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Research Article

Assessing the impact of different water stresses on physio-chemical properties and yield-related traits in tomato genotypes: Insights into stability and response

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Abstract

Tomato is a highly sensitive crop to moisture stress, and grown widely under varying conditions of moisture deficit. To identify the stable genotypes and characterize their responses to moisture stress, thirty-two diverse genotypes were evaluated at three imposed moisture regimes i.e., sub-optimal irrigation at 75±5% of the field capacity (FC; L1), irrigation at 50±5% of the FC (L2), and irrigation at 25±5% of the FC (L3) inside a passively ventilated plastic greenhouse. A wide range of variability was observed for 23 analyzed physio-chemical traits under study. All the analysed traits (except root-shoot ratio, chlorophyll index, total biomass, sugar content, and acidity) have shown higher heritability and moderate to high genetic advance, indicating that these traits are governed by additive gene action and responsive to selection under water stress conditions. All the growth and yield parameters were shown to decrease significantly with the increase of intensity of moistures stress. Likewise, physiological parameters, namely chlorophyll and the relative water content tended to decrease, while the rate of water loss and proline content tended to increase following an increase in stress level. Fruit quality traits like total sugar, vitamin-C, and lycopene contents were tended to improve with the increase of designated moisture stress. The additive main effects and multiplicative interaction (AMMI) analysis of variance revealed the significant effects of moisture stress, genotype, and genotype × environment interaction for yield and yield-related traits. Based on multi-trait stability index (MTSI) analysis, MT-11, VL Tomato-4 and Megha Tomato-3 were considered most stable and promising genotypes for promotion for commercial production under the moisture stress conditions.

Keywords: breeding; environment; germplasm; lycopene; proline; stress tolerance

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Introduction

Tomato (*Solanum lycopersicum* L.), a globally cultivated solanaceous vegetable crop, stands as an important dietary source of antioxidants, such as lycopene, β-carotene, and ascorbic acid. Renowned for its nutritional richness, tomatoes find extensive use in cooking, table consumption, and the production of various processed products. India is the second-largest producer of tomato after China, accounting for 11.2% of the world's production (FAOSTAT, 2021; Press Information Bureau [PIB], 2022). Despite India's significant contribution to global tomato production and the importance of the crop in this nation, a strong limiting factor is that regional disparities exist within the country. Specifically, the North-eastern region, placed in the sub-Himalayan region of India, occupies 8.0% of the country's geographical area with 4.4% of the country's population, with a small proportion (≈2.86%) of total tomato production in the country (PIB, 2022). The region, marked by diverse conditions, predominantly features a humid subtropical to montane climate. The terrain and topography of the region are predominantly hilly (66%) with valleys of the Brahmaputra and Barak rivers. The region receiving the large amount of total rainfall (≈90%) during the monsoon season (June – September), witnesses moderate to severe moisture stress from November to February (Dikshit *et al*., 2014). The cost of tomatoes in the North-eastern region consistently remains high due to the region's limited local production. As a result, the majority of the supply must be sourced from other parts of the country. This reliance on distant sources incurs substantial transportation expenses, which not only drive up the price for consumers but also contribute to associated carbon emissions. The farmers of the region are growing tomatoes during the spring-summer season mainly as a rainfed crop under a rice-tomato cropping system. Moreover, the crop's yield and quality consistently suffer from suboptimal conditions. Abiotic stresses, such as water stress during the early vegetative stage, coupled with a deficiency of some essential nutrients (e.g., calcium, magnesium, and phosphorus) in the prevailing acidic soil, contribute to the challenges. In recent times, changes in the regional weather patterns, presumably influenced by climate change, have led to rainless winters, resulting in prolonged dry spells and substantial water stress.

Developing a water-stress-tolerant cultivar is crucial not only for enhancing crop productivity but also for optimizing land utilization with limited water resources (Waister and Hudson, 1970; Boyer, 2010; Farooq *et al*., 2019; Rane *et al*., 2022; Sharma *et al*., 2023; Verma *et al*., 2024). Breeding programs focused on creating novel crops resilient to water stress present an opportunity to leverage local landraces and diverse accessions found in the Himalayan region. In the context of water deficit stress, typically caused by reduced water availability, addressing the overproduction of reactive oxygen species (ROS) and restoring redox balance within plant cells becomes a pertinent factor for consideration. Larson (1988) suggested that novel or improved cultivars can adapt specific antioxidant mechanisms to neutralize harmful cellular factors. They can also accumulate osmo-protectants such as ascorbate, glyoxylate, polyamines, proline, and glycine betaine. These compounds play a vital role in maintaining transitory osmotic adjustment, imparting tolerance to the plant under stressful conditions.

Genetic mechanisms governing water-stress tolerance are intricate and often involve multi-genic inheritance. Recent years have seen substantial advancements in genotyping technologies, significantly enhancing genetic improvement. However, the full potential of molecular tools in water-stress breeding is hindered by the lack of precise phenotyping for water-stress-related traits (Kumar *et al*., 2021). Several physiological traits associated with water stress tolerance, such as reduced leaf area, increased stomatal and cuticular resistance, fewer and smaller stomata, vertical leaf orientation, and higher water use efficiency, play crucial roles in minimizing water loss by the plant. Additionally, an active and deeper root system, with higher root–shoot ratios, enhances water uptake from the soil solution, particularly during periods of low water availability in crop growth (Farooq *et al*., 2012).

Moreover, as a polygenic trait, understanding the linkage and relationships between yield and other yield-contributing traits is crucial for designing effective criteria for crop improvement. Choosing genotypes

based on components that exhibit simpler inheritance, rather than total yield alone, proves more advantageous (Grafius, 1959).

Polygenic traits, encompassing characteristics such as yield and quality attributes, are acknowledged for their intricate dependence on the interplay of genotype, environmental factors, and their dynamic interactions. To identify stable genotypes across diverse environments, a comprehensive understanding of genotype and environmental interactions is essential. The Additive Main Effects and Multiplicative Interaction (AMMI) method stands out as a popular statistical approach for stability analysis, particularly well-suited for datasets with numerous environmental influences. This method provides a nuanced understanding of the genotype-by-environment (G×E) interaction, elucidating patterns of relationships between genotypes and environments through accurate trait estimates (Zobel *et al*., 1988). For polygenic traits, the Multi-Trait Stability Index (MTSI) has emerged as a recently developed and effective tool. It aids in selecting elite genotypes by considering both mean performance and stability across various variables. MTSI has demonstrated effectiveness in the selection of genotypes resistant to abiotic stresses in various crop species, including drought and salinity-resistant genotypes in soybean (Zuffo *et al*., 2020), drought-tolerant genotypes of chickpea (Hussain *et al*., 2021), and maize inbred lines suitable for optimal and drought stress conditions (Balbaa *et al*., 2022). In light of these considerations, the primary aim of this investigation is to analyze and understand how different tomato accessions respond to water stress. The central focus is to discern and identify genotypes that exhibit stability and adaptability under controlled conditions of water stress, with the goal to provide valuable insights into the selection and promotion of genotypes that can thrive and maintain optimal performance in the face of increasingly severe water stress challenges.

Materials and Methods

Experimental setup

The experiment was conducted within a naturally ventilated polyhouse (plastic greenhouse) during the February – June of 2021 at the Horticulture Experimental Farm, ICAR Research Complex for NEH Region, Umiam, Meghalaya. The maximum and minimum average temperatures recorded inside during the cropping period ranged from 28.8-36.7 °C and 13.8-26.4 °C, respectively. The relative humidity ranged from 46.5–86.5%. A total of 34 advanced genotypes, including popular cultivars, were used for evaluation in pots of 15-litre capacity under polyhouse. The pots were filled with topsoil (sandy texture) enriched with farmyard manures. The recommended dose of NPK fertilizers applied was 120:60:60 kg per hectare on a per plant basis. Half of N and the full dosage of P and K were applied in the potting mixture, and the remaining half doses of N were applied in 2 split doses at 30 and 60 days after planting. The sowing of seeds commenced in February within nursery trays, and after one month of growth, the seedlings were transplanted into pots. Immediate irrigation was applied upon transplantation, and this watering regimen persisted on alternate days for duration of one week to foster optimal establishment. The experiment was laid out in a completely randomized block design with three replications, and each replication had 8 plants.

Water stress treatments

The level of water stress maintained was L1 (sub-optimal irrigation at 75±5% of the Field Capacity, FC), L2 (irrigation at 50±5% of the FC) and L3 (irrigation at 25.0 ±5% of the FC) using a soil moisture measurement system (IC-MPKit-406B, ICT International) for monitoring the water stress levels throughout the crop period.

Observations for growth and yield-related traits

The observations were recorded for growth and yield-related traits such as plant height (cm), number of flowers per cluster, fruit setting (%), pollen viability (%), fruit length (cm), fruit diameter (cm), fruit weight

(g), yield/plant (kg), number of seeds per fruit, root length (cm), root volume (ml), root-shoot ratio, and total biomass (g/plant) on dry weight basis at 45 days after transplanting.

Analysis of quality parameters

The quantification of total soluble solids content (TSS) was conducted using a Digital Handheld Refractometer, with the results expressed as a percentage of °Brix. Titratable acidity (TA) was determined employing a phenolphthalein indicator, following the methodology outlined by Nielson (2017). Total sugar content was assessed using the Phenol-Sulfuric method, as detailed by Dubois *et al*. (1956). The estimation of ascorbic acid was carried out through the direct colorimetric method, in accordance with the procedure outlined by Sadasivam and Manickam (1996). Lycopene content extraction employed a Hexane: Acetone: Ethanol (2:1:1, v/v/v) mixture, following the extraction protocol of Anthon and Barett (2007). The lycopene content was subsequently calculated using the formula: Lycopene (mg/kgFW) = (Abs 503 nm × 537× 8 × 0.55) / (0.10 × 172).

Analysis of physiological traits

Physicochemical parameters, including chlorophyll index, chlorophyll a/b ratio, rate of water loss (%), relative water content (%), and proline content (µM/gFW) in leaves, were recorded during the reproductive stage under sustained water stress conditions. The methodology detailing the data collection is outlined below.

Leaf chlorophyll estimation

The chlorophyll index as a reflection of chlorophyll density per unit area was determined by using a non-invasive chlorophyll meter (SPAD-502 plus; Konica Minolta Inc, Chiyoda, JP) clamped to 3rd-4th matured leaves from the shoot tip. The observations were recorded from the six randomly selected plants and averaged to express as SPAD index or SPAD chlorophyll meter reading (SCMR).

The contents of chlorophyll a/b pigment in leaves were estimated by the acetone extraction method, and the absorbance value was recorded using a spectrophotometer (UV-2100, UNICO, Shanghai, CN), and the following formulae were used to calculate the chlorophyll a and b content in the leaves and expressed in mg/g on a fresh weight basis (Misyura *et al*., 2012):

Chlorophyll a (mg/g) = (12.72 x A663-2.58 x A645) *(V/W) *(1/1000)

Chlorophyll b (mg/g) = (22.87 x A645-4.67 x A663) *(V/W) *(1/1000)

Where: V represents the final volume of the extraction solvent used, W represents the weight of the plant tissue sample, and A663, A645 and A480 are the optical absorbance values recorded respectively.

Determination of relative water content

The determination of relative water content (RWC) followed the method outlined by Hajong *et al*. (2022). Three leaf discs were sampled from the third fully expanded leaf from the top, and their fresh weight was measured using an electronic balance. Subsequently, the leaf discs were floated in a petri dish filled with distilled water for four hours. Following this, the leaf discs were gently blotted and reweighed, representing the turgid weight. Post turgid weight determination, the leaf discs were subjected to oven-drying at 80 °C for 48 hours, and the dry weight was recorded. RWC was computed expressed as a percentage as already reported (Barrs and Weatherley, 1962).

Determination of rate of water loss

To assess the rate of water loss (RWL), freshly harvested leaves were promptly transported from the field to the laboratory and laid out in a ventilated area. Subsequent fresh weight measurements were recorded at hourly intervals until reaching a point of no further weight difference (maximum duration: 4 hours). RWL is

quantified as the amount of water lost per unit leaf area per unit time and expressed as milliliters per square centimeter per hour (ml/cm^2/hr).

Leaf proline quantification

Leaf proline content was quantified using the method described by Bates *et al*. (1973). Fresh leaf samples (0.20 g) were weighed precisely and ground into a fine powder with a mortar. The resulting homogenate was prepared by adding 2 mL of 3% (w/v) aqueous dinitro sulfo-salicylic acid, followed by centrifugation at 12,000 g for 2 minutes at 4-8 °C. The clear filtrate obtained was used for the assay. To this filtrate, glacial acetic acid and ninhydrin reagent (1 mL each) were added, and the closed test tubes containing the reaction mixture were subjected to a boiling water bath for 1 hour, followed by cooling. The reaction was terminated by introducing 2 mL of toluene into the mixture. Readings were promptly recorded at a wavelength of 520 nm. Proline concentration was deduced from a standard curve, calculated on a fresh weight basis, and expressed as micromoles of proline per gram of fresh weight (µmol/g FW).

Statistical analysis

The mean values of all three replicates were used for the analysis of variance (Panse and Sukhatme, 1967). Phenotypic and genotypic variances of the genotypes, heritability, and genetic advance for all the physiochemical traits were estimated as described by Burton and Devane (1953), Hanson *et al*. (1956), and Johnson *et al*. (1955), respectively. The AMMI (Additive Main Effects and Multiplicative Interaction)-based stability parameters (ASTABs) were measured as AMMI stability value (ASV), AMMI Stability Index (ASI), Averages of the Squared Eigenvector Values (EV), Absolute value of the relative contribution of IPCs to the interaction (ZA), Weighted Average of Absolute Scores (WAAS), Sums of the Absolute Value of the IPC Scores (SIPC) as described by Ajay *et al*. (2020), and MTSI (multi-trait stability index) using the "metan: Multi Environment Trials Analysis" package (http:// www.r-project.org/) in R version 4.2.1 (Olivoto *et al*., 2019; Olivoto *et al*., 2020).

Results

Analysis of genetic parameters

Significantly variability was noticed for all the 23 traits studied under the L1 and L3 levels of water stress conditions (Table 1). The phenotypic coefficient of variation (PCV) was consistently higher than the genotypic coefficient of variation (GCV), indicating that environmental factors contributed significantly to trait variation under both control and water stress conditions. Likewise, GCV and PCV range from low (pollen viability) to high (root-shoot ratio and rate of water loss) under both conditions. Moreover, higher GCV and PCV > 20% were observed for fruit weight, number of seeds per fruit, root volume, root-shoot ratio, rate of water loss, total biomass, and proline content under control conditions along with root length excluding fruit weight under water stress conditions. These high GCV and PCV values suggest that these traits have strong genetic control and could be effectively improved through selective breeding, even under varying water stress conditions.

Under the L1 conditions, except root-shoot ratio, all the traits were found to be highly heritable (> 60%). In a similar line, high heritability was also observed for the majority of the traits except for the number of fruits per cluster, fruit setting percentage, acidity, and total chlorophyll a/b ratio content under water stress conditions. Moreover, the data have shown a substantial reduction in heritability for the traits like number of fruits per cluster, fruit setting percentage, acidity, TSS, and total chlorophyll a/b content under water stress conditions over the irrigated conditions (Table 1).

Table 1. Comparative analysis of genetic parameters of tomato for physicochemical traits under irrigated and water stress conditions

Traits	L1: Level of water stress (Normal)								L3: Level of water stress (Severe stress)							
	Mean	Min	Max	CV	GCV	PCV	h^2	GAM	Mean	Min	Max	CV	GCV	PCV	h^2	GAM
Plant height(cm)	97.83	65.00	136.25	5.29	16.88	17.69	91.06	33.18	80.09	55.00	110.00	4.43	14.66	15.31	91.64	28.91
No of flower/cluster	6.23	4.00	9.00	9.24	16.98	19.33	77.17	30.73	5.07	4.00	6.00	9.48	11.71	15.59	56.43	18.12
Fruit setting (%)	68.27	62.00	75.00	7.59	12.06	9.65	80.05	15.91	54.37	34.00	89.84	2.75	21.19	29.35	52.12	31.51
Fruit weight (g)	54.37	34.00	89.84	2.75	23.19	23.35	98.62	47.44	45.93	30.38	69.87	2.83	18.60	18.81	97.74	37.87
Fruit length (mm)	42.55	32.00	58.79	3.83	13.34	13.87	92.39	26.41	38.61	25.60	54.00	2.83	14.64	14.91	96.39	29.61
Fruit dia.(mm)	48.28	36.00	66.00	3.48	12.59	13.07	92.90	25.00	44.64	35.00	53.45	3.08	8.94	9.45	89.38	17.40
Yield (kg/plant)	0.99	0.10	1.46	12.40	15.09	19.53	59.71	24.03	0.56	0.32	0.81	11.83	16.18	20.04	65.15	26.90
No of seeds per fruit	81.63	48.00	146.00	4.59	23.64	24.08	96.37	47.80	65.90	32.00	123.00	2.53	25.94	26.06	99.06	53.17
Pollen viability (%)	89.28	73.68	98.00	0.77	7.41	7.44	98.94	15.17	83.26	72.00	95.38	1.69	6.11	6.33	92.92	12.12
Total biomass (g/plant)	26.31	13.05	52.60	6.40	28.58	29.29	95.23	57.45	16.98	10.77	39.28	5.66	28.67	29.23	96.25	57.95
Root-shoot ratio	0.22	0.05	0.88	36.07	39.95	53.83	55.09	61.08	0.15	0.01	0.35	17.28	49.16	52.11	89.01	95.54
Root length (cm)	28.56	18.00	44.00	4.62	17.05	17.67	93.15	33.90	20.52	10.49	32.49	7.93	20.21	21.71	86.67	38.76
Root volume (ml)	18.32	10.00	36.00	11.97	29.96	32.26	86.22	57.30	12.01	7.00	30.00	13.21	28.73	31.62	82.56	53.78
Acidity (%)	0.61	0.22	0.88	5.82	14.81	15.91	86.64	28.40	0.75	0.51	1.02	12.49	8.02	10.87	54.48	12.19
TSS (°B)	5.05	4.20	6.00	2.73	8.18	8.63	90.00	15.99	5.35	4.00	6.65	5.50	8.45	11.08	58.17	13.27
Total Sugar (%)	1.84	1.05	2.78	4.30	17.16	17.69	94.10	34.29	1.91	1.20	2.81	2.15	15.64	15.78	98.15	31.92
Vitamin C (mg/100 g)	20.64	14.00	27.23	3.88	12.76	13.34	91.52	25.15	21.54	16.05	28.15	3.95	11.31	11.97	89.14	21.99
Lycopene (mg/100 g)	6.50	5.12	8.30	3.53	9.47	10.10	87.81	18.27	7.73	5.74	10.77	5.60	12.62	13.81	83.56	23.77
Proline (µM/g FW)	4.82	1.35	8.15	17.79	23.97	29.86	64.49	39.66	22.80	12.50	35.12	7.43	20.21	21.53	88.08	39.07
Chlorophyll Index	57.51	42.40	74.45	3.19	13.50	13.87	94.70	27.06	53.15	40.90	68.80	2.48	11.33	11.60	95.44	22.81
Chlorophyll ab (mg/g)	4.14	2.59	5.36	5.59	12.56	13.75	83.45	23.63	3.51	2.59	4.31	6.77	7.34	9.99	54.04	11.12
RWL (ml/cm2/hr)	0.08	0.02	0.18	10.64	49.14	50.28	95.52	98.93	0.35	0.06	0.86	10.63	42.98	44.28	94.24	85.96
RWC (%)	71.84	55.00	88.00	1.47	10.20	10.30	97.97	20.79	62.21	48.00	75.60	3.26	9.91	10.43	90.23	19.39

Genetic advance as percentage of the mean (GAM) for all the traits also varied from moderate to high under both conditions (Table 1). The reduction in genetic advance varied from high to moderate water stress for traits like number of fruits per cluster, fruit diameter, relative water content, acidity, and total chlorophyll a/b content. However, some of the traits like fruit setting percentage, TSS, and lycopene content have shown an increase in genetic advance from moderate to high water stress. Moreover, except for pollen viability, other traits were high in heritability under both conditions.

Effect of different level of water stress on quantitative traits

Effect on growth and yield attributes

Significant ($p<0.05$) variations were observed among the genotypes with different levels of water stress for all the traits (Table 2). The average plant height under control conditions (L1) was 97.83 cm and it decreased by 7.43% with irrigation at 7 days intervals Mean pollen viability also varied from 83.3% (L3) to 89.3% (L1) and there was a significant reduction in average pollen viability by 1.46 and 6.75% at L2 and L3, respectively, over the control. The accessions have also shown wider variability for pollen viability, and it ranges from 74.1 – 97.7% at L1 and 72.8 – 93.1% at L3 (Table 2). Similarly, fruit setting percentage was also affected by genotypes and level of water stresses, and it ranged from 54.3–65.7 (L3) –69.7 to –74.2% (L1). There was a significant reduction in the average fruit setting percentage by 8.0% and 20.8% at L2 and L3 over the control (L1). The number of seeds per fruit was also affected by genotypes and level of water stresses, and it ranges from 51.7% (US Hybrid 626) to 141.0% (09/TODVAR-1) at L1, and 33.7% (RCT-3) to 119.3% (09/TODVAR-1). A significant reduction in average fruit set was observed with an increase in the level of water stresses i.e., 6.1% and 19.3% at L2 and L3 over the control. The number of fruits per cluster was also decreased by 9.9% when irrigated at 7-day intervals (L2) over the control (6.23) and it was further reduced by 18.6% when irrigated at 10-day intervals (L3). Similarly, the reduction in fruit size was also observed with an increase in the level of water stress: 1.93% and 9.25% in fruit length, 3.8% and 8.7% in fruit diameter and 6.9% and 15.5% in fruit weight over the control at L2 and L3, respectively. Among the genotypes, the minimum (35.1 & 33.5 g) and maximum (85.3 & 67.0 g) fruit weights were recorded by genotypes Pusa Rohini and 09/TODVAR-6 under L1 and L3 conditions, respectively. Fruit yield is a complex trait and is affected by the many attributing traits as well. A wide variation was observed among the accessions, and it ranges 0.63 kg/plant (Selection-1) to 1.36 kg/plant at L1(MT-11) under normal conditions and 0.40 kg (Selection-1 & MCTR-5) to 0.81 kg/plant (MT-3) under water stress conditions (L3). The reduction in average yield at L2 was 7.90% and it further

decreased by 43.23% at L3. Under severe water stress conditions (L3) the high-yielding and promising accessions noted were MT-3, VL Tomato-4, 09/TODVAR-7 and LE-1-2.

Table 2. The impact of the water stress treatments (L_1, L_2, and L_3) on the recorded quantitative variables, determined through ANOVA

Variables	L_1	L_2	L_3	Mean	Min.	Max.	Std Dev	SE (t)	LSD (P<0.05)
Plant height (cm)	97.83[a]	90.56[b]	80.09[c]	89.49	78.14	99.38	7.98	1.99	5.51
No of flower/cluster	6.23[a]	5.62[b]	5.07[c]	5.64	4.94	6.28	0.51	0.07	0.21
Pollen viability (%)	89.28[a]	87.97[a]	83.26[b]	86.84	82.44	89.43	2.78	0.48	1.32
Fruit set (%)	74.19[a]	68.27[b]	58.78[c]	67.08	58.50	74.46	6.74	0.15	0.42
Fruit weight (g)	54.37[a]	50.74[b]	45.93[c]	50.34	45.22	55.23	3.73	0.36	1.00
Fruit length (mm)	42.55[a]	41.73[a]	38.61[b]	40.96	37.79	42.79	1.86	0.29	0.83
Fruit dia. (mm)	48.28[a]	46.55[b]	44.64[c]	46.49	43.84	48.79	1.73	0.42	1.27
No of seeds/fruit	81.63[a]	76.66[b]	65.90[c]	74.73	64.63	82.50	7.03	0.85	2.37
Yield(kg/plant)	0.98[a]	0.91[b]	0.56[c]	0.82	0.52	1.00	0.20	0.02	0.07
Total biomass (g)	26.31[a]	20.78[b]	16.98[c]	21.36	16.94	26.95	4.09	0.51	1.43
Root length (cm)	28.56[a]	25.29[b]	20.52[c]	24.79	20.35	29.28	3.52	0.31	0.86
Root volume (ml)	18.33[a]	15.76[b]	12.00[c]	15.36	11.75	18.88	2.79	0.37	1.03
Root shoot ratio	0.15[b]	0.16[b]	0.22[a]	0.18	0.15	0.25	0.03	0.01	0.03
TSS (^{0}B)	5.05	5.25	5.40	5.22	4.66	5.93	0.37	0.05	NS
Acidity (%)	0.61[b]	0.75[a]	0.74[a]	0.71	0.52	0.80	0.09	0.03	0.10
Total Sugar (%)	1.84[b]	1.99[a]	1.94[a]	1.91	1.69	2.08	0.11	0.07	0.21
Vitamin -C (mg/100g)	20.64[b]	23.14[a]	21.66[a]	21.44	19.25	22.78	1.02	0.24	1.01
Lycopene (mg/100g)	6.50[c]	6.79[b]	7.73[c]	7.01	6.45	7.76	0.57	0.07	0.20
Proline (µM/g FW)	4.82[c]	14.40[b]	22.80[a]	14.01	4.67	24.09	7.86	0.63	1.74
Chlorophyll ab (mg/g)	4.14[a]	4.13[a]	3.51[b]	3.93	3.37	4.28	0.33	0.12	0.33
Chlorophyll Index	57.51[a]	56.27[a]	52.15[b]	55.64	52.16	58.72	2.10	0.88	2.45
RWC (%)	71.89[a]	67.54[b]	62.21[c]	67.20	61.69	72.17	4.20	0.43	1.21
RWL (ml/cm^2/hr)	0.08[c]	0.18[b]	0.34[a]	0.20	0.08	0.35	0.11	0.01	0.01

Notably, there were significant effects ($p < 0.05$) among treatment groups for all measured traits

Effect on physiological traits

Root length and root volumes were also very important parameters related to abiotic stresses, especially water stress. Among the genotypes as well as different levels of water stress, wide variations in root length and volume, i.e., 11.7 cm (L3, LE-626) to 41.5 cm (L1, VL Tomato-4) and 7.7 (L3, 09/TODVAR-7) to 34.0 ml (L1, MCTR-4B), were observed respectively. A significant reduction in average root length (11.5 and 28.2 %) and volume (14.0 and 40.1%) was observed at L2 and L3, respectively, over the control (L1). Under water stress conditions (L3), the maximum root length and volume were observed in VL Tomato-4, 09/TODVAR-1 and MCTR-4B.

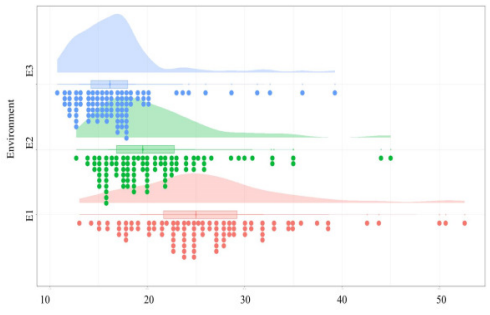
The genotypes have also shown significant ($p < 0.05$) variations for total yield and root-shoot ratio with levels of water stress. The total yield varied from 14.10 -51.1 g/plant at L1 and 11.4 – 35.9 g/plant at L3 (Figure

1a). Moreover, among the accessions, the maximum biomass yield was observed in accessions Sel-9A (35.94 g) at L3 level of water stress. The reduction in average total yield was 21.0 and 44.9%, respectively, at L2 and L3 over the control (26.3 g). Similarly, the root-shoot ratio also varied from 0.01 – 0.33 and 0.08 – 0.50 at L1 and L3, respectively. The increase in average root shoot ratio was 7.04% and 46.27%, at L2 and L3 over the control respectively (0.15).

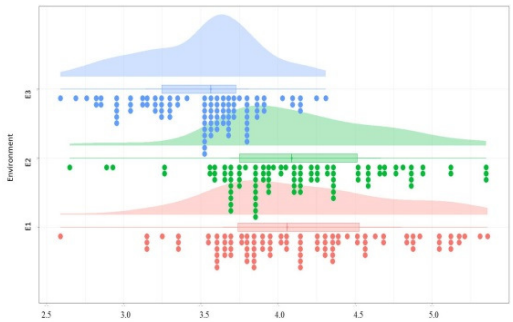
The physicochemical traits such as total chlorophyll a/b, chlorophyll index (CI) and relative water content (RWC) have decreased significantly ($p < 0.05$) with an increase in the level of soil water stress (Figure 1b-d). The varieties have also shown differential physiological responses to levels of water stress. The extent of decrease in total chlorophyll a/b, CI and RWC was 0.34 and 15.28%; 2.14 and 7.58; 5.98 and 13.41% at L2 and L3, respectively, over the control (Table 2). Moreover, there was a wide variation in the rate of water loss (RWL), which ranges from 0.03 – 0.17 at L1 and 0.08 – 0.78 at L3. The rate of water loss increases significantly with subsequent increases in the level of water stress (Figure 1e). Similarly, proline content (PC) has also shown variation among the genotypes with different levels of water stress, and it ranges from 1.88µM/g FW under control conditions to 31.97µM/g FW under water stress conditions (L3). The average increase in proline content (Figure 2f) varied from 199.1% and 372.8% at L2 and L3, over the control (4.82 µM/g FW), respectively.

Effect on quality attributes

All the genotypes were also evaluated for quality parameters at different levels of water stress. All the quality parameters increased with the increase in water stress. Among the genotypes, wider variations were observed for all the quality traits such as TSS (4.22 – 6.15°B), acidity (0.35 – 0.98%), total sugar (1.18 – 2.62%), vitamin C (15.83 – 27.6mg/100g), and lycopene (5.18 – 10.19 mg/100g) content under different moisture regimes. Among these traits, acidity, sugar, and TSS content showed an increase in content by 23.6%, 4.1%, and 7.3%, respectively, at L2 over the control and a further slight decline in content with a subsequent increase in the level of water stress (L3) but higher than the control (Table 2). Moreover, vitamin C and lycopene content have shown an increasing trend with subsequent increases in the level of water stress from L2 to L3 (Figure 1g-h).



a. Total biomass



b. Chlorophyll ab

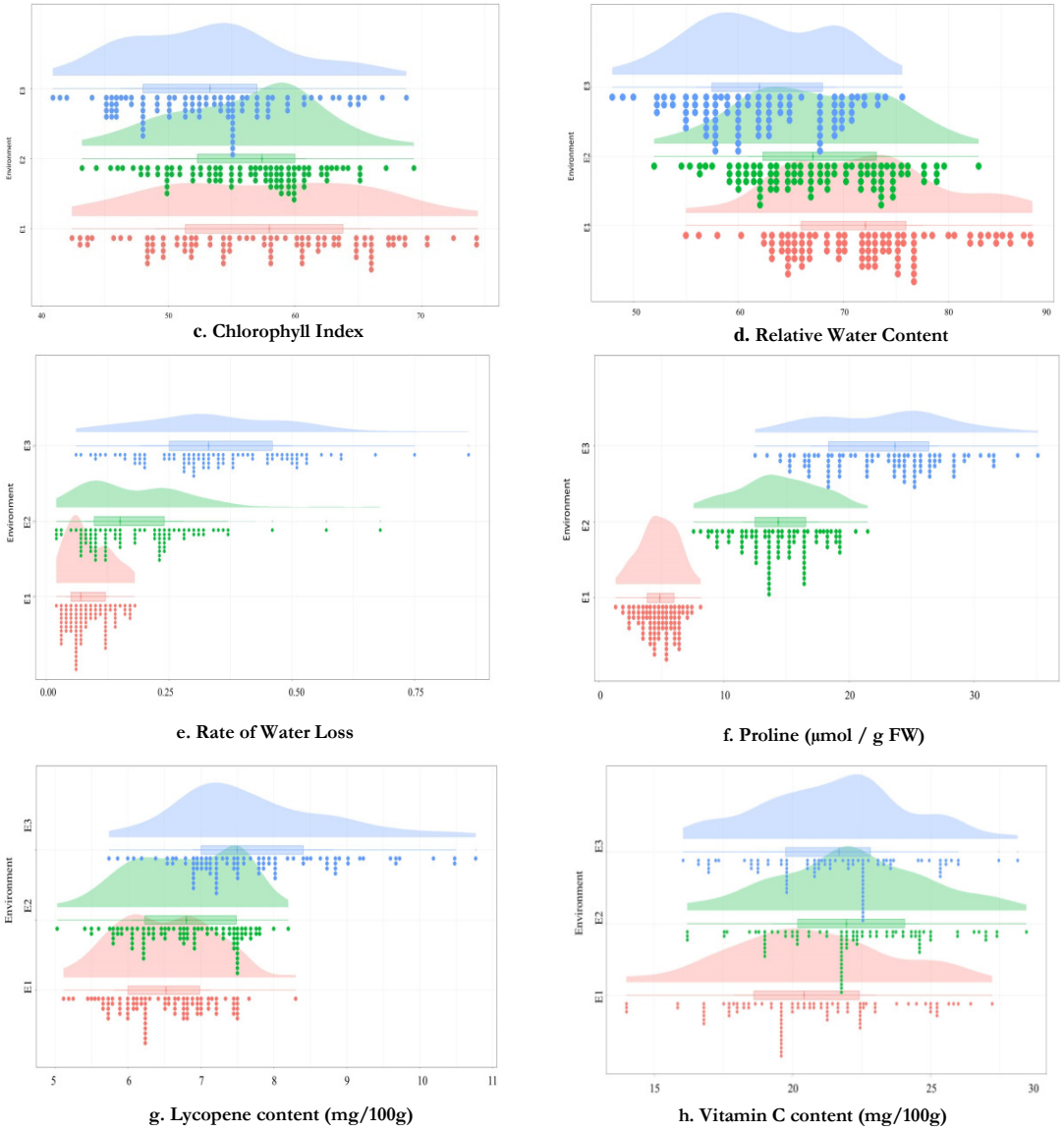


Figure 1. Effect of different level of water stresses *i.e.*, L_1: E_1 (**Pink**), L_2:E_2 (**Green**), and L_3:E_3 (**Blue**) on important physiological and quality attributes in tomato

Stability analysis for yield-attributing traits

AMMI analysis of variance

The analysis of variance (ANOVA) has revealed the significant effects ($p<0.01$) for genotypes (fixed), years/environments (random), and genotypes by environments interaction (GEI) on yield and yield-attributing traits (Table 3). Among the factors, the environment has significantly contributed to fruit setting (26.9), and yield per plant (56.8) while genotype has contributed to fruit weight (70.92). Genotype has also influenced significantly, i.e., 19.6%, and 24.9% of the total variation for fruit setting and fruit yield, respectively. The G×E interaction component was partitioned into the first two interaction principal components (IPCA), which were found non-significant. The IPCA1 explained 96.5, 81.6, and 52.7% and IPCA2 explained 3.5, 18.4, and 47.3% of the G×E interaction for fruit set, fruit weight, and fruit yield, respectively; thus, the first two principal components could explain 100% of the G×E variation. AMMI 1 and AMMI 2 biplot analysis

Table 3. AMMI analysis of variance for selected yield and related traits of tomato grown under different water stress environment

Traits		Fruit setting (%)			Fruit weight (g)			Yield (kg/plant)		
Source	DF	MSS	Proportion	Explained SS (%)	MSS	Proportion	Explained SS (%)	MSS	Proportion	Explained SS (%)
ENV	2	4844.70**		26.88	1720.39**		8.57	4.96**		56.84
REP (ENV)	6	8.40			20.67			0.00		
GEN	31	227.74**		19.59	918.63**		70.92	0.14**		24.87
GEN:ENV	62	152.83**		26.29	62.69**		9.68	0.01**		3.56
PC1	32	285.64	96.5		99.14	81.6		0.01	52.7	
PC2	30	11.16	3.5		23.81	18.4		0.01	47.3	
Residuals	186	1.533			1.79			0.00		
Total	349	103.25			115.04			0.05		

AMMI 1 and AMMI 2 biplot analysis

In the AMMI1 biplot, the main effects (genotype mean and environment mean) are plotted against IPCA1 scores for both genotypes and environments. For percent fruit setting, Hybrid US-626, Sel-3, RCMT-8, MT-11, MT-3, MCTR-4B, MCTR-7B, and MT-2 were found close to the center point (Figure 2a) and stable across the years. Likewise, the AMMI 2 biplot (Figure 2b) based on IPCA1 vs. IPCA2 explained the magnitude of the interaction between genotypes and environments. The genotypes Sel-3, TMC-2, Hybrid US-626, MT-3, and MT-11 were found closer to the centre and were found stable for percent fruit set over the years, while genotypes TMC-1, MCTR4A, 09/TODVAR-6, and MCTR4 showed differences in mean percent fruit setting over the years.

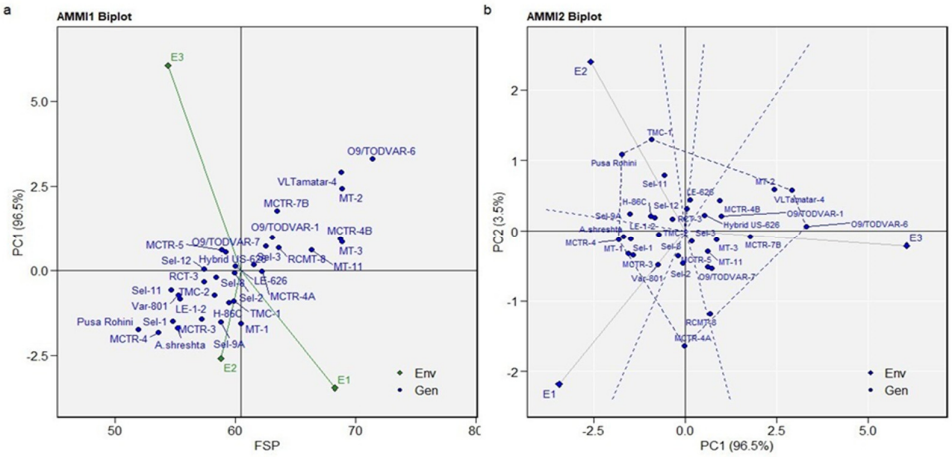


Figure 2. AMMI biplot for fruit setting (%) in tomato genotypes under water stress conditions **a)**. genotypes and environments IPC1 scores (AMMI 1) and **b)**. IPC2 vs. IPC1 scores (AMMI 2)

Similarly, for fruit weight, the AMMI 1 biplot (Figure 3a) identified the genotypes MCTR-5, Sel-3, RCMT-8, MT-11, and 09/TODVAR-1 as stable genotypes as they lied closer to the centre point of the biplot. The AMMI2 biplot (Figure 3b) differentiated the stable genotypes Sel-3, LE1-2, TMC-2, H-86, and MT-11, with the genotypes PusaRohini, Hybrid US 626, Sel-12, and MCT-4B showing differences in mean fruit weight across the years. Further, yield was also affected by genotype, environment, and interactions.

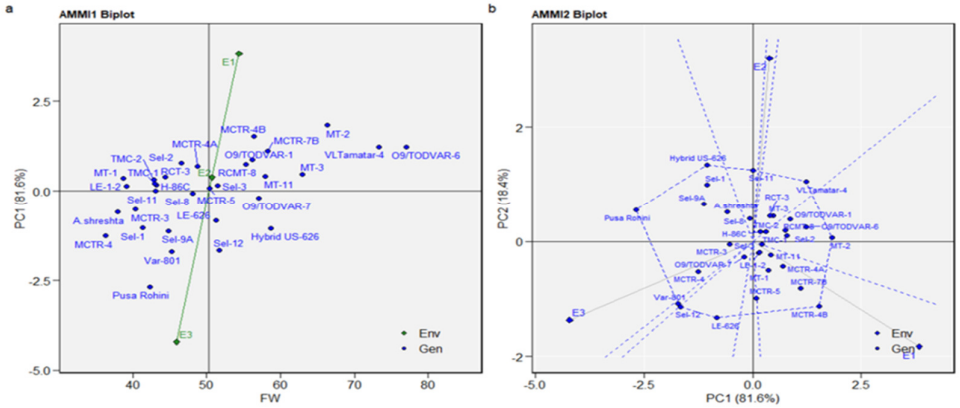


Figure 3. AMMI biplot for fruit weight (g) in tomato genotypes under water stress conditions **a)**. genotypes and environments IPC1 scores (AMMI 1) and **b)**. IPC2 vs. IPC1 scores (AMMI 2)

The biplot AMMI 1 (Figure 4a) elucidated that genotypes Sel-8, LE-626, MT-1, MCTR-4A, and MCTR-4B were found stable and closer to the centre of the biplot, while genotypes VL Tomato-4, MT-11, and 09/TODVAR-7 were higher in average yield per plant across the level of water stress. Moreover, AMMI2 biplots (Figure 4b) identified the stable genotypes least affected by GEI as MT-1, Var-801, LE-626, Sel-8, and 09/TODVAR-6 while, genotypes Sel-1, MT-11 Sel-12, TMC-1, and Sel-2 showed differences in mean yield per plant over the years. AMMI stability value

The accessions have shown a wide range of variations for AMMI stability value (ASV) which ranged from 1.12-79.20 for fruit setting, 0.51-11.90 for fruit weight, and 0.01-0.35 for fruit yield (Table 4). The genotype with the lowest ASV is considered a stable genotype for the respective trait. Among the genotypes, the most stable genotypes with lowest ASV value were identified as Sel-12, MCTR-4A, Sel-2, and LE-626 for fruit setting; Sel-8, LE-1-2, H-86, and 09/TODVAR-7 for fruit weight; and MT-1, Var-801, and MCTR-4 for fruit yield. Similarly, the lower values were also observed by other stability parameters for these genotypes.

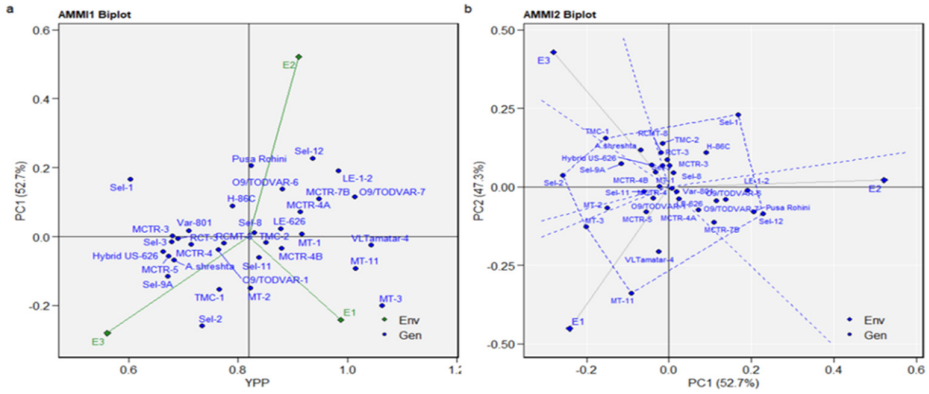


Figure 4. AMMI biplot for fruit yield (kg/plant) in tomato genotypes under water stress conditions **a)**. genotypes and environments IPC1 scores (AMMI 1) and **b)**. IPC2 vs. IPC1 scores (AMMI 2)

Multi-trait stability index (MTSI) and genotype selection

A multi-trait stability index (MTSI) analysis was carried out to identify the genotypes stable for all the yield-attributing traits within each environment (moisture regime). Based on MTSI, out of 32 accessions, 5 accessions, i.e., MT-11, Megha Tomato-2, Megha Tomato-3, VL Tomato-4, and Sel-9A were found to be most stable based on all the traits studies at 10% selection intensity. These genotypes cross the cut-off point (red

circle) as presented in Figure 5a. Further, based on only yield and related traits, the genotypes were found stable and selected as Megha Tomato-3, 09/TODVAR-7, MCTR-4A, VL Tomato-4, and MCTR-4B (Figure 5b).

The results of the factor analysis have explained the response of the traits to selection (Table 4). Among the traits the highly responsive to the selection were number of seeds per fruit (14.85) followed by plant height and fruit weight. Moreover, traits such as root shoot ratio, chlorophyll index, and sugar content were negative in response to selection. The commonality ranged from 0.60 (acidity) to 0.89 (root length), and unique factors ranged from 0.12 (root length) to 0.40 (acidity) for all the different biometric traits (Table 5). The maximum uniqueness value was for quality traits like acidity followed by sugar content, PFP, and TSS. In the present study, common variance explains approximately 77.00% of the total variance present among the traits.

Table 4. Stability measures selected yield and related traits of tomato grown under different water stress environment

Genotypes	Fruit Setting (%)							Fruit Weight (g)							Fruit Yield (kg/plant)						
	FS	ASI	ASV	EV	SIPC	ZA	WAAS	FW	ASI	ASV	EV	SIPC	ZA	WAAS	Y	ASI	ASV	EV	SIPC	ZA	WAAS
ArkaShresh ta	55.20	1.64	46.30	0.03	1.78	0.22	1.64	38.00	0.49	2.68	0.01	1.11	0.11	0.58	0.68	0.07	0.14	0.02	0.19	0.15	0.09
H-86C	59.40	0.91	25.60	0.01	1.15	0.12	0.91	43.20	0.14	0.77	0.00	0.33	0.03	0.17	0.79	0.07	0.15	0.03	0.20	0.16	0.10
Hybrid US-626	59.20	0.51	14.50	0.00	0.76	0.07	0.52	58.70	0.89	4.85	0.08	2.39	0.21	1.10	0.66	0.04	0.08	0.01	0.11	0.09	0.06
LE-1-2	55.40	0.82	23.10	0.01	1.04	0.11	0.82	39.20	0.12	0.66	0.00	0.34	0.03	0.15	0.98	0.10	0.21	0.04	0.20	0.17	0.11
LE-626	60.00	0.13	3.62	0.01	0.58	0.02	0.14	51.30	0.72	3.91	0.07	2.16	0.18	0.92	0.88	0.02	0.05	0.00	0.06	0.05	0.03
MCTR-3	57.20	1.38	39.00	0.02	1.78	0.19	1.39	40.40	0.43	2.32	0.00	0.57	0.08	0.44	0.68	0.03	0.07	0.01	0.07	0.05	0.03
MCTR-4	53.60	1.76	49.80	0.03	1.96	0.24	1.77	36.30	1.03	5.61	0.03	1.78	0.21	1.12	0.71	0.01	0.03	0.00	0.03	0.02	0.01
MCTR-4A	62.20	0.06	1.81	0.13	1.66	0.02	0.08	48.80	0.57	3.10	0.01	1.13	0.12	0.64	0.91	0.05	0.11	0.01	0.14	0.11	0.07
MCTR-4B	68.80	0.91	25.90	0.02	1.38	0.13	0.93	56.40	1.26	6.86	0.08	2.66	0.27	1.45	0.88	0.03	0.06	0.00	0.08	0.06	0.04
MCTR-5	58.80	0.58	16.50	0.02	1.12	0.08	0.60	50.40	0.19	1.05	0.03	1.07	0.06	0.25	0.67	0.05	0.10	0.01	0.13	0.11	0.07
MCTR-7B	63.50	1.71	48.30	0.03	1.85	0.23	1.71	58.30	0.92	4.99	0.04	1.93	0.20	1.06	0.95	0.08	0.17	0.03	0.22	0.18	0.11
MT-1	60.40	1.50	42.50	0.03	1.88	0.21	1.51	38.70	0.31	1.66	0.01	0.86	0.07	0.38	0.92	0.00	0.01	0.00	0.01	0.01	0.01
MT-11	66.30	0.59	16.70	0.01	0.91	0.08	0.60	57.90	0.35	1.88	0.00	0.66	0.07	0.39	1.01	0.17	0.35	0.16	0.43	0.33	0.21
MT-2	68.90	2.34	66.20	0.07	3.02	0.32	2.36	66.40	1.50	8.14	0.05	1.89	0.27	1.51	0.82	0.09	0.18	0.03	0.22	0.18	0.11
MT-3	68.90	0.83	23.40	0.01	0.99	0.11	0.83	63.00	0.39	2.13	0.01	0.92	0.09	0.47	1.06	0.12	0.26	0.07	0.33	0.26	0.17
O9/TODVAR-1	63.00	0.94	26.60	0.01	1.19	0.13	0.95	56.20	0.71	3.87	0.02	1.26	0.14	0.78	0.76	0.03	0.06	0.00	0.07	0.06	0.04
O9/TODVAR-6	71.40	3.19	90.20	0.10	3.37	0.43	3.19	77.00	1.01	5.48	0.03	1.48	0.19	1.05	0.88	0.08	0.16	0.03	0.18	0.14	0.09
O9/TODVAR-7	62.50	0.69	19.50	0.02	1.25	0.10	0.71	57.00	0.17	0.92	0.00	0.47	0.04	0.21	1.01	0.06	0.14	0.02	0.16	0.13	0.08
PusaRohini	51.90	1.67	47.20	0.08	2.82	0.24	1.71	42.40	2.19	11.90	0.12	3.23	0.41	2.29	0.82	0.12	0.24	0.06	0.28	0.23	0.15
RCMT-8	63.60	0.65	18.30	0.07	1.85	0.10	0.69	55.30	0.61	3.31	0.01	0.94	0.12	0.64	0.77	0.05	0.11	0.02	0.13	0.10	0.06
RCT-3	57.40	0.33	9.43	0.00	0.52	0.05	0.34	44.40	0.33	1.81	0.01	0.84	0.08	0.40	0.69	0.04	0.09	0.01	0.09	0.07	0.04
Sel-1	54.80	1.45	41.00	0.02	1.62	0.20	1.45	41.40	0.87	4.73	0.05	2.03	0.20	1.03	0.60	0.14	0.30	0.10	0.40	0.31	0.20
Sel-11	54.60	0.56	15.70	0.03	1.37	0.08	0.58	43.10	0.23	1.25	0.05	1.25	0.06	0.24	0.84	0.03	0.07	0.00	0.07	0.06	0.04
Sel-12	57.40	0.04	1.12	0.00	0.36	0.01	0.05	51.70	1.38	7.51	0.09	2.81	0.29	1.57	0.94	0.13	0.27	0.07	0.31	0.25	0.16
Sel-2	59.90	0.08	2.20	0.01	0.54	0.02	0.09	46.60	0.64	3.49	0.01	0.89	0.12	0.66	0.73	0.14	0.29	0.08	0.30	0.24	0.15
Sel-3	61.50	0.17	4.81	0.00	0.32	0.02	0.18	51.50	0.13	0.71	0.00	0.35	0.03	0.16	0.68	0.03	0.07	0.01	0.08	0.06	0.04
Sel-8	58.40	0.20	5.68	0.01	0.57	0.03	0.21	48.10	0.09	0.51	0.01	0.48	0.03	0.13	0.83	0.02	0.05	0.00	0.06	0.04	0.03
Sel-9A	58.80	1.47	41.70	0.02	1.77	0.20	1.48	44.90	0.92	5.02	0.03	1.77	0.19	1.03	0.67	0.07	0.15	0.02	0.19	0.15	0.10
TMC-1	59.90	0.88	25.00	0.09	2.21	0.13	0.93	43.00	0.18	0.95	0.00	0.27	0.03	0.18	0.77	0.11	0.23	0.06	0.31	0.24	0.15
TMC-2	58.30	0.70	19.80	0.00	0.77	0.09	0.70	42.90	0.26	1.40	0.00	0.48	0.05	0.29	0.85	0.07	0.14	0.03	0.16	0.12	0.07

Var-801	55.30	0.71	20.20	0.02	1.22	0.10	0.73	45.30	1.41	7.66	0.08	2.79	0.30	1.59	0.71	0.01	0.02	0.00	0.03	0.03	0.02
VLTamato-4	68.80	2.80	79.20	0.09	3.48	0.38	2.82	73.30	1.03	5.59	0.06	2.28	0.23	1.20	1.04	0.10	0.21	0.06	0.23	0.18	0.11

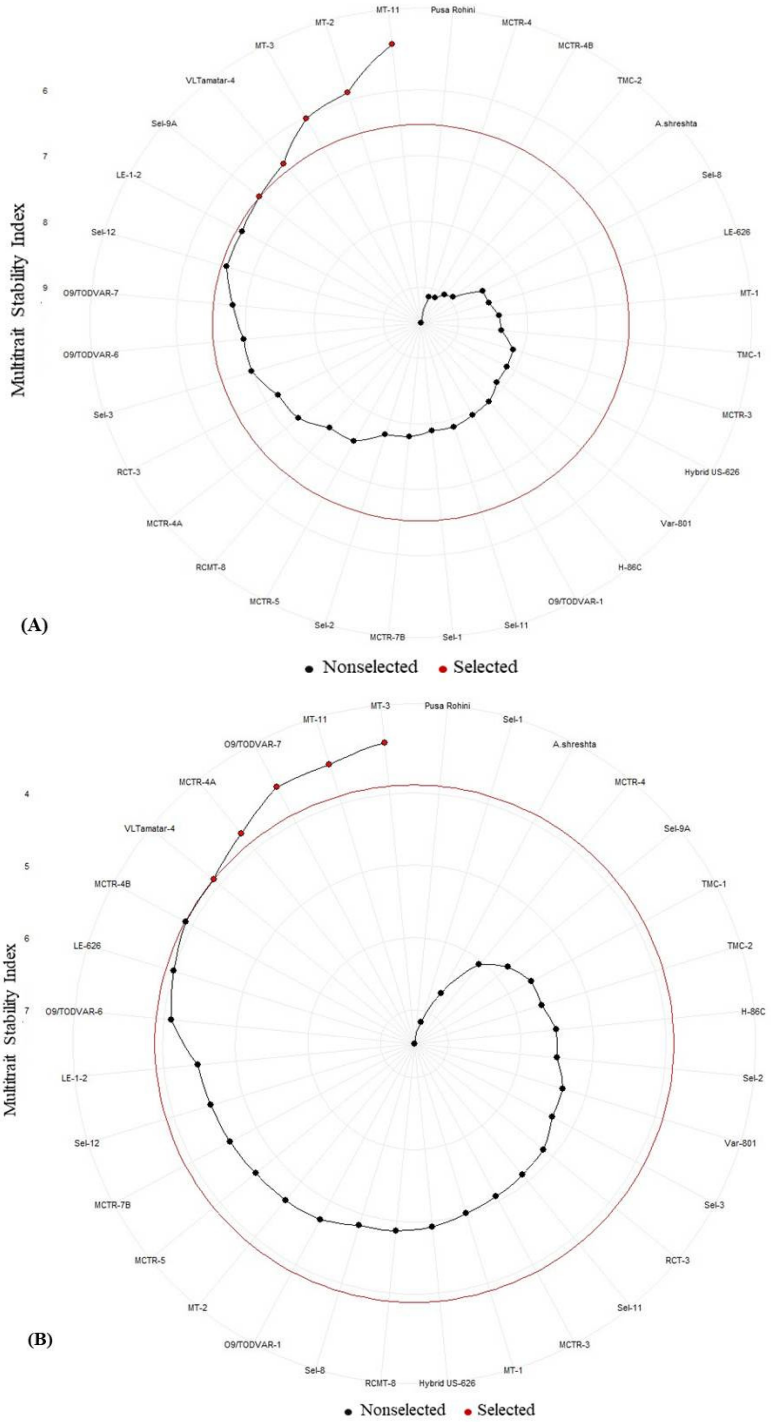


Figure 5. Ranking of genotypes in ascending order based on the multi-trait stability index, with a selection intensity threshold of 10% (red circle)
(A) Selection considering all traits; (B) Selection based on fruit yield traits

Table 5. Factors linked to correlated traits, selection differential, and selection response for tomato traits

Traits	Factor	Xo	Xs	SD	SD percent	Response to selection	Communality	Uniquenesses
No of flower/cluster	FA 1	5.64	6.13	0.49	8.77	0.33	0.76	0.24
Lycopene content	FA 1	7.01	7.02	0.01	0.13	0.01	0.77	0.23
Fruit diamter	FA 2	46.50	51.10	4.56	9.81	4.16	0.74	0.26
Root-shoot ratio	FA 2	0.18	0.17	-0.01	-3.24	-0.01	0.83	0.17
Chlorophyll Index	FA 2	55.60	55.50	-0.15	-0.27	-0.14	0.73	0.27
Total Biomass	FA 2	21.40	21.00	-0.39	-1.82	-0.37	0.74	0.26
No of seeds/fruit	FA 3	74.70	89.90	15.20	20.40	14.85	0.85	0.15
Rate of water loss	FA 3	0.21	0.20	0.00	-0.44	0.00	0.76	0.24
Chlorophyll ab	FA 3	3.93	4.39	0.46	11.80	0.32	0.79	0.21
Root volume	FA 4	15.40	16.30	0.91	5.90	0.77	0.81	0.19
Vitamin C	FA 4	21.40	22.40	0.93	4.33	0.84	0.84	0.16
Plant height	FA 5	89.50	102.00	12.60	14.10	11.51	0.78	0.22
Proline content	FA 5	14.00	15.30	1.28	9.15	0.98	0.74	0.26
Fruit setting	FA 6	60.50	66.30	5.87	9.71	3.88	0.81	0.19
Fruit weight	FA 6	50.30	61.10	10.70	21.30	10.51	0.80	0.21
Root length	FA 6	24.80	26.40	1.64	6.60	1.47	0.89	0.12
Total Sugar	FA 6	1.91	1.82	-0.09	-4.63	-0.09	0.62	0.38
Fruit length	FA 7	41.00	46.20	5.19	12.70	4.90	0.77	0.23
Pollen viability	FA 7	86.80	92.10	5.22	6.01	5.01	0.72	0.28
Relative water content	FA 8	67.20	70.50	3.35	4.99	3.15	0.86	0.14
Acidity	FA 8	0.71	0.71	0.00	0.26	0.00	0.60	0.40
Yield per plant	FA 9	0.82	0.92	0.10	12.60	0.06	0.75	0.25
Total soluble solid	FA 9	5.22	5.40	0.19	3.58	0.14	0.74	0.26
Communality Mean: 0.77								
Selected genotypes: MT-11, MT-2, MT-3, VLTamatar-4 and Sel-9A								

Discussion

Effect of water stress on genetic parameters

Within the crop improvement program specific to this region, a critical objective is the identification and diversification of cropping systems that incorporate tolerant and stably adaptive genotypes capable of thriving under water stress conditions (Patane *et al*., 2011; Khapte *et al*., 2019). In the present study, wider variability was witnessed in various stress-responsive physio-chemical traits at different levels of water stress, which provides greater resources for developing stress-tolerant cultivars for the sub-Himalayan region. The genetic variability of a population is very important for effective selection of genotypes adaptive to a particular adverse environment. Both GCV and PCV are useful in detecting the magnitude of variability present in the base population. The findings of the present study reveal notable GCV exceeding 20% for critical physiological traits including root-shoot ratio, rate of water loss, root volume, root length, total biomass, and proline content. Similarly, yield-related traits such as the number of seeds per fruit and fruit weight also exhibit high GCV values. These outcomes indicate a broader genetic base and increased variability within these traits, offering insights into the extent of variation influenced by both genotype and environment. The observed high

influence of genotype suggests that cultivar selection could be effective, consistent with trends noted by Tripodi *et al*. (2022) in tomatoes cultivated under water stress conditions.

Yield, being a multifaceted trait, underscores the critical importance of associated traits for effective genotype selection. The present investigation indicates a higher PCV and a moderate GCV for yield, suggesting that environmental factors play a predominant role in influencing yield. This aligns with expectations, given that yield is governed by numerous genes whose contributions are significantly influenced by the prevailing environmental conditions. Consequently, during selection for yield improvement under stress conditions, due consideration should be given to the associated traits (Lee *et al*., 2022).

In contrast to our study, other researchers have reported higher heritability and genetic advances for yield per plant (Verma *et al*., 2021; Ilakiya *et al.,* 2022). Comparatively lower heritability and genetic advance for the studied traits in the present investigation may be due to water stress conditions applied in our evaluation experiment, influencing the expression of genes responsible for yield (Bray, 2002), and the distinct responses of genotypes to varying growing environments (water stress). Traits exhibiting low to moderate variability signal the necessity for further enhancement of the base population. From the mean data, it was inferred that most of the traits showed higher heritability (> 60%) and genetic advance as a percentage of the mean (> 20%), indicating that these traits are governed by additive gene action and that there is potential for selection of these traits under both conditions. Moreover, traits such as pollen viability, fruit setting TSS, and lycopene content under irrigated (sufficient moisture) conditions and the number of fruits per cluster, fruit diameter, pollen viability, chlorophyll a/b, TSS, and acidity content recorded under water stress conditions also showed higher heritability and moderate genetic advance, indicating that these traits are unequivocally governed by additive and non-additive gene action (Shelby, 2000). Higher heritability and varietal differential (moderate to high) genetic advance for these traits have also been observed earlier by Verma *et al*. (2021) and Ilakiya *et al*. (2022) in tomato grown under open and water stress conditions, respectively. These traits also offer scope for improvement through selection under irrigated as well as moisture-stress conditions.

Moreover, except for the root-shoot ratio, chlorophyll index value, total biomass, sugar content, and acidity, all other traits within the present population exhibited favorable responses to selection, as indicated in Table 5. Notably, the higher values for communality coupled with lower uniqueness across many traits suggest that the variance observed in these traits is collectively explained by a common factor. This emphasizes the effectiveness of a shared underlying factor in accounting for the total variations observed in the traits under consideration.

Effect of water stress on physicochemical parameters

The genotypes have also shown varied responses for all 23 traits under different moisture regimes (Table 2). Many of the traits have shown a decrease in their mean values with subsequent increases in the level of water stress. Growth and yield attributes like plant height, total biomass, pollen viability, fruit setting percentage, number of fruits per cluster, fruit length, diameter, weight, yield per plant, root length, and root volume decreased with subsequent increases in the level of water stress. Similar findings were also observed by other researchers in tomato (Ozbahce and Tari, 2010; Patane *et al*., 2011; Bahadur *et al*., 2015; Li *et al*., 2023).

The reduction in these quantitative traits may be due to a reduction in the efficacy of the assimilation and further mobilization of the photosynthates to various parts of the plants under moisture-stress conditions. It is also supported by the reduction in physiological parameters such as chlorophyll index value, chlorophyll a/b, and relative water content (RWC) and an increase in the rate of water loss and proline content under stressful environments (Figure 1b-f). Reductions in photosynthesis, and related traits such as chlorophyll content (Sakya *et al*., 2018); stomatal conductance (gs), leaf water potential (LWP), relative water content (Bahadur *et al*., 2015); biomass production (Pazzagli *et al*., 2016) have also been observed earlier under deficit irrigation conditions.

Besides, quality parameters like TSS, total sugar, vitamin C, and lycopene content increased with water stress. Improvement in quality traits was also observed by other researchers under mild to moderate water stress conditions (Nuruddin *et al*., 2003; Ozbahce *et al.*, 2010; Patane *et al*., 2011; Ripoll *et al*., 2016; Coyago-Cruzabc *et al*., 2017; Hao *et al*., 2019; Alordzinu *et al*., 2022). This could be due to a reduction in water percentage in the fruits led by restricted water uptake under limited moisture conditions and consequently an increase in solute concentration such as proline, glucose, sucrose, fructose, malic acid, citric acid, and ascorbic acid in tomato plants under increased crunch for water stress (Nahar and Ullah, 2018; Khapte *et al*., 2019). This might be the product of the accumulation of photosynthesis that would be more distributed to the reproductive organs under limited water availability, eventually leading to an apparent enhancement in the sugar content. Moreover, the increase in TSS content with water stress was non-significant, which confirms the findings of the previous studies carried out on tomatoes (Klunklin and Savage, 2017). The content of vitamin C increased significantly (Figure 1h) under water stress, as the synthesis of vitamin C begins with glucose and has an intimate connection with carbohydrate metabolism. It can be inferred that the higher sugar accumulation during water stress promotes vitamin C content in fruits (Veit-Kohler, 1999). However, lycopene content increases continuously with subsequent increases in the level of water stress (Figure 1g). This could be due to the increase in lycopene synthesis promoted by signalling and activation of ethylene biosynthesis under water stress at the fruit expanding stage (Kumar *et al*., 2015). Theobald *et al*. (2007) also reported a 27% increase in lycopene content in tomato fruits under water-stressed conditions. Under water stress, the hormone ABA also plays an important role in closing the stomata to reduce water loss. Chaves *et al*. (2009) observed an increase in the accumulation of lycopene and β- carotene with an increase in the level of ABA content under water stress.

Stability for yield and related traits

In the present investigation, the AMMI model of stability for yield and related traits and the analysis of variance have shown the significant contribution of the environment, genotypes, and genotype-environment interaction on the expression of these traits under different moisture regimes (Table 3). On fruit setting and fruit yield per plant, the effect of environment was significantly higher over the genotype × environment interaction than genotypes alone. As far as fruit weight is concerned, the contribution of genotypes was significantly higher, followed by genotype × environment interaction and environment alone. A similar finding has also been observed by other researchers in tomatoes grown in similar stress environments across different seasons (Savale *et al*., 2016; Shankar *et al*., 2017; Kumar *et al.*, 2019).

Among the accessions, the most stable genotypes with the lowest ASV values under different moisture regimes were Sel-12, MCTR-4A, Sel-2, and LE-626 for increased fruit setting; Sel-8, LE-1-2, H-86, and 09/TODVAR-7 for higher fruit weight; and MT-1, Var-801, and MCTR-4 for augmented fruit yield (Table 4). From the mean performance, out of 32 genotypes, a total of 18 (56.25%) were found superior to the average yield. Based on the multi-trait stability index, out of 32 accessions, 5 accessions (MT-11, Megha Tomato-2, Megha Tomato-3, VL Tomato-4, and Sel-9A) were found most stable at 10% selection intensity (Figure 5a). While, based on only yield and related traits, the genotypes that were found stable and were selected are Megha Tomato-3, 09/TODVAR-7, MCTR-4A, VL Tomato-4, and MCTR-4B (Figure 5b). Moreover, considering both the analyses, genotypes like MT-11, VL Tomato-4, and Megha Tomato-3 were identified as common and stable genotypes. These identified genotypes found stable for yield as well as other traits under moisture stress conditions could be promoted for commercial production. Moreover, the genotypes found superior for fruit traits could be utilized in further development of varieties tolerant to moisture stress through hybridization and selection with stable genotypes.

Conclusions

The present investigation underscores the heightened sensitivity of tomatoes to water stresses, a prevalent condition in hill slopes within mountain agro-ecosystems. Physio-chemical traits exhibiting elevated variability, coupled with high heritability and genetic advance, demonstrate heightened responsiveness, thereby conferring a significant advantage for the selection of stable genotypes under water stress conditions. It is noteworthy the enhancements in quality parameters such as vitamin C and lycopene content under stress conditions. The AMMI stability analysis reveals the substantial influence of genotype, environment, and their interaction on yield and related traits. Identified through the Multi-Trait Stability Index (MTSI), the top three stable genotypes—MT-11, VL Tomato-4, and Megha Tomato-3—stand out as promising candidates could be used for commercial production under the tested environment. Moreover, genotypes with stable backgrounds across multiple traits hold potential for further integration into crop improvement programs targeted against water stress through hybridization and selection. Given the insights on the germplasm gained from this study, it is recommended that further work should be carried out to delve deeper into the underlying molecular mechanisms governing these responses, allowing for more precise and targeted strategies in developing tomatoes resilient to water stress. Additionally, exploring the adaptability of identified stable genotypes under diverse environmental conditions will enhance their broader applicability in varying agro-climatic settings.

Authors' Contributions

Conceptualization: VKV and KR; Data curation: VKV, MBD, ND and KR; Formal analysis: VKV, HR and AK; Funding acquisition: SHR and VKV; Investigation: VKV, KR and SH; Methodology: VKV, KR, PB and PK; Project administration: VKM and SH; Resources: VKV, KR and AK; Software: AK and VKV; Supervision: VKV, KR and SH; Validation: VKV, KR, PK and PB; Visualization: VKV, AK, PK and GC; Writing - original draft: VKV and KR; Writing - review and editing: PK, GC, KR and AK. All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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