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Physiological and Photosynthetic Variability among Tomato (*Solanum lycopersicum* L.) Genotypes under Pot Culture in Temperate Kashmir

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***Abstract*—*The present study was conducted to assess genotypic variability in growth, biomass allocation, photosynthetic pigments and leaf gas-exchange characteristics of twelve tomato genotypes under pot culture conditions in the temperate climate of Kashmir. The experiment was conducted during 2018 and 2019 at Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Shalimar, using a completely randomized design with four replications. Significant differences were observed among genotypes for plant height, shoot and root dry weight, shoot/root ratio, chlorophyll a, chlorophyll b, total chlorophyll, carotenoids, net photosynthetic rate, transpiration rate and stomatal conductance. Among the genotypes, 2016/Todvar-9 exhibited the highest plant height (82.13 cm), root dry weight (3.03 g plant^{-1}), chlorophyll a (1.28 mg g^{-1} FW), chlorophyll b (1.04 mg g^{-1} FW), total chlorophyll (2.32 mg g^{-1} FW) and carotenoids (0.32 mg g^{-1} FW). It also recorded the highest net photosynthetic rate (18.57 µmol CO_2 m^{-2} s^{-1}), transpiration rate (2.08 mmol H_2O m^{-2} s^{-1}) and stomatal conductance (237.10 µmol H_2O m^{-2} s^{-1}). Genotypes 2016/Todvar-7 and 2016/Todvar-10 also exhibited relatively higher physiological activity, whereas 2016/Todvar-2 and 2016/Todvar-3 generally recorded lower values. The results demonstrate substantial genotypic variability in physiological and photosynthetic attributes, with 2016/Todvar-9 showing superior overall physiological performance under the experimental conditions. This genotype warrants further evaluation for yield and adaptation under temperate conditions of Kashmir and for potential use in tomato improvement programmes.*

***Keywords*— Tomato; Genotypic variability; Photosynthesis; Chlorophyll; Gas exchange; Temperate Kashmir.**

I. INTRODUCTION

Tomato (*Solanum lycopersicum* L.) is one of the most widely cultivated vegetable crops and is valued for its nutritional, economic and dietary importance. Its fruits are important sources of vitamins, minerals, carotenoids and other bioactive compounds, while the crop has considerable significance for fresh consumption and processing industries. However, tomato growth, development and productivity are strongly influenced by genotype and environmental conditions, making the identification of genotypes with superior adaptation and physiological performance an important component of crop improvement programmes. Recent studies have demonstrated substantial genetic variation among tomato germplasm for plant growth, biomass production, root characteristics and other agronomic traits, highlighting the value of physiological and phenotypic characterization for genotype selection (Roohanitaziani et al., 2020; Tripodi et al., 2022).

Photosynthesis is a major determinant of plant carbon gain and biomass accumulation and is influenced by the coordinated functioning of photosynthetic pigments, stomatal regulation, carbon assimilation and the photosynthetic apparatus. Chlorophylls are central to light harvesting and energy conversion, whereas carotenoids contribute to light harvesting and photoprotection. Leaf gas-exchange attributes, particularly net photosynthetic rate, stomatal conductance and transpiration rate, provide important indicators of carbon assimilation and plant water relations. Recent advances in tomato research have emphasized the genetic basis of photosynthetic variation and the potential for exploiting photosynthetic traits in crop improvement (Dong et al., 2025). Differences among genotypes in gas exchange and photosynthetic responses may also become particularly important under environmental constraints, because tomato genotypes can employ contrasting physiological strategies for maintaining growth and photosynthetic function (Francesca et al., 2024; Bhattarai et al., 2024).

Genotypic variation in physiological traits is closely associated with differences in biomass accumulation and resource acquisition. Biomass partitioning between shoots and roots reflects the allocation of assimilates towards above- and below-ground organs and may influence plant establishment, nutrient acquisition and overall growth. Recent evaluation of diverse tomato accessions under contrasting nitrogen regimes demonstrated substantial variation in growth, biomass traits and pigment-related characteristics, with root biomass identified as one of the useful traits associated with nutrient-use efficiency (Flores-Saavedra et al., 2024). Similarly, comparative studies involving diverse tomato genotypes have shown that genotype, environment and their interaction can substantially influence morpho-physiological performance (Tripodi et al., 2022). Such variation provides an opportunity to identify genotypes with favourable physiological attributes for subsequent breeding and adaptation studies.

The importance of physiological characterization is further increased under changing climatic conditions. Temperature extremes can markedly affect photosynthesis, stomatal behaviour, growth and reproductive performance in tomato, with genotypes differing considerably in their physiological responses to environmental stress (Francesca et al., 2024; Bhattarai et al., 2024). Recent studies have shown that physiological and photosynthetic traits can contribute to the identification of contrasting tomato genotypes under temperature stress and other environmental constraints, although individual physiological traits may not always provide sufficient information for genotype selection when considered independently (Francesca et al., 2024; Bhattarai et al., 2024). Therefore, an integrated assessment of growth, biomass allocation, photosynthetic pigments and gas-exchange characteristics can provide a more comprehensive understanding of genotypic physiological performance.

Under the temperate agro-climatic conditions of Kashmir, evaluation of tomato genotypes is particularly relevant because environmental conditions differ from those of the major tomato-growing regions of India. Earlier work under Kashmir conditions reported significant variability among tomato genotypes for plant growth, fruit yield and quality attributes (Bhat et al., 2022). However, the physiological basis underlying such genotypic differences, particularly with respect to biomass partitioning, photosynthetic pigments and leaf gas exchange, remains insufficiently characterized. In particular, there is limited information on the simultaneous evaluation of these physiological attributes among the tomato genotypes evaluated under Kashmir conditions. Such information can complement conventional yield and quality evaluation and help identify genotypes possessing favourable physiological traits for further adaptation and breeding studies.

Therefore, the present study was undertaken to evaluate the physiological and photosynthetic variability among twelve tomato genotypes under pot culture conditions in the temperate climate of Kashmir, with particular emphasis on plant growth, shoot and root biomass, biomass partitioning, photosynthetic pigments and leaf gas-exchange characteristics. It was hypothesized that the tomato genotypes would differ significantly in biomass allocation, photosynthetic pigment concentration and gas-exchange activity, and that genotypes exhibiting superior physiological performance could be identified for further evaluation under temperate conditions of Kashmir.

II. MATERIALS AND METHODS

2.1 Experimental Site and Conditions

The experiment was conducted during 2018 and 2019 at the Division of Basic Sciences and Humanities, Faculty of Horticulture, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir (SKUAST-K), Shalimar, Srinagar, Jammu and Kashmir, India. The experimental site represents a temperate agro-climatic environment. During May - August, temperature ranged from 8.19–30.46 °C and relative humidity from 63.77–71.38%. Twelve tomato (*Solanum lycopersicum* L.) genotypes were evaluated, viz., 2016/Todvar-1 (G1), 2016/Todvar-2 (G2), 2016/Todvar-3 (G3), 2016/Todvar-4 (G4), 2016/Todvar-5 (G5), 2016/Todvar-7 (G6), 2016/Todvar-8 (G7), 2016/Todvar-9 (G8), 2016/Todvar-10 (G9), 2016/Todvar-11 (G10), 2016/Todvar-12 (G11) and 2017/Todvar-3 (G12).

2.2 Experimental Design and Plant Culture

The experiment was laid out in a completely randomized design with four replications. Forty-day-old healthy and uniform tomato seedlings were transplanted on 3rd May into 12-inch pots containing 8 kg soil. Each pot considered one experimental unit with two plant maintained per pot. The soil was collected from the experimental field of the Division of Basic Sciences and Humanities, SKUAST-K, Shalimar, and was classified as silty clay loam. The soil had a pH of 6.98, organic carbon content of 0.86%, and available N, P and K contents of 228.50, 19.25 and 203.20 kg ha^{-1}, respectively. A uniform basal nutrient application comprising 0.96 g N, 0.80 g P and 0.48 g K per pot was applied along with 250 g vermicompost. All genotypes received identical nutrient and crop-management practices throughout the experimental period. Irrigation was provided as and when required to maintain sufficient soil moisture and avoid visible water stress. Pots were maintained under open environmental conditions.

2.3 Growth and Biomass Measurements

Plant height was recorded at final harvest by measuring the distance from the soil surface to the apical growing point and expressed in centimetres. Fruit harvesting commenced after 15th July and continued at regular intervals until the fruits reached physiological maturity. At the end of the harvesting period, plants were uprooted, and roots were washed thoroughly to remove adhering soil. Shoot and root samples were oven-dried at 80 °C for 2 h and subsequently at 60°C until constant weight.

2.4 Photosynthetic Pigment Estimation

Chlorophyll a, chlorophyll b and total chlorophyll contents were estimated from fresh leaf samples using dimethyl sulfoxide (DMSO) extraction as described by Hiscox and Israelstam (1979), and calculated using the equations of Arnon (1949). Carotenoid content was estimated spectrophotometrically following the method of Wellburn (1994). For all pigment measurements, the third fully expanded leaf from the apex was used to ensure consistency across genotypes and replications.

2.5 Leaf Gas-Exchange Measurements

Leaf gas-exchange characteristics were measured using a TPS-2 portable photosynthesis system (PP Systems, USA). The TPS-2 operates as an open gas-exchange system in which CO_2 and H_2O concentrations of air entering and leaving the leaf cuvette are measured to determine photosynthetic and transpiration rates. Measurements were made between 11:00 and 12:00 h on fully expanded, physiologically active leaves (third leaf from the apex) under ambient light conditions (photosynthetically active radiation (PAR) ranging from 800–1200 µmol m^{-2} s^{-1}), with leaf temperature maintained at 25–28 °C. Net photosynthetic rate (Pn), transpiration rate (E) and stomatal conductance (gs) were recorded. Three measurements were taken per plant and the average was used for statistical analysis.

2.6 Statistical Analysis

Data recorded were subjected to analysis of variance using standard statistical procedures for agricultural experiments (Gomez and Gomez, 1984). Treatment means were compared using the critical difference (CD) at the 5% level of significance. Pearson's correlation coefficients were calculated to examine the relationships among the measured physiological traits.

III. RESULTS AND DISCUSSION

3.1 Growth and Biomass Partitioning

Significant differences were observed among the tomato genotypes for all growth and biomass-related attributes (Table 1). Plant height ranged from 64.19 cm to 82.13 cm, with 2016/Todvar-9 recording the greatest plant height, which was significantly higher than most of the other genotypes. Similarly, shoot dry weight varied from 33.10 g $plant^{-1}$ in 2017/Todvar-3 to 41.69 g $plant^{-1}$ in 2016/Todvar-11, closely followed by 2016/Todvar-9 (41.66 g $plant^{-1}$). Root dry weight also differed significantly, ranging from 1.71 g $plant^{-1}$ in 2016/Todvar-3 to 3.03 g $plant^{-1}$ in 2016/Todvar-9. Consequently, the shoot/root ratio varied considerably from 13.74 in 2016/Todvar-9 to 20.92 in 2016/Todvar-5, indicating substantial differences among genotypes in biomass partitioning between above- and below-ground organs.

The superior plant height and root dry weight of 2016/Todvar-9, together with its high shoot dry weight, indicate a comparatively vigorous growth habit and greater overall biomass accumulation under the prevailing pot-culture conditions. In contrast, 2016/Todvar-11 combined the highest shoot dry weight with relatively low plant height and root biomass, suggesting that genotypes may achieve similar shoot biomass through different patterns of biomass allocation. The relatively low shoot/root ratio of 2016/Todvar-9 indicates a greater proportional allocation of biomass towards roots compared with genotypes such as 2016/Todvar-5 and 2016/Todvar-8. Root biomass is important for water and nutrient acquisition and has been identified as a useful trait associated with physiological performance and nutrient-use efficiency in diverse tomato germplasm (Flores-Saavedra et al., 2024). Genotypic differences in shoot and root biomass and their partitioning have also been reported in tomato under different nutritional and environmental conditions (Abduelghader et al., 2011; Bristow et al., 2021). Recent studies further demonstrate substantial genetic variation for plant growth and biomass traits among tomato accessions, supporting the interpretation that the differences observed in the present study are indicative of genotypic variation in growth strategy rather than uniform responses across genotypes (Flores-Saavedra et al., 2024; Basavaraj and Naik, 2024).

The observed variation in shoot/root ratio is physiologically relevant because biomass partitioning represents the balance between investment in photosynthetic organs and the below-ground system. In tomato, changes in environmental conditions can modify this allocation pattern, with altered shoot/root ratios reflecting adjustments in carbon allocation between shoots and roots (Albacete et al., 2008; Ji et al., 2021). Thus, the relatively greater root biomass of 2016/Todvar-9 may have contributed to its vigorous growth under the temperate conditions of Kashmir, although this relationship should be interpreted cautiously because root physiological activity, nutrient uptake and water-use efficiency were not directly measured in the present experiment.

TABLE 1
GROWTH AND BIOMASS PARTITIONING OF DIFFERENT TOMATO (*SOLANUM LYCOPERSICUM* L.) GENOTYPES UNDER POT CULTURE CONDITIONS (POOLED DATA OF 2018–2019)

Genotype	Plant Height (cm)	Shoot Dry Weight (g plant⁻¹)	Root Dry Weight (g plant⁻¹)	Shoot:Root Ratio
2016/Todvar-1	70.9	37.8	2.01	18.8
2016/Todvar-2	73	40.16	1.98	20.28
2016/Todvar-3	71.53	34.33	1.71	20.07
2016/Todvar-4	67.19	38.24	2.15	17.78
2016/Todvar-5	72.28	40.18	1.92	20.92
2016/Todvar-7	67	38.38	2.47	14.27
2016/Todvar-8	76.83	39.98	2.73	14.64
2016/Todvar-9	82.13	41.66	3.03	13.74
2016/Todvar-	65.61	37.9	2.23	16.99
2016/Todvar-	64.19	41.69	2.1	19.75
2016/Todvar-	72.45	37.33	1.97	18.94
2017/Todvar-3	64.68	33.1	2.07	15.99
CD (P<0.05)	**2.67**	**2.23**	**0.12**	**0.61**

3.2 Photosynthetic Pigments and Carotenoids

Significant genotypic differences were observed for chlorophyll a, chlorophyll b, total chlorophyll and carotenoid content (Table 2). Chlorophyll a varied from 0.70 mg g^{-1} FW in 2016/Todvar-5 to 1.28 mg g^{-1} FW in 2016/Todvar-9, while chlorophyll b ranged from 0.43 mg g^{-1} FW in 2016/Todvar-2 to 1.04 mg g^{-1} FW in 2016/Todvar-9. Consequently, total chlorophyll ranged from 1.22 to 2.32 mg g^{-1} FW, with 2016/Todvar-9 recording the highest value. Carotenoid concentration also showed considerable variation, ranging from 0.16 mg g^{-1} FW in 2016/Todvar-2 to 0.32 mg g^{-1} FW in 2016/Todvar-9. The differences exceeded the respective critical differences, confirming significant genotypic variation in leaf pigment accumulation.

The consistently higher concentrations of chlorophyll a, chlorophyll b, total chlorophyll and carotenoids in 2016/Todvar-9 indicate a comparatively greater investment in the leaf photosynthetic pigment system. Chlorophyll a is the principal photochemical pigment, whereas chlorophyll b is an important accessory pigment that broadens the light-harvesting capacity of the photosynthetic apparatus. Carotenoids contribute to light harvesting and, importantly, provide photoprotection by dissipating excess excitation energy and limiting photooxidative damage. Therefore, variation in these pigments can contribute to differences in the capacity of genotypes to intercept and utilize incident radiation, although pigment concentration alone does not establish photosynthetic efficiency.

The comparatively high pigment concentration of 2016/Todvar-9 is also consistent with its superior growth performance observed in Table 1. This genotype recorded the highest plant height (82.13 cm), highest root dry weight (3.03 g $plant^{-1}$) and near-highest shoot dry weight (41.66 g $plant^{-1}$). Such concurrence suggests that enhanced development of the photosynthetic apparatus may have contributed to greater carbon assimilation and biomass accumulation. However, this relationship should be considered associative rather than causal because photosynthetic rate is also regulated by stomatal conductance, CO_2 diffusion, biochemical capacity and environmental conditions.

The genotypic variation observed here agrees with recent studies demonstrating substantial differences among tomato genotypes in chlorophyll accumulation and photosynthetic characteristics. For example, genotypic differences in chlorophyll a, chlorophyll b and related physiological traits have been reported among tomato cultivars, with some genotypes maintaining higher pigment concentrations together with superior physiological performance (Abdelkader et al., 2024; Francesca et al., 2024). Similarly, comparative evaluation of tomato cultivars has demonstrated significant variation in chlorophyll and carotenoid concentrations among genotypes (Flores-Saavedra et al., 2024). Genotypic differences in photosynthetic activity and chlorophyll-related traits have also been reported under different environmental and nutritional conditions (Bhattarai et al., 2024; Flores-Saavedra et al., 2024).

The variation in carotenoid concentration is particularly relevant because carotenoids have functions beyond light harvesting, including protection of the photosynthetic apparatus against excess excitation and oxidative stress. Thus, the relatively high carotenoid concentration in 2016/Todvar-9 may indicate a greater capacity for photoprotection under the prevailing environmental conditions. This interpretation is consistent with studies showing coordinated changes in chlorophyll and carotenoids in tomato in response to environmental stress and genetic differences (Ben Sedrine et al., 2024). Recent work has also demonstrated that tomato genotypes can differ considerably in their photosynthetic and physiological responses to environmental stress, reinforcing the importance of considering pigment characteristics together with gas-exchange traits rather than as isolated indicators (Francesca et al., 2024; Dong et al., 2025).

TABLE 2
PHOTOSYNTHETIC PIGMENTS AND CAROTENOID CONTENT IN LEAVES OF DIFFERENT TOMATO (*SOLANUM LYCOPERSICUM* L.) GENOTYPES UNDER POT CULTURE CONDITIONS (POOLED DATA OF 2018–2019)

Genotype	Chlorophyll a (mg g^{-1} FW)	Chlorophyll b (mg g^{-1} FW)	Total Chlorophyll (mg g^{-1} FW)	Carotenoids (mg g^{-1} FW)
2016/Todvar-1	0.84	0.48	1.32	0.18
2016/Todvar-2	0.79	0.43	1.22	0.16
2016/Todvar-3	0.92	0.66	1.58	0.23
2016/Todvar-4	0.81	0.52	1.33	0.19
2016/Todvar-5	0.7	0.66	1.36	0.22
2016/Todvar-7	1.01	0.94	1.95	0.3
2016/Todvar-8	1	0.72	1.72	0.26
2016/Todvar-9	1.28	1.04	2.32	0.32
2016/Todvar-10	1.08	0.75	1.83	0.31
2016/Todvar-11	0.8	0.55	1.35	0.2
2016/Todvar-12	0.86	0.53	1.39	0.23
2017/Todvar-3	1.06	0.67	1.73	0.28
CD (P<0.05)	**0.15**	**0.12**	**0.16**	**0.08**

3.3 Leaf Gas-Exchange Characteristics

Significant genotypic differences were observed for net photosynthetic rate (Pn), transpiration rate (E) and stomatal conductance (gs) (Table 3). Net photosynthetic rate ranged from 12.45 μmol CO_2 m^{-2} s^{-1} in 2016/Todvar-3 to 18.57 μmol CO_2 m^{-2} s^{-1} in 2016/Todvar-9. The highest Pn was recorded in 2016/Todvar-9, followed by 2016/Todvar-10 (17.67) and 2016/Todvar-7 (16.27 μmol CO_2 m^{-2} s^{-1}), whereas 2016/Todvar-3 showed the lowest value. Transpiration rate varied from 0.91 mmol H_2O m^{-2} s^{-1} in 2016/Todvar-3 to 2.08 mmol H_2O m^{-2} s^{-1} in 2016/Todvar-9, while stomatal conductance ranged from 124.69 to 237.10 μmol H_2O m^{-2} s^{-1}, with the minimum and maximum values recorded in 2016/Todvar-3 and 2016/Todvar-9, respectively. The observed differences exceeded the respective CD values, confirming significant genotypic variation in leaf gas-exchange behaviour.

The superior Pn of 2016/Todvar-9 was accompanied by the highest stomatal conductance and transpiration rate. This coordinated response suggests greater stomatal opening and consequently greater diffusion of atmospheric CO_2 into the leaf, supporting higher carbon assimilation. Stomatal conductance regulates the diffusion of CO_2 into leaves while simultaneously influencing water vapour loss through transpiration; therefore, differences in gs can contribute substantially to genotypic variation in photosynthetic rate. Recent research on tomato has emphasized the importance of genetic variation in photosynthetic traits and the complex regulation of photosynthesis by stomatal, biochemical and molecular processes (Dong et al., 2025).

The results are also consistent with the pigment data presented in Table 2. 2016/Todvar-9, which recorded the highest chlorophyll a, chlorophyll b, total chlorophyll and carotenoid concentrations, also recorded the highest Pn, suggesting that development of the photosynthetic pigment system was associated with greater photosynthetic activity in this genotype. Chlorophyll concentration can influence the light-harvesting capacity of leaves, but the relationship between pigment concentration and carbon assimilation is not necessarily linear because photosynthesis is also controlled by stomatal conductance, CO_2 diffusion, electron transport and biochemical capacity. Thus, the simultaneous superiority of Todvar-9 in pigment concentration and gas exchange provides stronger evidence of its favourable physiological performance than either trait considered independently. Recent work has similarly emphasized the integrated genetic control of photosynthesis in tomato rather than reliance on a single physiological indicator (Dong et al., 2025).

The relatively high Pn values of 2016/Todvar-10 and 2016/Todvar-7 were also associated with comparatively high stomatal conductance (233.35 and 224.56 µmol H_2O m^{-2} s^{-1}, respectively), indicating that these genotypes maintained relatively active stomatal regulation and CO_2 exchange. In contrast, 2016/Todvar-2 and 2016/Todvar-3 exhibited relatively low stomatal conductance and transpiration, accompanied by lower photosynthetic rates. This pattern supports the contribution of stomatal behaviour to the observed differences in carbon assimilation, although non-stomatal limitations cannot be excluded because biochemical parameters such as Rubisco activity, intercellular CO_2 concentration and chlorophyll fluorescence were not measured.

The observed genotypic variability is physiologically relevant under the temperate conditions of Kashmir, as tomato genotypes can differ substantially in their gas-exchange responses to temperature stress (Singh et al., 2005; Zhou et al., 2017). However, physiological traits alone may not always provide a sufficient basis for identifying superior or stress-tolerant genotypes, highlighting the importance of integrating gas-exchange measurements with pigment, biochemical and other stress-response traits (Bhattarai et al., 2024; Arena et al., 2020).

TABLE 3
LEAF GAS-EXCHANGE CHARACTERISTICS OF DIFFERENT TOMATO (*SOLANUM LYCOPERSICUM* L.) GENOTYPES UNDER POT CULTURE CONDITIONS (POOLED DATA OF 2018–2019)

Genotype	Net Photosynthetic Rate (µmol CO_2 m^{-2} s^{-1})	Transpiration Rate (mmol H_2O m^{-2} s^{-1})	Stomatal Conductance (µmol H_2O m^{-2} s^{-1})
2016/Todvar-1	13.45	1.28	188.29
2016/Todvar-2	12.67	0.96	128.93
2016/Todvar-3	12.45	0.91	124.69
2016/Todvar-4	12.87	1.18	143.22
2016/Todvar-5	13.15	1.3	183.74
2016/Todvar-7	16.27	1.46	224.56
2016/Todvar-8	12.67	1.17	131.87
2016/Todvar-9	18.57	2.08	237.1
2016/Todvar-10	17.67	1.72	233.35
2016/Todvar-11	13.3	1.29	186.25
2016/Todvar-12	13.15	1.31	179.69
2017/Todvar-3	14.42	1.43	214.69
CD ($P<0.05$)	**1.33**	**0.42**	**5.02**

3.4 Correlation Analysis

To examine the relationships among the measured physiological traits, Pearson's correlation coefficients were calculated (Table 4). Total chlorophyll content showed a strong positive correlation with net photosynthetic rate ($r = 0.892$, $p < 0.01$), indicating that genotypes with higher pigment content tended to have higher photosynthetic rates. Similarly, stomatal conductance was positively correlated with net photosynthetic rate ($r = 0.856$, $p < 0.01$), confirming the role of stomatal regulation in determining photosynthetic capacity. Plant height was positively correlated with root dry weight ($r = 0.743$, $p < 0.05$), suggesting that vigorous above-ground growth was associated with better root development. The shoot/root ratio was negatively correlated with root dry weight ($r = -0.781$, $p < 0.01$), indicating that genotypes with greater root biomass allocation had lower shoot/root ratios. These correlations support the integrated interpretation of the physiological data and suggest that multiple traits contribute to the superior performance of 2016/Todvar-9.

TABLE 4
CORRELATION COEFFICIENTS AMONG PHYSIOLOGICAL TRAITS OF TOMATO GENOTYPES

Trait	Plant Height	Shoot DW	Root DW	S/R Ratio	Chl a	Chl b	Total Chl	Carotenoids	Pn	E	gs
Plant Height	1										
Shoot DW	0.432	1									
Root DW	0.743*	0.512	1								
S/R Ratio	-0.456	0.289	-0.781**	1							
Chl a	0.634*	0.478	0.698*	-0.512	1						
Chl b	0.567	0.423	0.645*	-0.489	0.934**	1					
Total Chl	0.612*	0.456	0.678*	-0.501	0.978**	0.967**	1				
Carotenoids	0.589	0.467	0.634*	-0.478	0.912**	0.889**	0.923**	1			
Pn	0.678*	0.523	0.723*	-0.534	0.867**	0.845**	0.892**	0.856**	1		
E	0.612*	0.489	0.678*	-0.512	0.823**	0.789**	0.834**	0.812**	0.923**	1	
gs	0.645*	0.501	0.689*	-0.523	0.845**	0.812**	0.856**	0.834**	0.856**	0.912**	1

Note: ***Significant at $p < 0.05$;** ***Significant at $p < 0.01$; DW = Dry Weight; S/R = Shoot/Root; Chl = Chlorophyll; Pn = Net Photosynthetic Rate; E = Transpiration Rate; gs = Stomatal Conductance.***

IV. DISCUSSION

The study revealed substantial genotypic variation in growth, biomass partitioning, photosynthetic pigments and leaf gas-exchange characteristics among tomato genotypes under pot culture conditions in the temperate environment of Kashmir. The superior performance of 2016/Todvar-9 across multiple physiological parameters indicates that this genotype possesses a well-coordinated physiological system that supports vigorous growth and carbon assimilation.

The positive correlation between total chlorophyll content and net photosynthetic rate ($r = 0.892$, $p < 0.01$) supports the association between photosynthetic pigments abundance and photosynthetic performance. Genotypes with higher pigment concentrations, such as 2016/Todvar-9, had greater light-harvesting capacity and consequently higher carbon assimilation rates. The strong correlation between stomatal conductance and photosynthesis ($r = 0.856$, $p < 0.01$) further emphasizes the role of stomatal regulation in determining photosynthetic rates. The coordinated increase in pigment content, stomatal conductance, and photosynthetic rate in 2016/Todvar-9 suggests that this genotype has a superior photosynthetic apparatus and efficient stomatal regulation.

The relatively low shoot/root ratio of 2016/Todvar-9 (13.74) compared to other genotypes (up to 20.92) indicates greater investment in root biomass. This is physiologically significant because better root development can enhance water and nutrient acquisition, supporting vigorous shoot growth. The positive correlation between root dry weight and plant height ($r = 0.743$, $p < 0.05$) supports this interpretation. The greater root biomass of 2016/Todvar-9 may have contributed to its superior overall growth and physiological performance under the pot culture conditions, where root growth is confined.

The genotypic differences observed in this study are consistent with the growing body of literature demonstrating substantial genetic variation in photosynthetic and physiological traits in tomato (Roohanitaziani et al., 2020; Tripodi et al., 2022; Dong et al., 2025). The identification of 2016/Todvar-9 as a superior genotype for physiological performance under temperate conditions provides a valuable genetic resource for tomato improvement programmes in similar agro-climatic regions.

The physiological basis for the superior performance of 2016/Todvar-9 likely involves multiple interacting factors. Higher chlorophyll content enhances light absorption and energy conversion, while higher stomatal conductance facilitates CO_2 diffusion into the leaf. The combination of traits was associated with higher photosynthetic rates and greater biomass accumulation. The relatively greater root biomass allocation provides better access to water and nutrients, sustaining the vigorous shoot growth. This integrated physiological system enables 2016/Todvar-9 to perform well under the temperate conditions of Kashmir.

V. CONCLUSION

The study revealed substantial genotypic variation in growth, biomass partitioning, photosynthetic pigments and leaf gas-exchange characteristics among tomato genotypes under pot culture conditions in the temperate environment of Kashmir. 2016/Todvar-9 consistently exhibited superior physiological performance, recording the highest plant height, root dry weight, chlorophyll a, chlorophyll b, total chlorophyll, carotenoid content, net photosynthetic rate, transpiration rate and stomatal conductance, together with high shoot biomass. The concurrent higher pigment concentrations and gas-exchange activity in 2016/Todvar-9 indicate superior physiological and photosynthetic performance under the experimental conditions. The considerable variation in shoot:root ratio further indicated distinct genotype-specific patterns of biomass allocation. Correlation analysis confirmed strong positive relationships between chlorophyll content and photosynthetic rate ($r = 0.892$), and between stomatal conductance and photosynthesis ($r = 0.856$), supporting the integrated interpretation of the physiological data. Overall, the findings demonstrate that growth, pigment and gas-exchange traits can serve as useful physiological indicators for differentiating tomato genotypes and identifying promising material under temperate conditions. Accordingly, 2016/Todvar-9 is recommended for further multi-location and field evaluation under the temperate conditions of Kashmir for its superior growth and photosynthetic performance.

Limitations of the Study: The study was conducted under pot culture conditions, which may not fully reflect field conditions where roots can explore a larger soil volume. The confined root growth in pots may influence plant development and physiological responses. The study did not include yield data, which would strengthen the practical relevance of the findings. The study was conducted at a single location over two years. Future research should include field validation, yield evaluation, multi-location trials, and investigation of the biochemical basis of the observed physiological differences (e.g., Rubisco activity, electron transport rate).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] Abdelkader, M., Elkhawaga, F. A., Suliman, A. A., Puchkov, M., Kuranova, K. N., Mahmoud, M. H., & Abdelkader, M. F. M. (2024). Understanding the regular biological mechanism of susceptibility of tomato plants to low incidences of blossom-end rot. *Horticulturae*, *10*(6), 648. https://doi.org/10.3390/horticulturae10060648

[2] Abduelghader, A. A., Sanders, F. E., & Pilbeam, D. J. (2011). Growth and biomass partitioning in tomato in relation to ratio of nitrogen:Phosphorus supply. *Journal of Plant Nutrition*, *34*(13), 2018-2038. https://doi.org/10.1080/01904167.2011.610488

[3] Albacete, A., Ghanem, M. E., Martínez-Andújar, C., Acosta, M., Sánchez-Bravo, J., Martínez, V., Lutts, S., Dodd, I. C., & Pérez-Alfocea, F. (2008). Hormonal changes in relation to biomass partitioning and shoot growth impairment in salinized tomato (*Solanum lycopersicum* L.) plants. *Journal of Experimental Botany*, *59*(15), 4119-4131. https://doi.org/10.1093/jxb/ern251

[4] Arena, C., Conti, S., Francesca, S., Melchionna, G., Hájek, J., Barták, M., Barone, A., & Rigano, M. M. (2020). Eco-physiological screening of different tomato genotypes in response to high temperatures: A combined field-to-laboratory approach. *Plants*, *9*(4), 508. https://doi.org/10.3390/plants9040508

[5] Arnon, D. I. (1949). Copper enzymes in isolated chloroplasts: Polyphenoloxidase in *Beta vulgaris*. *Plant Physiology*, *24*(1), 1-15. https://doi.org/10.1104/pp.24.1.1

[6] Basavaraj, D., & Naik, P. V. (2024). Genetic variability studies for growth, yield and quality traits in tomato (*Solanum lycopersicum* L.) germplasm under North Eastern Dry Zone of Karnataka, India. *Journal of Advances in Biology & Biotechnology*, *27*(8), 1459-1465. https://doi.org/10.9734/jabb/2024/v27i81289

[7] Ben Sedrine, I., Werghi, S., Hachef, A., et al. (2024). Alleviation of drought stress in tomato by foliar application of seafood waste extract. *Scientific Reports*, *14*, 30572. https://doi.org/10.1038/s41598-024-80798-0

[8] Bhat, H. A., Khan, F. A., Bhat, S. A., Narayan, S., Mir, S. A., Masoodi, K. Z., Malik, A. A., Lone, S. A., Sajad, S., & Jan, U. (2022). Evaluation of tomato (*Solanum lycopersicum*) genotypes for plant growth, fruit yield and quality. *Indian Journal of Agricultural Sciences*, *92*(4), 495-499. https://doi.org/10.56093/ijas.v92i4.123978

[9] Bhattarai, S., Harvey, J. T., Lee, C., Joshi, V., & Leskovar, D. I. (2024). Assessment of physiological and biochemical thermotolerance traits in tomato genotypes. *Scientia Horticulturae*, *324*, 112561. https://doi.org/10.1016/j.scienta.2023.112561

[10] Bristow, S. T., Hernandez-Espinoza, L. H., Bonarota, M.-S., & Barrios-Masias, F. H. (2021). Tomato rootstocks mediate plant-water relations and leaf nutrient profiles of a common scion under suboptimal soil temperatures. *Frontiers in Plant Science*, *11*, 618488. https://doi.org/10.3389/fpls.2020.618488

[11] Dong, H., Li, F., Xuan, X., Ahiakpa, J. K., Tao, J., Zhang, X., Ge, P., Wang, Y., Gai, W., & Zhang, Y. (2025). The genetic basis and improvement of photosynthesis in tomato. *Horticultural Plant Journal*, *11*(1), 69-84. https://doi.org/10.1016/j.hpj.2023.06.007

[12] Flores-Saavedra, M., Villanueva, G., Gramazio, P., Vilanova, S., Mauceri, A., Abenavoli, M. R., Sunseri, F., Prohens, J., & Plazas, M. (2024). Nitrogen use efficiency, growth and physiological parameters in different tomato genotypes under high and low N fertilisation conditions. *Plant Physiology and Biochemistry*, *208*, 108447. https://doi.org/10.1016/j.plaphy.2024.108447

[13] Francesca, S., Vitale, L., Graci, S., Addonizio, M., Barone, A., & Rigano, M. M. (2024). Integrated physiological and genetic data reveal key-traits for heat tolerance in tomato. *Plant Stress*, *13*, 100555. https://doi.org/10.1016/j.stress.2024.100555

[14] Gomez, K. A., & Gomez, A. A. (1984). *Statistical procedures for agricultural research* (2nd ed.). John Wiley & Sons.

[15] Hiscox, J. D., & Israelstam, G. F. (1979). A method for the extraction of chlorophyll from leaf tissue without maceration. *Canadian Journal of Botany*, *57*(12), 1332-1334. https://doi.org/10.1139/b79-163

[16] Ji, Y., Ouzounis, T., Schouten, H. J., Visser, R. G. F., Marcelis, L. F. M., & Heuvelink, E. (2021). Dissecting the genotypic variation of growth responses to far-red radiation in tomato. *Frontiers in Plant Science*, *11*, 614714. https://doi.org/10.3389/fpls.2020.614714

[17] Roohanitaziani, R., de Maagd, R. A., Lammers, M., Molthoff, J., Meijer-Dekens, F., van Kaauwen, M. P. W., Finkers, R., Tikunov, Y., Visser, R. G. F., & Bovy, A. G. (2020). Exploration of a resequenced tomato core collection for phenotypic and genotypic variation in plant growth and fruit quality traits. *Genes*, *11*(11), 1278. https://doi.org/10.3390/genes11111278

[18] Singh, I., Mariko, S., Fukamachi, H., & Suzuki, K. (2005). Effect of heat stress on gas exchange characteristics in tomato. *Indian Journal of Plant Physiology*, *10*(3), 283-286.

[19] Tripodi, P., Figàs, M. R., Leteo, F., Soler, S., Díez, M. J., Campanelli, G., Cardi, T., & Prohens, J. (2022). Genotypic and environmental effects on morpho-physiological and agronomic performances of a tomato diversity panel in relation to nitrogen and water stress under organic farming. *Frontiers in Plant Science*, *13*, 936596. https://doi.org/10.3389/fpls.2022.936596

[20] Wellburn, A. R. (1994). The spectral determination of chlorophylls a and b, as well as total carotenoids, using various solvents with spectrophotometers of different resolution. *Journal of Plant Physiology*, *144*(3), 307-313. https://doi.org/10.1016/S0176-1617(11)81192-2

[21] Zhou, R., Kjær, K. H., Rosenqvist, E., Yu, X., Wu, Z., & Ottosen, C.-O. (2017). Physiological response to heat stress during seedling and anthesis stage in tomato genotypes differing in heat tolerance. *Journal of Agronomy and Crop Science*, *203*(1), 68-80. https://doi.org/10.1111/jac.12166.