte leakage, and the time required for first and 50% flowering exhibit contrasting patterns in relation to variables associated with fruit set, pollen viability, stomatal conductance, assimilation rate, SPAD value, leaf area, and fruit yield. This study of tomato genotypes has yielded valuable insights into the intricate relationships among the measured variables. It sheds light on how various growth, physiological, and phenological attributes impact the yield and postharvest quality of different tomato genotypes. These insights are vividly depicted in the PCA and heatmap clustering analyses.

Organic hydroponic tomato production emerges as a highly viable solution, particularly in arid climates, for food security and safety concerns in the burgeoning global population. With meticulous management and the utilization of well-suited tomato genotypes such as ‘Velocity’ and ‘Sigma’, hydroponic systems hold the promise of substantially amplifying agricultural productivity. This presents a remarkable opportunity for the organic produce sector to play a pivotal role in meeting escalating food demands and bolstering Qatar’s gross domestic product, as well as benefiting other nations grappling with analogous challenges. The genotypes ‘Velocity’ and ‘Sigma’ exhibit substantial potential and could be considered prime candidates for deployment in organic hydroponic systems, grafting initiatives, and breeding programs with a primary focus on augmenting yield and fortifying resistance against abiotic stressors.

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