

Physiological and Yield Responses of Tomato Cultivars under Off-Season Summer Conditions in Bangladesh

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1 **Title**

2 **Physiological and Yield Responses of Tomato Cultivars**
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4 **Short Title**

5 Off-Season Tomato Performance

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31 **ABSTRACT:** Tomato production in Bangladesh is traditionally confined to the winter season;
32 however, demand and market prices peak during the off-season (March–June), when

cultivation is constrained by high temperatures and erratic rainfall. This study evaluated the morpho-physiological adaptation and yield stability of 20 tomato cultivars to identify heat-tolerant cultivars suitable for off-season cultivation under subtropical summer conditions. High ambient temperatures (peaking at 38.2 °C) combined with heavy precipitation events (up to 73.4 mm) during the reproductive phase imposed severe physiological bottlenecks, resulting in complete yield failure of late-maturing cultivars. Beer Super produced the highest yield (42.6 t ha⁻¹), attributed to its ability to maintain vegetative vigor, including greater plant height (136.88 cm), higher leaf number (44.92), larger leaf area (195.20 cm²), and lower disease incidence (13.75%) and severity (25.08%). Udayan ranked second (40.4 t ha⁻¹) and exhibited significant earliness, flowering at 27.33 days after transplanting. In contrast, Pusa Rubi, Black Tomato, and Pomodoro failed to set fruit, indicating total reproductive failure under summer stress. Pearson correlation analysis revealed that yield was positively governed by fruit length ($r = 0.508$, $p < 0.01$) and negatively influenced by disease incidence ($r = -0.371$, $p < 0.01$). Overall, cultivars exhibiting vigorous vegetative growth, early flowering, and reduced disease pressure maintained superior yield under summer stress. Beer Super and Udayan are therefore identified as promising cultivars for off-season tomato production in Bangladesh, offering farmers an alternative production window and enhancing climate-resilient horticulture.

Keywords: Correlation coefficient, growth, heat-tolerant, high-yielding

1.Introduction

With the rapid rise in global population and the uncertainties brought by climate change, the demand for fruits and vegetables continues to increase worldwide. Tomato (*Lycopersicon esculentum* Mill., $2n = 24$), a member of the family Solanaceae, is among the most widely cultivated and consumed vegetables around the world due to its rich nutritional profile and broad use in culinary practices (Tilesi et al., 2021). Consequently, the need for tomato production has escalated in parallel with population growth (Chaudhary et al., 2019). According to FAOSTAT (2024), global tomato production in 2023 reached an estimated 192 million tons. This marks tomatoes as the world's most produced vegetable, with growth of approximately 25% since 2010. According to BBS (2024), tomato production in Bangladesh was approximately 491487.79 metric tons with a harvested area of about 76876.32 acres for the year 2023-24. In this situation, high-yielding cultivars with climate-resilient quality have substantial roles in agricultural practices and food security.

Tomato originated in the Andean region of South America come to the Indian subcontinent by way of Portuguese explorers during the early 16th century. The English word Tomato comes from the Spanish word 'tomate', derived from the Nahuatl (Aztec language) word 'tomatl' (Mehta, R., 2017). At present, tomato is consumed around the world either as a fresh or as a processed product such as canned tomatoes, sauce, juice, ketchup, and soup. Not only that, tomato is a staple in many diets because of its abundance of vitamin C, essential minerals, and dietary fiber (Vats et al., 2022). It is known for its richness in carotenoids, especially the antioxidants lycopene and β -carotene (Dasgan et al., 2021). Tomatoes contain phytochemicals with anti-oxidative, anti-proliferative, anti-carcinogenic, anti-tumorigenic, anti-inflammatory, anti-mutagenic, and anti-atherogenic properties (Rudrapal, M et al., 2022). These phytochemicals contribute to a range of health benefits, such as the ability to reduce inflammation, fight cancer and cardiovascular disease (CVD), and prevent oxidative stress-related diseases (Laranjeira et al., 2022).

Tomato typically grows at an optimum temperature of 30 ± 2 °C during the day and 20 ± 2 °C at night (Vijaykumar and Beena, 2020). Prolonged high temperature exposure, particularly above 34 °C during the day and 24 °C at night, is reported to cause flower drop and loss in tomato

fruit set (Hazra et al., 2009). Tomato is mainly cultivated as a winter crop in Bangladesh as summer cultivation faces multiple challenges, including erratic rainfall, hailstorms, “kalbaishakhi” (tropical cyclones), temperature fluctuations, and persistent hot and humid conditions. These stresses adversely affect plant physiology, fruit set, and productivity, discouraging farmers from summer tomato production due to higher costs and lower returns.

Nevertheless, off-season tomato production holds immense potential. Consumer demand and market prices for tomatoes are typically higher in the summer months, creating a unique opportunity for growers to achieve substantial profit margins. Heat-tolerant cultivars with stable agronomic performance could not only enhance production but also contribute to ensuring year-round availability, thereby strengthening national food and nutritional security in the face of climate variability.

While extensive research has been conducted on winter tomato production, studies addressing the physiological responses, yield attributes, and adaptability of tomato during the summer season in Bangladesh remain limited. This gap in knowledge hinders the development of improved varieties and the formulation of agronomic strategies tailored to hot and humid environments. To address this challenge, the present study aims to evaluate the performance of 20 tomato cultivars, including indigenous, cultivated, and exotic types, under summer growing conditions. The goal was to narrow down the germplasm to the most promising candidates for future multi-environmental validation. Growth and yield-related traits will be assessed to identify superior genotypes capable of maintaining productivity under stress. The study hypothesizes that the cultivars will show significant variation in vegetative stability when exposed to ambient summer temperatures exceeding 32°C. Cultivars that maintain higher vegetative vigor under fluctuating humidity will show lower disease incidence, higher reproductive success, and higher yield, whereas non-acclimatized, heat-sensitive cultivars will fail to set fruit due to the lack of a constant cooling mechanism, regardless of temporary rain protection. Findings from this study are expected to provide valuable insights for breeding high-yielding, heat-tolerant varieties and to promote sustainable tomato cultivation during the hot and humid summer season in Bangladesh.

2. Materials and methods

2.1 Description of the experimental site

To identify suitable tomato cultivars for the summer growing conditions in the sub-tropical climatic zone characterized by high temperature and high humidity, an experiment was conducted during February - May 2025 at the Horticulture Farm of Bangladesh Agricultural University (BAU) located in Mymensingh (latitude 24 °75" N, longitude 90° 50" E, and an elevation of 18 meters above sea level). The region experiences high temperature and high humidity, heavy precipitation, and relatively long days during the Kharif season (April-September) and scanty rainfall, low temperatures, low humidity, and a short-day period during the Rabi season (October-March). This preliminary evaluation was conducted under a temporary rain-shelter structure. While limited to a single season, the study involved high-frequency monitoring of morpho-physiological traits to establish baseline heat-response patterns. Consequently, the environmental data recorded at the nearby weather yard, Department of Irrigation and Water Management, BAU, Mymensingh, accurately reflect the thermal stress experienced by the cultivars. The summarized decadal meteorological conditions during the crop cycle are presented in Table 1, while high-frequency daily data supporting the results are provided in Table S1. As per UNDP and FAO (1988), the area lies in medium-high land which belongs to the Old Brahmaputra Flood Plain Alluvial Tract under the AEZ-9 (Table 2).

Table 1. Decadal (10-day) average meteorological data during February to May 2025 at the Horticulture Farm, Bangladesh Agricultural University, Mymensingh.

Month	Period (days)	Air Temperature (0C)			Humidity (%)			Rainfall (mm)
		Max.	Min.	Mean	Max.	Min.	Mean	
February	1-10	1-10	26.35	15.14	20.77	98.10	48.70	80.40
	11-20	11-20	28.06	16.27	21.19	97.00	44.80	77.30
	21-28	21-28	29.44	16.80	23.15	96.75	46.38	75.13
March	1-10	1-10	30.43	17.45	23.98	96.20	35.50	70.00
	11-20	11-20	31.67	21.72	26.72	94.10	52.70	75.60
	21-31	21-31	31.57	20.67	26.15	93.91	52.27	75.55
April	1-10	1-10	32.81	23.44	28.14	93.60	59.10	78.60
	11-20	11-20	31.92	22.46	27.21	94.20	60.10	78.40
	21-30	21-30	32.48	23.41	27.96	92.47	62.83	79.58
May	1-10	1-10	34.02	24.08	29.08	93.60	52.00	75.20
	11-20	11-20	31.26	23.61	27.09	93.50	81.80	79.90
	21-31	21-31	32.36	25.95	29.17	94.73	68.91	85.82

Table 2. The morphological properties of the experimental field

Constituents	Characteristics
Location	Horticulture field laboratory, BAU
Soil Series	Sonatola
Soil Tract	Old Alluvium Brahmaputra
Land type	Medium High Land
General soil type	Non-calcareous dark grey floodplain
General soil type	Old Brahmaputra Floodplain (AEZ-9)
Topography	Fairly level
Soil type and colour	Dark grey Terrace Soil
Drainage	Moderate

2.2 Raising of seedlings

The seeds of twenty tomato cultivars were sown through the broadcasting method on 4th February 2025 in a finely prepared seedbed of 3 m x 1 m in size and a depth of 21 cm, with a 50 cm drainage channel between the beds. Before sowing, tomato seeds were treated with Vitavax-200 @ 5 g/kg seeds, and well-decomposed cow dung was mixed with soil at the rate of 5 kg/bed. The seeds germinated within 5 to 6 days after sowing.

2.3 Experimental material

Twenty tomato cultivars with diverse genetic backgrounds collected from the Bangladesh Institute of Nuclear Agriculture (BINA), Mymensingh, and various commercial sources were evaluated in this study. The cultivar names, their assigned identification codes (Le₁–Le₂₀), and their respective sources of collection are detailed in Table 3.

Table 3. List of twenty tomato cultivars used in the study with their identification codes and sources of collection.

Code	Cultivar name	Source
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Le ₁	Binatomato-6	BINA, Mymensingh
Le ₂	Binatomato-7	BINA, Mymensingh
Le ₃	Binatomato-11	BINA, Mymensingh
Le ₄	Binatomato-12	BINA, Mymensingh
Le ₅	Binatomato-13	BINA, Mymensingh
Le ₆	Ratan	Lal Teer Seed Limited, Bangladesh
Le ₇	Raja Super	M/s. SARDAR BROTHERS & Co. West Bengal, India
Le ₈	Beer Super	Joypur Beej Mela, Joypurhat, Bangladesh
Le ₉	Rubi	Lal Teer Seed Limited, Bangladesh
Le ₁₀	Pusa Rubi	Lal Teer Seed Limited, Bangladesh
Le ₁₁	Roma VF	Ispahani Agro Limited, Bangladesh
Le ₁₂	Udayan	Mollika Seed Company, Bangladesh
Le ₁₃	Unnayan	Lal Teer Seed Limited, Bangladesh
Le ₁₄	Jholmol	Mollika Seed Company, Bangladesh
Le ₁₅	Julia	Rain Agro Tech Limited, Bangladesh
Le ₁₆	Deshi Patharkuchi	Debgiri Agro Products Limited, West Bengal, India
Le ₁₇	Chakra	Bharat Nursery Pvt. Ltd. India
Le ₁₈	Black tomato	BINA, Mymensingh
Le ₁₉	Pomodoro	Research & Italian passion, Italy
Le ₂₀	Tomato selection-4	Pahuja Seeds Pvt. Ltd. India

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147 2.4 Experimental design

148 A total of 20 tomato cultivars, including indigenous, commercial, and exotic genotypes, were
149 evaluated in this study. The experiment was laid out in a Randomized Complete Block Design
150 (RCBD) with three replications (Figure 1). Each experimental plot measured 1.0 m × 2.0 m
151 and contained six plants, arranged in two rows with three plants per row. Plant spacing was
152 maintained at 60 cm between rows (leaving 20 cm on each side of the plot edges) and 60 cm
153 between plants (leaving 40 cm at the top and bottom edges) within a row to minimize border
154 effects. Individual plots were separated by 50 cm, and blocks were separated by 1.0 m.

(A) RCBD field layout (3 replication X 20 cultivars)

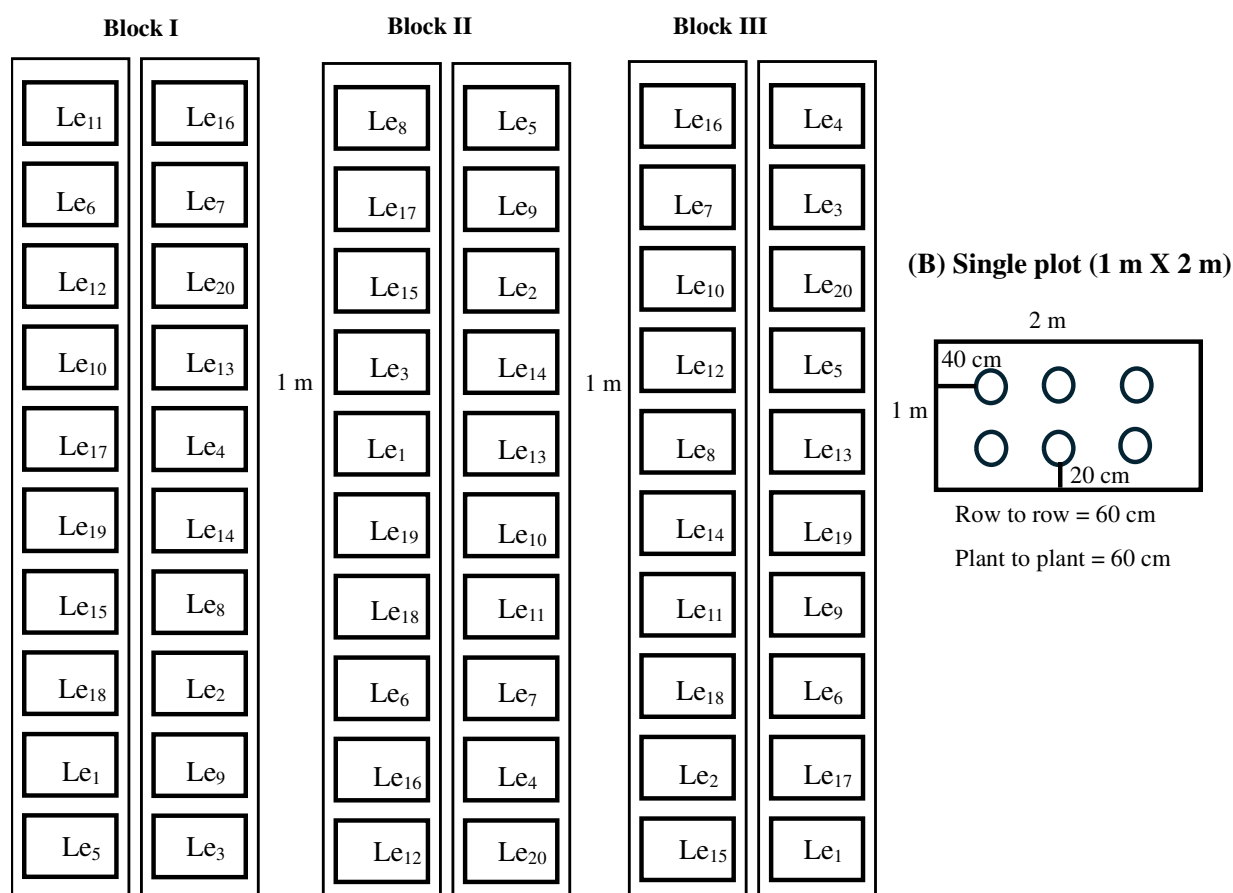


Figure 1. Experimental design and field layout. (A) Randomized Complete Block Design (RCBD) featuring three replications of 20 tomato cultivars; (B) Dimensional schematic of an individual experimental plot (1 m X 2 m).

2.5 Land preparation and transplanting

The land of the experimental field was first opened on February 5, 2025, with the help of a power tiller. The land was ploughed and cross-ploughed to obtain good tilth, followed by leveling. The manures and fertilizers were applied at the rate of Urea 180 kg/ha, TSP 100 kg/ha, MoP 125 kg/ha, Cow dung 10 t/ha (FRG, 2018). The entire amount of well-decomposed cow dung, TSP, half of the MoP, and urea were applied during final land preparation. The remaining amount of urea and MoP were applied in three installments at 15 DAT, 30 DAT and 45 DAT. Healthy and uniform-sized seedlings of 30 days old were collected from the seedbeds and transplanted in the pits of the experimental plots at a spacing of 60 cm X 60 cm in the late afternoon on 6th March, 2025. The seedlings were shaded by pieces of banana leaf sheath for three days to protect the seedlings from direct sunlight.

2.6 Rain shelter preparation

To avoid excessive heat buildup and microclimate distortion, polythene covers were deployed only during rainfall events and were removed during sunny periods (Figure 2), allowing plants to remain exposed to ambient temperature, humidity, and solar radiation. This system ensured rainfall exclusion without altering natural thermal conditions, enabling an accurate assessment of cultivar performance under summer stress. The temporary rain shelter was prepared at 20 DAT in the shape of a boat hull with a height of the sheet of 1.20-1.35 meters on both sides and 1.80-2.10 meters in the middle. Bamboo poles and rope were used to support the structure. In

addition, 50-75 cm is left between the two sheets to facilitate drainage of rainwater from the canopy.



Figure 2. Adaptive rain-shelter system used for summer cultivation: cover removed during sunny periods to maximize light interception (left); shelter with polyethylene cover deployed during precipitation events (right).

2.7 Intercultural operations

A series of intercultural operations like weeding, gap filling, staking, and irrigation were performed according to the requirements throughout the experimental period. The small shoots that grow in the "axil" (the angle between the main stem and a branch or leaf) were removed (desuckering), keeping 1-2 main branches at 30 DAT. Hormone (GA3 @15ppm) was sprayed on the newly blooming flowers in the early morning (6 am- 7 am) to prevent shedding of flowers. A total of 12 yellow sticky traps @2 sticky traps per row) were installed in the experimental field to protect the young seedlings from sucking insects. Imidacloprid @ 2ml/L of water and Spinosad @ 0.5ml/L of water were sprayed alternately at fortnight interval. Dithane M-45 was applied within the first week after transplanting to prevent root rot. To prevent bacterial wilt, the soil was drenched with copper oxychloride @ 35g/10L of water using a sprayer initially. At the severe stage, imidacloprid @ 2ml/ L + copper oxychloride @ 35g/10L was sprayed together. Mancer 75WP (carbendazim 12% + mancozeb 63%) @ 2g/L was sprayed to prevent tomato early blight. Fungicide and insecticide were sprayed alternately at 7-day intervals from a week after transplanting to a week before first harvesting.

2.8 Harvesting and data collection

Fruits were harvested at the green mature stage (Figure 3). Harvesting started on May 02, 2025, and continued up to May 31, 2025. Data were recorded from five random plants in each replication for each 20 tomato cultivars at different days after transplanting (DAT) and average value was calculated to study the following parameters- plant height (cm), total number of leaves per plant, leaf area (cm^2), chlorophyll content per leaf ($\mu\text{mole m}^{-2}$), flavanol content per leaf ($\mu\text{mole m}^{-2}$), anthocyanin content per leaf ($\mu\text{mole m}^{-2}$) and NFI (Nitrogen Flavanol Index), number of flower clusters per plant, number of flowers per plant, number of fruits per plant, disease incidence (%), disease severity (%), fruit length(cm), fruit diameter(cm), individual fruit weight(g), fruit yield per plant(kg), fruit yield per plot(kg) and fruit yield per hectare(t).

The height of the plants was recorded from the ground level to the tip of the longest stem. The total number of leaves per plant was counted from a randomly selected sample. The chlorophyll, flavanol, anthocyanin, and NFI (Nitrogen Flavanol Index) content of individual leaves per plant was taken using MPM-100 Multi Pigment Meter. These parameters were

counted from 20 DAT and continued up to 60 DAT at an interval of 10days. Fully expanded 4th and 5th leaves were used for leaf area measurement using ImageJ software (version 1.54p) at 20, 40 and 60 DAT. The number of flower clusters and flowers per plant were counted from five selected plants of each plot starting from 35 DAT and continued up to 75 DAT at an interval of 10 days. Similarly, the number of fruits per plant was counted at 55, 65, 75 and 85 DAT. The dates of first flowering, fruiting and harvesting were recorded, and the observations were calculated from the date of transplanting. Disease incidence was measured by calculating the percentage of plants infected under each treatment and replication using the following formulae-

Disease incidence (%)= (Number of infected plants)/(Total number of plants assessed) X 100

For disease severity, the plants were critically observed, and percent portion of infected plant area was recorded at 60 DAT. All the infected plants were taken to determine the percent plant area infected and carefully evaluated based on eye estimation.

At harvest, fruit length of five randomly selected fruits was measured from the neck to the bottom of the fruit, and fruit diameter was measured at the middle portion of the fruit by a slide caliper. The weight of five harvested mature fruits was recorded using an electric balance in grams (g). The total number of fruits per plant was multiplied by the individual fruit weight per plant to determine fruit yield per plant and expressed in kilograms (kg). A pan scale balance was used to take the weight of fruits per plot. It was measured by totaling fruit yield from each unit plot separately during the period from first to final harvest in kilograms (kg). Fruit yield per hectare ($t\ ha^{-1}$) was calculated by converting plot yield using standard area conversion procedures.



Figure 3. Representative tomato fruits harvested at the mature green stage under summer cultivation conditions. Fruits obtained from 17 cultivars are presented; Le₁₀, Le₁₈, and Le₁₉ are excluded due to complete reproductive failure as discussed in Section 3.1. Cultivar codes correspond to those defined in Table 3.

2.9 Statistical analysis

Data were subjected to Analysis of Variance (ANOVA) using the RCBD model done in the MSTAT computer program. The mean values for all the parameters were calculated and the analysis of variance for the characters was accomplished by F-test. The significance of difference between pairs of means was tested by the Least Significant Difference (LSD) test at 5 and 1 % levels of probability (Gomez and Gomez, 1984). To establish relationships between morpho-physiological traits and yield, Pearson correlation coefficients were calculated in R (version 4.4.1) with packages "MASS", "writex1", "glmnet", "corrplot", "ggplot2".

3. Result and dissuasion

3.1. Meteorological influence on phenology and reproductive success

The experimental period was characterized by progressively increasing thermal stress and fluctuating precipitation, which significantly influenced the morpho-physiological development of the tomato cultivars. During the initial vegetative phase in early March, mean temperatures (21–24 °C) were conducive to seedling establishment, resulting in uniform vigor across all twenty cultivars. However, a sharp increase in maximum temperatures exceeding the critical threshold of 30 °C by mid-March, peaking at 35.6 °C on March 19th, followed by 20th

March (34.5 °C) triggered a rapid transition to reproductive growth (Table S1). This thermal stimulus induced early flowering in heat-responsive genotypes such as Udayan and Unnayan, which reached anthesis in approximately 27 days. Throughout the critical reproductive phase in April and May, plants were exposed to chronic heat stress, with maximum temperatures consistently exceeding 32 °C and mean temperatures reaching up to 31 °C. High ambient temperatures are known to impair pollen viability and stigma receptivity in tomato. The impact of this thermal stress was exacerbated by heavy precipitation events, notably a 51.6 mm rainfall recorded on April 30th during the peak fruit-setting stage. The coincidence of high temperatures (38.2 °C on May 10th) and subsequent heavy rainfall (41 mm on May 11th followed by 39.4 mm on May 17th) created a high-humidity microclimate under the rain-shelter system. These hydrothermal conditions served as a physiological bottleneck for several genotypes, especially for the late-maturing cultivars like ‘Pusa Rubi,’ ‘Pomodoro,’ and ‘Black Tomato,’ that exhibited complete reproductive failure. This lack of yield is attributed to the synergistic effects of heat-induced flower drop and moisture-stress-induced fruit abortion. Abdul-Baki (1991) also claimed that the yield of tomato varied depending on the level of heat tolerance of the hybrids. Furthermore, the high humidity favored increased disease pressure during the maturation stage in May and June. While ‘Beer Super’ demonstrated relative resilience, Pomodoro and Black Tomato were highly susceptible to fungal pathogens under these conditions, leading to a total loss of productivity. These findings align with Ide et al. (2022), who observed that prolonged waterlogging and high humidity significantly reduce fruit set and fruiting ratios. Our results confirm that under sub-tropical summer conditions, the ability to maintain reproductive stability during peak thermal and precipitation events is the primary determinant of cultivar suitability. Thus, cultivars showed significant variation in vegetative stability when exposed to ambient summer temperatures exceeding 32°C, as hypothesized.

3.2 Effects of cultivars on growth and yield of tomato

Plant height

Statistically significant variation was observed for the effects of twenty tomato cultivars in terms of plant height (Table 4). The highest plant height was recorded from Le₁ (41.94 cm) followed by Le₁₃ (39.24 cm), and Le₈ (80.90 cm) followed by Le₇ (80.63 cm) at 20 and 30 DAT, respectively. The lowest plant height was observed in Le₂₀ (25.09 cm) and Le₁₀ (44.06 cm) at 20 and 30 DAT, respectively. Results revealed that Raja Super (Le₇) recorded the highest plant height, 105.19 cm and 128.32 cm, followed by Beer Super (Le₈), 98.22 cm, 123.71 cm and 136.88 cm, and 139.39 cm at 40, 50 and 60 DAT, respectively. This might be due to the rapid cell division and cell enlargement capacity of Raja Super compared to other cultivars. On the other hand, the lowest plant height 57.56 cm, 66.56 cm, and 77.67 cm was observed from Pusa Rubi (Le₁₀) at 40, 50, and 60 DAT, respectively. An increasing trend was noticed at each DAT. Multiple genes linked to plant height, associated with gibberellin (GA) hormone signaling, influence internode elongation that causes this variation (Liu et al., 2020). Moreover, environmental factors like temperature and rainfall, growing conditions like polytunnel (Phookan et al., 1990), or variation in the planting time are also responsible for variation in plant height among cultivars. Yasmin et al. (2022) found medium temperature (21-25°C) combined with the tidy variety resulted in the longest plant height (105.3 cm) in BARI tomato 3. Knapp et al. (2024) also reported that plant height varied significantly among the tomato cultivars.

Number of leaves

The effect of cultivars with respect to number of leaves per plant was found to be significant at 1% level of significance (Table 4). The maximum and minimum number of leaves per plant

was observed from Le₁₀ (8.45) and Le₁₉ (6.34), respectively at 20 DAT. Deshi pathorkuchi (Le₁₆) recorded the maximum number of leaves per plant: 12.60, 21.22, and 33.56 at 30, 40, and 50 DAT, respectively. On the other hand, the minimum number of leaves per plant 8.11, 12.33, and 19.22 at 30, 40, and 50 DAT, respectively, was observed from Pomodoro (Le₁₉). Whereas, at 60 DAT, the maximum and minimum number of leaves per plant was observed from Le₁ (48.89) and Le₁₉ (23.441), respectively. The leaf number increases faster at the early stage and showed a slower rate at later stage due to rapid cell division in the leaf primordia that increases the number of cells as well as photosynthetic capacity. The extent and rate of this increase in plant height and leaf number depend on the variety's genetics and are further shaped by environmental and management factors (Aurora et al., 2024). Varieties with greater plant height and more leaves often show higher yield potential, as these traits are positively correlated with fruit production and overall plant vigor (Olawuyi et al.,2023).

Table 4. Main effect of cultivars on plant height and numbers of leaves at different days after transplanting (DAT) under summer cultivation conditions.

Cultivars	Plant height (cm) at different DAT					No. of leaves per plant at different DAT				
	20	30	40	50	60	20	30	40	50	60
Le ₁	41.94	76.78	90.36	115.11	129.96	8.22	8.89	13.89	30.33	48.89
Le ₂	38.61	76.17	86.73	98.33	110.49	7.22	9.00	12.67	25.05	34.50
Le ₃	35.42	78.11	92.76	104.44	128.89	6.85	9.11	15.11	23.16	35.00
Le ₄	34.17	76.98	87.90	115.74	134.48	8.00	9.33	18.82	25.78	31.00
Le ₅	26.51	60.37	78.04	97.86	116.82	8.19	9.89	15.22	25.33	34.33
Le ₆	29.48	58.64	65.59	74.52	85.56	7.67	8.56	12.60	23.86	33.67
Le ₇	30.24	80.63	105.19	128.22	139.39	6.78	11.33	20.33	30.56	39.26
Le ₈	37.93	80.90	98.22	123.71	136.88	8.00	10.89	18.67	32.94	44.92
Le ₉	29.66	76.23	84.93	94.22	115.33	8.11	10.11	19.56	23.04	36.00
Le ₁₀	29.51	44.06	57.56	66.56	77.67	8.45	10.39	12.71	20.11	23.13
Le ₁₁	33.18	79.37	86.29	94.11	115.69	8.00	11.27	16.11	27.22	39.74
Le ₁₂	34.81	75.81	83.65	101.11	113.67	7.22	11.22	17.56	25.56	43.11
Le ₁₃	39.24	74.17	83.84	93.66	106.11	7.33	9.11	13.67	22.78	35.83
Le ₁₄	32.26	80.19	90.99	112.88	135.30	8.33	11.17	17.22	26.22	36.25
Le ₁₅	31.25	73.77	86.29	100.22	118.63	8.00	10.33	14.44	24.45	35.17
Le ₁₆	39.27	79.33	95.41	105.49	126.37	7.72	12.60	21.22	33.56	40.60
Le ₁₇	30.11	77.17	87.33	101.56	113.55	7.44	11.00	17.44	30.78	41.44
Le ₁₈	27.17	74.37	83.75	98.67	124.63	7.22	9.89	14.66	28.50	37.69
Le ₁₉	26.70	64.57	68.60	79.44	84.39	6.34	8.11	12.33	19.22	23.44
Le ₂₀	25.09	74.48	83.42	98.31	113.67	6.45	12.44	20.89	26.52	40.28
LSD0.05	5.10	4.85	7.33	6.66	6.46	1.43	2.27	3.10	4.04	4.79
LSD0.01	6.82	6.56	9.91	9.00	8.73	1.94	3.07	4.15	5.47	6.47
Level of significance	**	**	**	**	**	**	**	**	**	**

¹ Cultivar codes (Le₁–Le₂₀) are defined in Table 3.

² ** indicates significance at the 1% level of probability.

Leaf area

The effect of cultivars was statistically significant in terms of individual leaf area per plant (Figure 4). The maximum leaf area of 100.94 cm², 214.48 cm², and 252.41 cm² were observed from tomato selection-4 (Le₂₀) at 20, 40, and 60 DAT, respectively. Whereas the minimum leaf area was recorded from Le₁₀ (35.38 cm²), Le₁₇ (43.12 cm²), and Le₁₈ (67.23 cm²) at 20, 40, and 60 DAT, respectively. At an earlier stage, the leaf area and number increase quickly due to fast cellular proliferation under genetic control to maximize light interception, improving carbon dioxide uptake, which is crucial for the photosynthetic process. The expansion rate declines progressively until leaf growth approaches a maximum size, then expansion halts. Hou et al. (2016) also found variation in leaf area among cultivars. Logistic and Richards models further described the dynamic increase in LAI and plant height over time accurately (Xiao et al., 2022). Whereas Wen et al. (2024) found a correlation between temperature and leaf area.

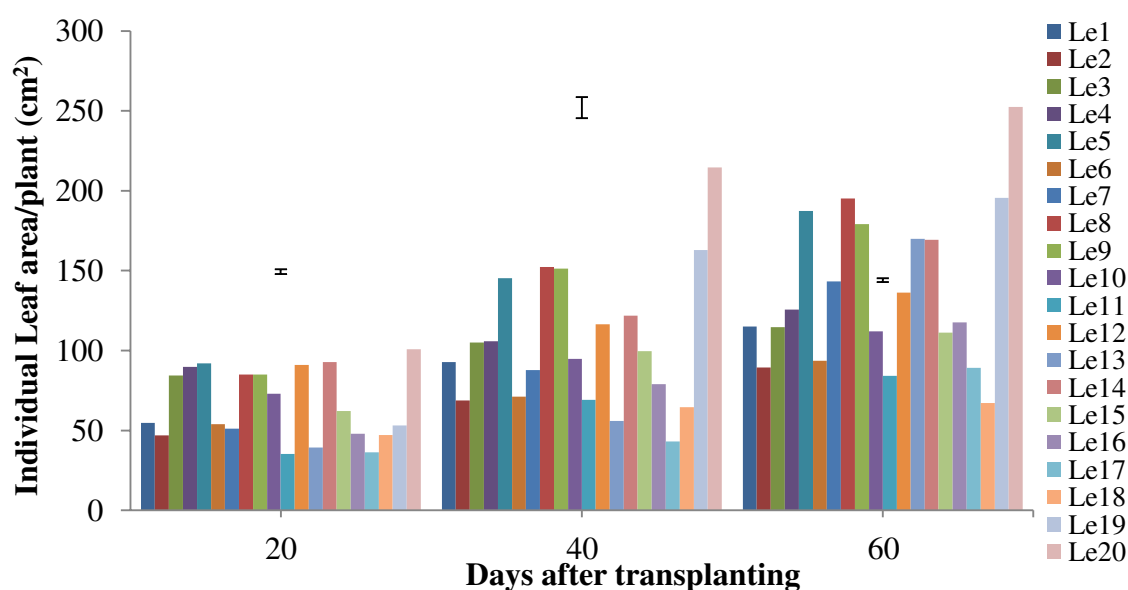


Figure 4. Effects of tomato cultivars on individual leaf area per plant at different days after transplanting (DAT) under summer cultivation conditions. Vertical bar represents the least significant difference (LSD) at the 1% level of probability. Cultivar codes (Le₁–Le₂₀) are defined in Table 3.

Days to first flowering

A significant difference was observed due to the effect of cultivars in the case of days to first flowering (Figure 5). The days to first flowering influence the length of the growing season and yield potential. The shortest duration of flowering (27.33 days) was visible in Le₁₂ (Uadayan) followed by Le₁₃ (Unnayan) (27.67 days) and Le₈ (Beer Super) (29.67 days), while the longest duration of 36.33 days was required for first flowering in Le₁₈ (Black Tomato). This could be due to the higher capacity of Uadayan to supply assimilates to the apex during the sensitive phase before initiation. Mahmuda et al. (2020) also found a wide range (32 to 51 DAT) of days to first flowering among genotypes, depending on the variety and local conditions in summer-grown tomatoes. While, Bae et al. (2024) stated that early planting in the summer (e.g., March or April) can promote earlier flowering.

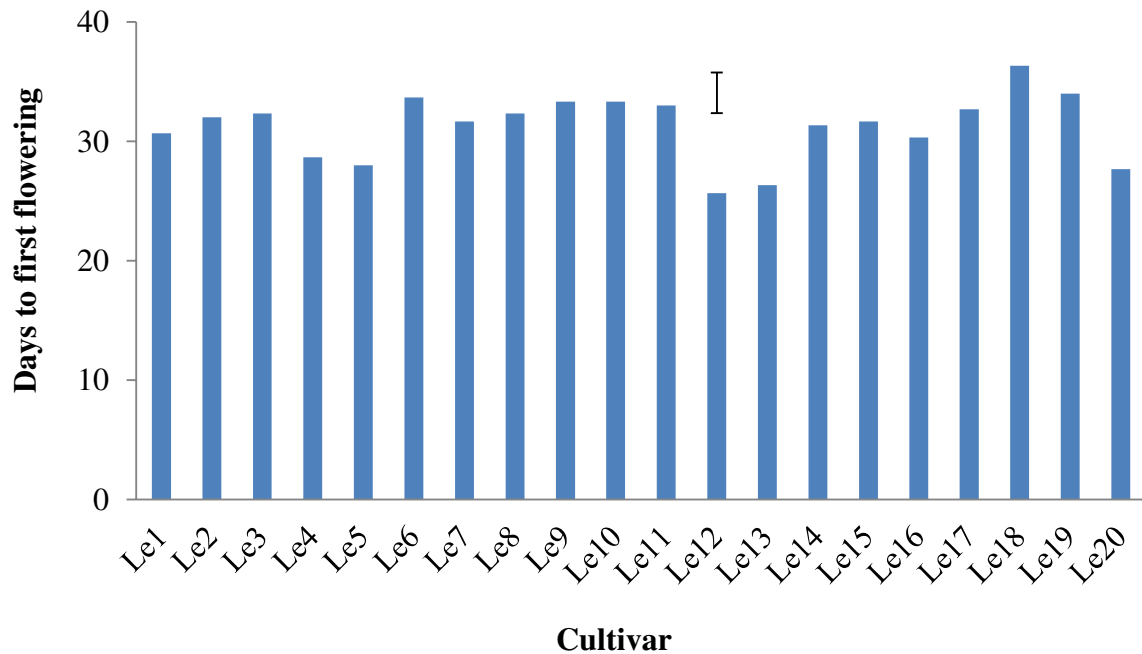


Figure 5. Effects of tomato cultivars on days to first flowering at different days after transplanting (DAT) under summer cultivation conditions. Vertical bar represents the least significant difference (LSD) at the 1% level of probability. Cultivar codes (Le₁–Le₂₀) are defined in Table 3.

Number of flower clusters and flowers per plant

The number of flower clusters and flowers per plant were statistically significant due to the effect of cultivars (Table 5). The highest number of flower clusters per plant (15.00) and (20.89) was recorded in Udayan (Le₁₂) at 45 and 55DAT, respectively. Again, the highest number of flower clusters per plant (21.33) and (15.00) was recorded in Roma V. F (Le₁₁) at 65 and 75 DAT, respectively. While the lowest number of flower clusters per plant (4.44), (5.72), (6.83) and (6.43) was recorded in Pusa Rubi (Le₁₀) at 45, 55, 65 and 75 DAT, respectively. The result showed that the number of flower clusters per plant increased up to 65 DAT and then started decreasing. The number of flowers per plant also followed a similar trend as did the number of flower clusters per plant (Table 5). The maximum number of flowers per plant (21.28) and (35.66) were recorded from Le₈, and the minimum values (3.50) and (4.94) were observed in Le₁₈ at 45 and 55 DAT, respectively. The highest values (34.72) and (19.74) were recorded in Udayan (Le₁₂) and Ratan (Le₆), respectively, at 65 and 75 DAT, while the minimum values (6.74) and (5.50) were observed in Le₁₀ during that time. Parallel to our results, Chawsh et al. (2025) and Rasheed et al. (2023) stated that the number of flowers per plant and per cluster also varied widely among varieties and positively correlated with fruit yield per plant, making them reliable selection criteria for breeding (Ramana et al., 2025; Sharmita et al., 2023).

375 **Table 5.** Main effect of cultivars on number of flower cluster and number of flowers at different
376 days after transplanting (DAT) under summer cultivation conditions.

Cultivars	Number of flower cluster at different DAT					Number of flowers at different DAT				
	35	45	55	65	75	35	45	55	65	75
Le1	4.39	8.60	10.28	10.33	4.83	4.17	7.50	19.22	13.83	8.50
Le2	3.77	6.56	6.89	7.00	5.33	3.60	11.95	17.67	10.67	6.39
Le3	4.56	6.99	9.56	12.89	10.50	4.10	12.28	20.61	17.89	12.17
Le4	4.28	8.50	13.33	20.83	10.60	5.50	16.33	25.72	17.33	7.28
Le5	3.80	5.28	7.77	11.83	6.20	4.06	7.56	15.28	12.49	7.32
Le6	3.61	7.56	10.56	15.55	13.17	6.23	13.05	22.61	15.33	19.74
Le7	4.93	11.83	17.56	12.00	5.43	3.28	12.50	19.81	14.11	10.61
Le8	6.60	13.00	11.83	8.72	6.43	8.06	21.28	35.66	23.65	13.50
Le9	4.60	8.17	13.50	13.44	8.06	3.99	8.49	13.00	20.56	9.85
Le10	3.27	4.44	5.72	6.83	6.43	2.39	3.78	5.14	6.74	5.50
Le11	3.72	7.83	15.22	21.33	15.00	2.94	11.78	22.01	25.33	19.23
Le12	5.10	15.00	20.89	17.72	12.22	7.88	22.67	29.99	34.72	18.89
Le13	4.89	8.78	13.49	9.33	6.09	8.33	13.72	19.61	15.50	13.16
Le14	4.39	8.61	16.39	13.39	10.39	5.50	13.28	25.66	21.06	15.72
Le15	5.83	11.43	15.89	15.17	9.17	8.17	15.11	25.72	19.94	14.83
Le16	7.33	13.94	16.74	12.83	9.17	10.49	20.44	25.62	22.56	10.61
Le17	3.77	9.05	15.72	18.96	12.61	6.07	15.71	21.89	26.77	15.00
Le18	2.93	4.61	6.56	8.32	7.33	0.00	3.50	4.94	6.94	10.94
Le19	3.66	6.39	7.83	10.24	8.32	2.50	5.83	8.50	10.00	7.24
Le20	5.67	16.06	19.57	12.33	9.46	7.15	15.50	23.17	24.61	13.00
LSD0.05	1.23	2.59	2.61	3.25	1.95	1.43	2.80	3.28	3.23	2.55
LSD0.01	1.67	3.47	3.53	4.40	2.64	1.93	3.78	4.43	4.36	3.45
Level of significance	**	**	**	**	**	**	**	**	**	**

377 ¹ Cultivar codes (Le1–Le20) are defined in Table 3.

378 ² ** indicates significance at the 1% level of probability.

379 Leaf pigments

380 All pigments showed statistical significance due to different cultivars for different DAT except
381 flavanol content at 20 DAT (Tables 6 & 7). The maximum chlorophyll content was observed
382 in Le11 (0.85 $\mu\text{mol m}^{-2}$), Le17 (0.72 $\mu\text{mol m}^{-2}$), Le13 (0.76 $\mu\text{mol m}^{-2}$), and Le11 (0.87 $\mu\text{mol m}^{-2}$)
383 at 20, 30, 40, 50, and 60 DAT, respectively. On the other hand, the lowest values were recorded
384 in Le7 and Le19 (0.60 $\mu\text{mol m}^{-2}$), Le19 (0.51 $\mu\text{mol m}^{-2}$), Le10 (0.47 $\mu\text{mol m}^{-2}$), Le10 (0.53 $\mu\text{mol m}^{-2}$),
385 and Le9 (0.48 $\mu\text{mol m}^{-2}$) at 20, 30, 40, 50, and 60 DAT, respectively. The results found a
386 higher chlorophyll content in the leaves initially than in the later stages, ranging from 0.51 to
387 0.87 $\mu\text{mol m}^{-2}$. Tomato leaves typically show an early rise in chlorophyll to maximize
388 photosynthesis, followed by a decline during senescence. Similar to chlorophyll content, other
389 pigments also showed significant variation among the studied cultivars. The maximum flavanol
390 content was observed in Le3 (0.04 $\mu\text{mol m}^{-2}$), Le11 (0.24 $\mu\text{mol m}^{-2}$), Le3 (0.12 $\mu\text{mol m}^{-2}$), Le6
391 (0.10 $\mu\text{mol m}^{-2}$) and Le7 (0.43 $\mu\text{mol m}^{-2}$) at 20, 30, 40, 50 and 60 DAT, respectively. While the
392 lowest value was recorded in Le9 (0.00 $\mu\text{mol m}^{-2}$) at 20 DAT, Le12, Le18 and Le19 (0.05 $\mu\text{mol m}^{-2}$)
393 m^{-2}) at 30 DAT, Le8 (0.02 $\mu\text{mol m}^{-2}$) at 40 DAT, Le12 and Le20 (0.05 $\mu\text{mol m}^{-2}$) at 50 DAT and

Le₁₁, Le₁₂, and Le₁₈ (0.05 $\mu\text{mol m}^{-2}$) at 60 DAT. The flavanol content ranged from 0.00 to 0.43 $\mu\text{mol m}^{-2}$ at different DAT. Opposite to chlorophyll content, flavanol content increases over time. Pesaresi et al. (2014) also found a similar result where flavanols increase more gradually during maturation, providing protective antioxidant roles. The maximum anthocyanin content was observed in Le₁₇ and Le₁₈ (0.54 $\mu\text{mol m}^{-2}$) at 20 DAT, Le₁₈ (0.86 $\mu\text{mol m}^{-2}$) at 30 DAT, Le₁₈ (0.45 $\mu\text{mol m}^{-2}$) at 40 DAT, Le₁ (0.45 $\mu\text{mol m}^{-2}$) at 50 DAT, and Le₁ (0.47 $\mu\text{mol m}^{-2}$) at 60 DAT. On the contrary, the lowest values were recorded in Le₇ (0.29 $\mu\text{mol m}^{-2}$), Le₁₄ (0.40 $\mu\text{mol m}^{-2}$), Le₁₄ (0.20 $\mu\text{mol m}^{-2}$), Le₁₂ (0.23 $\mu\text{mol m}^{-2}$), and Le₁₄ (0.18 $\mu\text{mol m}^{-2}$) at 20, 30, 40, 50, and 60 DAT, respectively. As expected, maximum anthocyanin content (0.86 $\mu\text{mol m}^{-2}$) was recorded from the Black tomato (Le₁₈) (Table 7) and exhibited a range of 0.18 to 0.86 $\mu\text{mol m}^{-2}$ during different DAT. Like chlorophyll, anthocyanin content also rose initially and later showed a decreasing trend. This may be due to variance in environmental stress and different stress response capacity in different tomato cultivars. The maximum NFI (Nitrogen Flavanol Index) was observed in Le₂ (2.36) and Le₁ (2.35) at 20 and 30 DAT, respectively. While the lowest values were recorded in Le₉ (1.40) and Le₁₈ (1.03) at 20 and 30 DAT, respectively. The maximum NFI (3.08), (3.02), and (4.36) was observed in Le₁₄ at 40, 50, and 60 DAT, respectively. Whereas the lowest values were recorded in Le₁₈ (1.13), Le₈ (1.60), and Le₁ (1.40) at 40, 50, and 60 DAT, respectively. Whereas the NFI (Nitrogen Flavanol Index) ranged from 1.13 to 3.08 and decreased over time, as the result disclosed a decline in nitrogen content and a rise in flavanol content. This might be due to a typical stress response where flavanols accumulate to protect the plant from oxidative stress induced by nutrient limitation. The findings of Junker-Frohn et al. (2019) and Stewart et al. (2001) align with our results in the present research work.

Table 6. Main effect of cultivars on chlorophyll and flavanol content at different days after transplanting (DAT) under summer cultivation conditions.

Cultivars	Chlorophyll (micromole per m ²) at different DAT					Flavanol (micromole per m ²) at different DAT				
	20	30	40	50	60	20	30	40	50	60
Le ₁	0.67	0.70	0.61	0.63	0.65	0.02	0.06	0.07	0.09	0.10
Le ₂	0.74	0.64	0.55	0.63	0.54	0.02	0.07	0.09	0.09	0.07
Le ₃	0.67	0.66	0.50	0.67	0.61	0.04	0.09	0.12	0.09	0.09
Le ₄	0.74	0.61	0.61	0.59	0.53	0.03	0.07	0.09	0.09	0.09
Le ₅	0.69	0.61	0.48	0.58	0.57	0.01	0.06	0.07	0.08	0.08
Le ₆	0.78	0.62	0.50	0.68	0.65	0.02	0.06	0.07	0.10	0.06
Le ₇	0.60	0.58	0.62	0.66	0.69	0.02	0.05	0.10	0.08	0.43
Le ₈	0.83	0.70	0.48	0.63	0.52	0.02	0.07	0.02	0.06	0.06
Le ₉	0.68	0.65	0.61	0.59	0.48	0.00	0.06	0.06	0.08	0.07
Le ₁₀	0.64	0.55	0.47	0.53	0.62	0.03	0.07	0.04	0.07	0.13
Le ₁₁	0.85	0.61	0.53	0.63	0.87	0.04	0.24	0.04	0.07	0.05
Le ₁₂	0.80	0.55	0.49	0.58	0.84	0.01	0.05	0.04	0.05	0.05
Le ₁₃	0.66	0.56	0.76	0.59	0.67	0.04	0.06	0.07	0.06	0.08
Le ₁₄	0.71	0.62	0.50	0.75	0.65	0.03	0.06	0.08	0.09	0.07
Le ₁₅	0.78	0.63	0.63	0.68	0.62	0.02	0.07	0.07	0.09	0.09
Le ₁₆	0.79	0.70	0.64	0.64	0.68	0.03	0.07	0.11	0.07	0.09
Le ₁₇	0.75	0.72	0.56	0.65	0.53	0.02	0.06	0.06	0.08	0.09
Le ₁₈	0.81	0.55	0.48	0.70	0.81	0.01	0.06	0.06	0.07	0.05
Le ₁₉	0.60	0.51	0.58	0.70	0.57	0.01	0.05	0.04	0.06	0.07
Le ₂₀	0.73	0.53	0.50	0.54	0.60	0.03	0.05	0.05	0.05	0.08
LSD0.05	0.16	0.14	0.13	0.19	0.37	0.04	0.12	0.05	0.03	0.22

LSD0.01	0.21	0.19	0.18	0.25	0.49	0.05	0.17	0.07	0.04	0.30
Level of significance	**	**	**	**	*	NS	**	**	**	**

¹Cultivar codes (Le₁–Le₂₀) are defined in Table 3.

²** and * indicate significance at the 1% and 5% levels of probability, respectively.

³ NS indicates non-significant differences.

Table 7. Main effect of cultivars on anthocyanin content and NFI (Nitrogen Flavanol Index) at different days after transplanting (DAT) under summer cultivation conditions.

Cultivars	Anthocyanin (micromole per m ²) at different DAT					NFI (micromole per m ²) at different DAT				
	20	30	40	50	60	20	30	40	50	60
Le ₁	0.30	0.61	0.27	0.45	0.47	2.23	2.35	2.24	1.71	1.40
Le ₂	0.32	0.51	0.27	0.29	0.45	2.36	1.95	2.04	1.94	2.19
Le ₃	0.38	0.61	0.29	0.29	0.30	1.85	2.16	1.90	2.38	2.31
Le ₄	0.37	0.44	0.28	0.25	0.29	2.03	2.22	2.21	2.39	1.81
Le ₅	0.44	0.56	0.32	0.35	0.40	1.62	2.01	1.73	1.65	1.65
Le ₆	0.43	0.76	0.41	0.34	0.42	1.87	1.62	1.22	1.74	1.61
Le ₇	0.29	0.53	0.22	0.32	0.35	2.08	1.62	2.87	2.11	2.63
Le ₈	0.45	0.63	0.33	0.41	0.33	1.92	1.62	1.55	1.60	1.62
Le ₉	0.33	0.60	0.29	0.36	0.37	1.40	1.86	2.25	1.72	1.52
Le ₁₀	0.45	0.47	0.41	0.28	0.37	1.46	1.65	1.21	1.96	1.76
Le ₁₁	0.48	0.69	0.41	0.35	0.35	1.84	1.46	1.29	1.98	2.67
Le ₁₂	0.44	0.55	0.35	0.23	0.43	1.89	1.95	1.45	2.60	1.94
Le ₁₃	0.40	0.59	0.27	0.29	0.28	1.74	1.62	2.94	2.08	2.60
Le ₁₄	0.37	0.40	0.20	0.25	0.18	2.06	2.12	3.08	3.02	4.36
Le ₁₅	0.50	0.76	0.38	0.28	0.41	1.59	1.40	1.83	2.55	1.64
Le ₁₆	0.39	0.63	0.25	0.27	0.21	2.04	1.86	2.60	2.68	3.32
Le ₁₇	0.54	0.66	0.33	0.36	0.24	1.44	2.09	1.72	1.86	2.82
Le ₁₈	0.54	0.86	0.45	0.39	0.38	1.71	1.03	1.13	1.94	1.74
Le ₁₉	0.33	0.58	0.25	0.31	0.33	1.89	1.51	2.30	1.74	1.85
Le ₂₀	0.44	0.65	0.43	0.35	0.32	1.65	1.22	1.15	1.67	1.74
LSD0.05	0.19	0.17	0.13	0.16	0.19	0.83	1.16	0.94	0.92	2.13
LSD0.01	0.25	0.23	0.18	0.21	0.26	1.13	1.57	1.27	1.24	2.88
Level of significance	*	**	**	**	**	*	*	**	**	**

¹ Cultivar codes (Le₁–Le₂₀) are defined in Table 3.

² ** and * indicate significance at the 1% and 5% levels of probability, respectively.

Disease incidence and disease severity

Tomato cultivars significantly influenced the disease incidence percentage of the tomato plant at 1% level of significance (Figures 6 & 7). Disease incidence and disease severity were observed at 60 DAT of plant growth stage. The maximum disease incidence (91.67%) and disease severity (63.88%) were attained from cultivar Pomodoro (Le₁₉) and Pusa Rubi (Le₁₀), respectively. The minimum disease incidence (13.75%) and disease severity (25.08%) were recorded from cultivar Beer Super (Le₈). The variation in disease incidence and disease severity might be due to the differences in defense mechanisms among the cultivars, as the survey of Begum & Meah (2013) revealed that Binatomato-2, Binatomato-3, Ratan, and were resistant, and the varieties Pusa Ruby and Roma VF were moderately susceptible to bacterial wilt.

Tomato yellow leaf curl (Hossain et al.,2025) and bacterial wilt (Nowicki et al., 2011) were identified by observing the typical symptoms of these diseases caused by Tomato Yellow Leaf Curl Virus (TYLCV) and *Ralstia solanacearum* bacteria, respectively, in the present study.

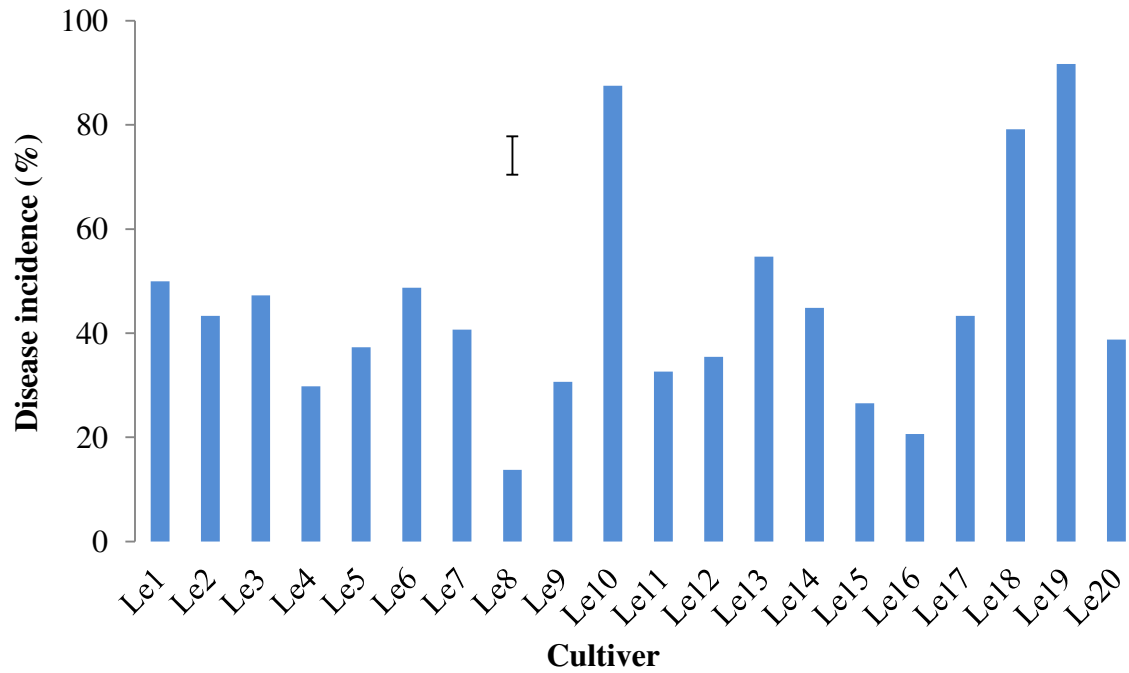


Figure 6. Effects of tomato cultivars on disease incidence at summer grown field condition at 60 days after transplanting (DAT). Vertical bar represents the least significant difference (LSD) at the 1% level of probability. Cultivar codes (Le₁–Le₂₀) are defined in Table 3.

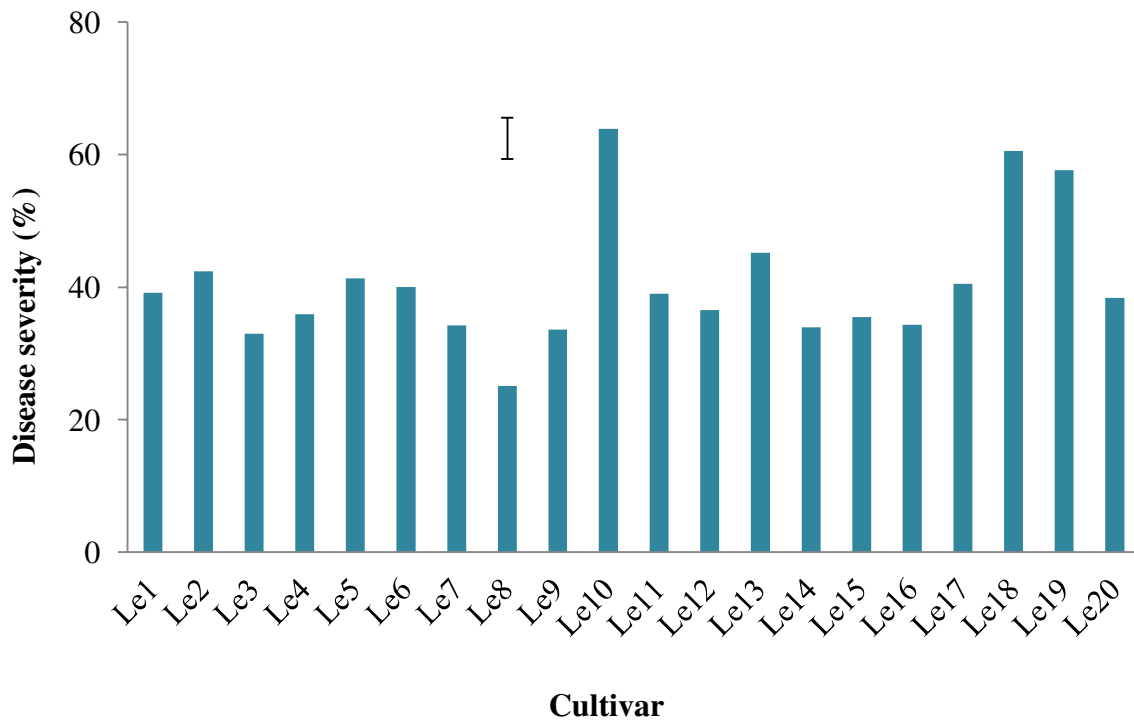


Figure 7. Effects of tomato cultivars on disease severity in summer-grown field conditions at 60 days after transplanting (DAT). Vertical bar represents the least significant difference (LSD) at the 1% level of probability. Cultivar codes (Le₁–Le₂₀) are defined in Table 3.

Days to first fruiting

While all 20 cultivars (Le₁–Le₂₀) were evaluated for physiological and vegetative parameters, only 17 cultivars progressed to fruit maturation. Three cultivars, Pusa Rubi (Le₁₀), Black Tomato (Le₁₈), and Pomodoro (Le₁₉), exhibited complete reproductive failure due to hydrothermal stress and were therefore excluded from the yield analysis. A significant difference was observed for the cultivars in terms of days to first fruiting (Figure 8). The earliest fruiting (43.67 days) was visible in Le₁₂ (Udayan) followed by Le₁₃ (Unnayan) (44.67 days), while the longest duration (57.33 days) was required for first fruiting in Le₆ (Ratan), followed by Le₉ (Rubi) (56.67 days). While the cultivars Pusa Rubi, Black tomato, and Pomodoro did not give any fruits under summer cultivation. The timing of flowering and fruiting is largely determined by genetic differences among varieties. Zhang et al. (2018) claimed that changes in enhancer regions of key genes SP5G can alter flowering time by affecting gene expression regulating daylength adaptation in tomatoes. Traits like plant height, number of branches, and flower clusters are also genetically controlled and influence the timing and abundance of flowering and fruiting (Joshi & Satyal, 2024; Uzair et al., 2025).

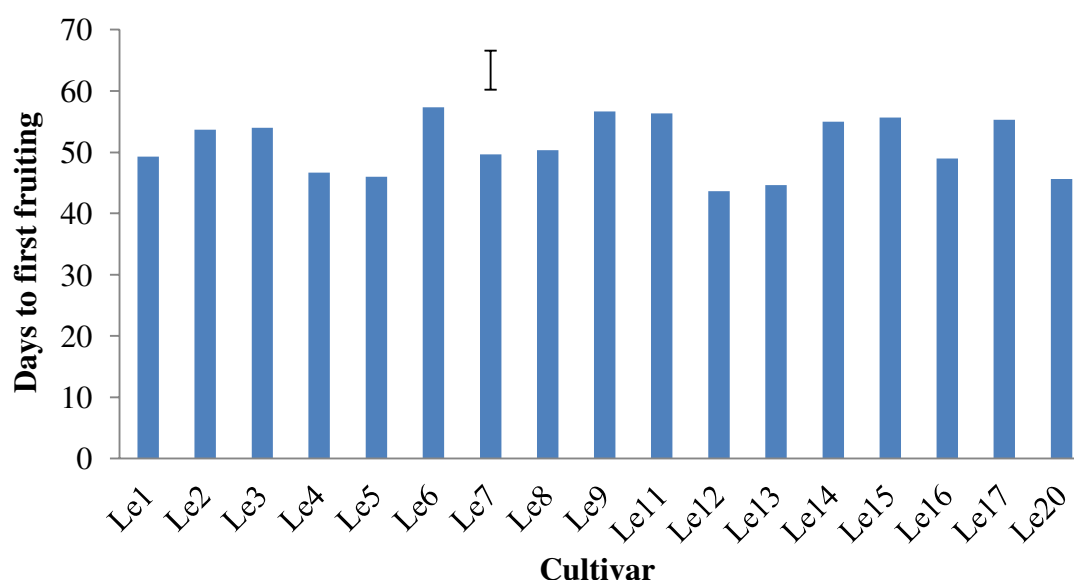


Figure 8. Effects of 17 tomato cultivars on days to first fruiting at different days after transplanting (DAT) under summer cultivation conditions. Vertical bar represents the least significant difference (LSD) at the 1% level of probability. Data are presented for 17 cultivars; Le₁₀, Le₁₈, and Le₁₉ were excluded due to complete reproductive failure, as discussed in Section 3.1. Cultivar codes correspond to those defined in Table 3.

Number of fruits per plant

Different cultivars showed significant variation in the number of fruits per plant under the present trial (Figure 9). At 55 DAT, the maximum number of fruits per plant (15.22) was recorded from the cultivar Beer Super (Le₈), followed by Le₂₀ (13.83). The maximum number of fruits per plant (25.39) was recorded in Le₇ (Raja Super), followed by Le₂₀ (22.11) at 65 DAT. Raja Super (Le₇) and Beer Super (Le₈) mostly produced the maximum number of fruits per plant, giving 29.06 and 34.62 fruits at 75 and 85 DAT, respectively. On the contrary, the minimum number of fruits per plant, Le₁(3.55), Le₆ (6.95), Le₁ (11.27), and Le₂₀ (6.16), were

observed at 55, 65, 75, and 85 DAT, respectively. Usually, varieties with more fruit clusters, more flowers per cluster, and optimal plant architecture tend to produce more fruits per plant (Uzair et al., 2025; Ramana et al., 2025). While factors like plant spacing, nutrition, and stress tolerance can further influence fruit set, varietal potential remains the primary driver (Uzair et al., 2025).

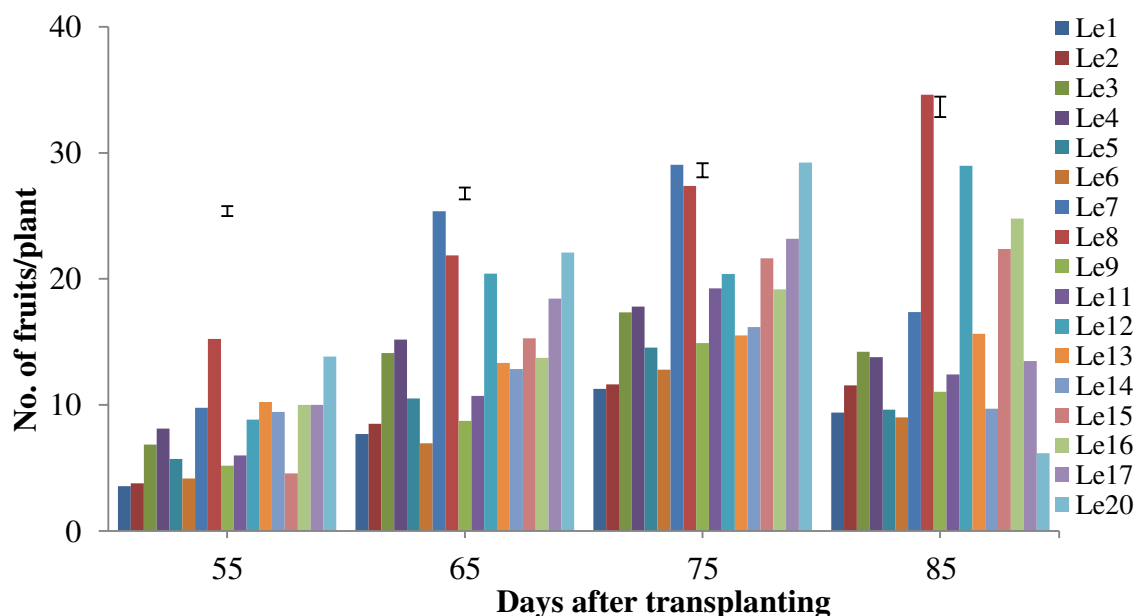


Figure 9. Effects of 17 tomato cultivars on the number of fruits per plant at different days after transplanting (DAT) under summer cultivation conditions. Vertical bars represent the least significant difference (LSD) at the 1% level of probability. Data are presented for 17 cultivars; Le₁₀, Le₁₈, and Le₁₉ were excluded due to complete reproductive failure, as discussed in Section 3.1. Cultivar codes correspond to those defined in Table 3.

Days to first fruit harvest

A significant difference was observed in terms of days to first fruit harvest (Figure 10). The shortest duration of fruit harvest (62.00 days) was observed in Udayan (Le₁₂) followed by Unnayan (Le₁₃) (62.67 days) and Tomato selection-4 (Le₂₀) (64.00), while the longest duration (75.67 days) was required for Le₆(Ratan), followed by Rubi Le₉ (75.00 days) and Roma VF (Le₁₁) (74.67). Parallel to our results, Rahman et al. (1998) observed that fruit maturity is generally faster in summer due to higher temperatures. However, extreme heat can sometimes delay ripening or reduce fruit quality if temperatures exceed optimal levels (above 25–26°C) (Harel et al., 2014). Whereas Naeem et al. (2022) and Nguyen et al. (2023) claimed that genes controlling flowering and ripening play a key role in determining how quickly a variety flowers and matures in summer.

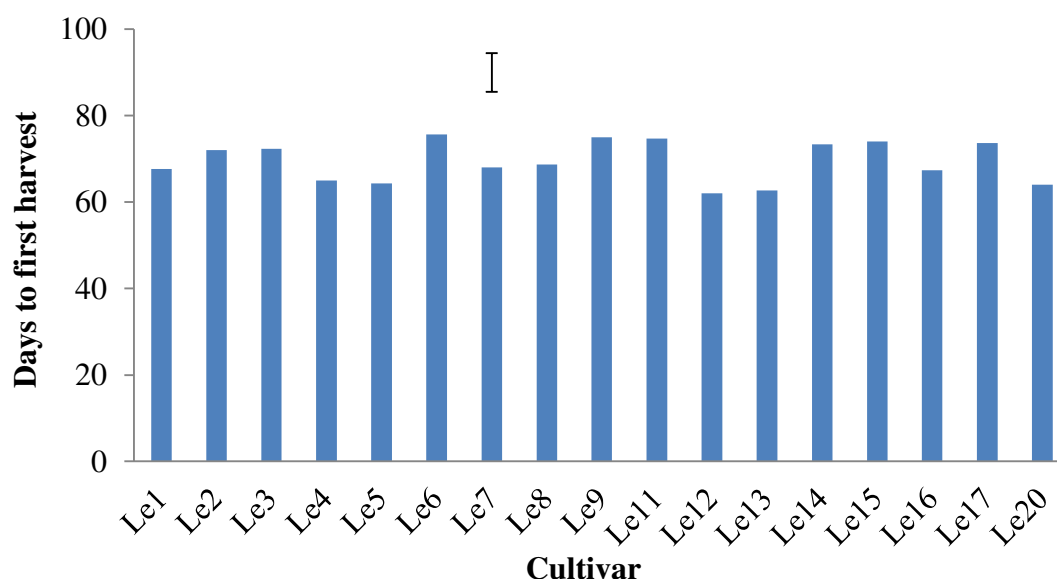


Figure 10. Effects of 17 tomato cultivars on days to first fruit harvest at different days after transplanting (DAT) under summer cultivation conditions. Vertical bars represent the least significant difference (LSD) at the 1% level of probability. Data are presented for 17 cultivars; Le10, Le18, and Le19 were excluded due to complete reproductive failure, as discussed in Section 3.1. Cultivar codes correspond to those defined in Table 3.

Yield and yield-contributing characters

At harvest, the highest fruit length (6.62 cm), fruit diameter (6.56 cm), and weight of individual fruit (110.25 g) were recorded for Le13 (Unnayan), L7 (Raja Super), and Le5 (Binatomato-13), respectively (Table 8). While the lowest fruit length (3.63 cm), fruit diameter (4.52 cm), and weight of individual fruit (35.18 g) were recorded in Le20 (Tomato selection-4). These findings are consistent with Salim et al. (2020), who reported fruit length and diameter ranges of 3.91–6.57 cm and 3.63–8.15 cm, respectively, and with Kouam et al. (2018). Furthermore, Coyago-Cruz et al. (2019) documented fruit weights ranging from 45.6 to 274.9 g in common tomato varieties, which align with our results and those of Flores et al. (2017). In general, the weights of the common varieties, which ranged from 45.6 to 274.9 g (Coyago-Cruz et al., 2019), support our result as well as that of Flores et al. (2017). Again, high temperature causes poor fruit set, flower drop, and smaller fruits (Bae et al., 2024). The highest fruit yield per plant (1.42 kg), fruit yield per plot (8.50 kg) (Table 8), and fruit yield per ha (42.6 t) was recorded in Le8 (Beer Super) (Figure 11). On the other hand, the lowest fruit yield per plant (0.58 kg), fruit yield per plot (3.51 kg), and fruit yield per ha (17.6 kg) were recorded in Le6 (Ratan). Udayan (Le12) (40.4 t), Deshi pathorkuchi (Le16) (39.1 t), and Unnayan (Le13) (38.8 t) also demonstrated commendable yields. Yield per plant and per hectare is strongly influenced by cultivar. These outcomes corroborate the findings of Mehraj et al. (2014), who found maximum yield per plant (667.1 g), yield per plot (6.7 kg), and calculated yield per ha (22.3 t) from Mini Chika during the summer season. Several studies have already been established that high-yielding varieties often combine larger fruit size with a greater number of fruits per plant, but some trade-offs exist; varieties with more fruits may have smaller average fruit size (Joshi & Satyal, 2024). The variation in yield may be due to environmental factors, heat tolerance ability of cultivars, and disorders like blossom-end rot (Ayarna et al., 2021), fungal and bacterial diseases, and waterlogging conditions promoting fungal and bacterial diseases, reducing marketable yield and fruit quality (Engida, 2017). During the summer-rainy season of Bangladesh, high

temperatures and humidity limit tomato adaptation and reduce yield due to increased flower abortion and fruit drop.

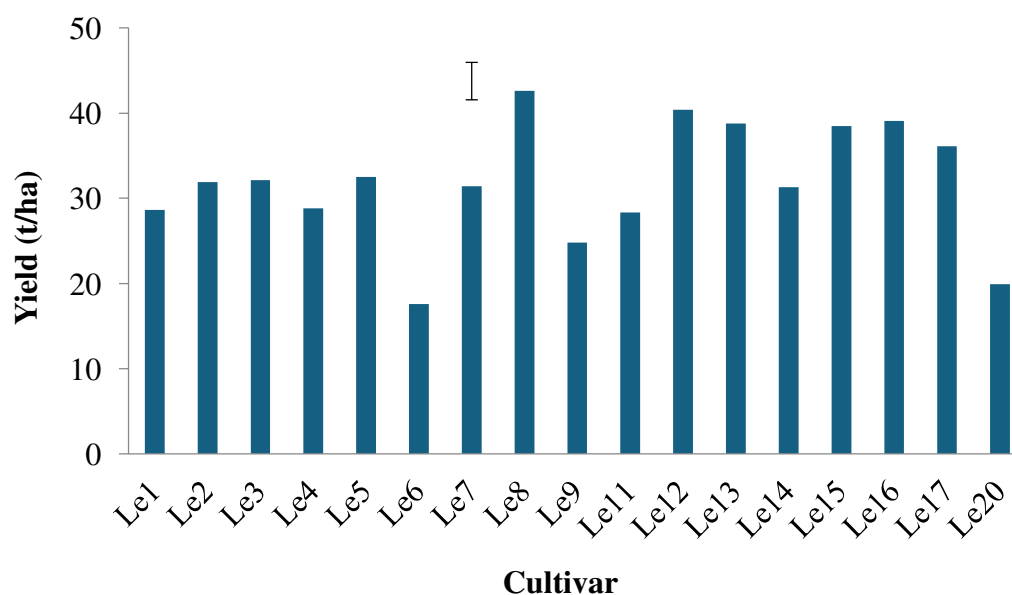
Table 8. Main effect of cultivars on yield and yield contributing characters of tomato under summer cultivation conditions

Cultivars	Fruit length (cm)	Fruit diameter (cm)	Individual fruit weight(g)	Yield per plant (kg)	Yield per plot (kg)
Le1	4.70	5.48	57.25	0.95	5.72
Le2	4.84	5.49	75.36	1.07	6.40
Le3	4.83	5.08	66.72	1.07	6.42
Le4	4.66	5.48	59.01	0.96	5.76
Le5	6.13	5.51	110.25	1.09	6.51
Le6	5.31	5.46	78.41	0.58	3.51
Le7	4.50	6.56	89.70	1.05	6.29
Le8	6.27	5.55	89.62	1.42	8.50
Le9	4.64	5.69	73.01	0.83	4.95
Le11	4.20	5.62	65.58	0.94	5.65
Le12	5.84	4.82	67.97	1.35	8.10
Le13	6.62	4.89	69.03	1.29	7.77
Le14	5.55	4.92	67.48	1.05	6.27
Le15	4.77	5.66	81.59	1.28	7.69
Le16	4.55	5.06	63.55	1.30	7.80
Le17	4.57	6.05	90.14	1.20	7.21
Le20	3.63	4.52	35.18	0.66	3.95
LSD0.05	0.40	0.48	8.38	0.26	1.56
LSD0.01	0.54	0.65	11.28	0.35	2.10
Level of significance	**	**	**	**	**

¹ Data for 17 cultivars are presented; Le₁₀, Le₁₈, and Le₁₉ are excluded due to complete reproductive failure as discussed in Section 3.1.

² Cultivar codes correspond to those defined in Table 3.

³ ** = Significant at 1% level of probability.



541

542 **Figure 11.** Effects of 17 tomato cultivars on yield (t/ha) under summer cultivation conditions.
543 Vertical bars represent the least significant difference (LSD) at the 1% level of probability. Data
544 are presented for 17 cultivars; Le₁₀, Le₁₈, and Le₁₉ were excluded due to complete reproductive
545 failure, as discussed in Section 3.1. Cultivar codes correspond to those defined in Table 3.

546 3.3. Inter-relationship between Morpho-physiological Traits and Yield

547 Pearson correlation analysis was performed on the 17 cultivars that successfully reached
548 reproductive maturity to elucidate the associations between growth parameters, biotic stress,
549 and yield components under summer conditions (Figure 12). Cultivars Le₁₀, Le₁₈, and Le₁₉
550 were excluded from this analysis. The specific relationships between morpho-physiological
551 traits and yield components are presented in Table S2. The analysis revealed that total yield
552 was primarily governed by the synergistic effects of phenological timing and biotic stress
553 resilience. A highly significant negative correlation was observed between disease incidence
554 and yield ($r = -0.371$), confirming that the high-humidity microclimate within the rain-shelter
555 was a primary limiting factor for productivity. In contrast, plant height exhibited a significant
556 positive correlation with yield ($r = 0.368$), suggesting that cultivars capable of maintaining
557 vegetative vigor were better adapted to the thermal transition from spring to summer. The
558 negative associations observed between productivity and phenological markers, specifically
559 days to first fruiting ($r = -0.287$) and days to fruit harvesting ($r = -0.290$), provide statistical
560 evidence for a heat escape mechanism. The results of Naveen et al. (2017) also observed that
561 plant height exhibited a significant correlation (phenotypic and genotypic) and days to first
562 flowering exhibited a significant correlation (phenotypic and genotypic) with fruit yield per
563 hectare. This indicates that early-maturing cultivars, such as ‘Udayan’, completed their
564 reproductive cycles before the onset of extreme temperatures and monsoon precipitation typical
565 of the late summer season. Regarding yield components, fruit length showed a strong positive
566 correlation with total yield ($r = 0.508$), identifying fruit elongation as a critical morphological
567 marker for productivity in heat-tolerant genotypes. While individual fruit weight typically
568 serves as a primary driver of yield in temperate conditions, it exhibited a strong association (r
569 $= 0.365$) in this study. This shift in yield architecture suggests that under subtropical summer
570 stress, yield stability is determined more by reproductive success and biomass of individual
571 fruits than by flower number ($r = 0.283$) and fruit number ($r = 0.206$). This disparity suggests
572 that under hydrothermal stress, yield stability was determined more by the plant's ability to
573 maximize the expansion of existing sinks (fruit size) than by the initiation of new reproductive
574 organs. The weak correlation with flower number likely indicates a breakdown in reproductive
575 efficiency; while cultivars initiated numerous flowers, high ambient heat and fluctuating
576 humidity probably induced pollen sterility or style exertion, leading to significant flower
577 abscission. Consequently, high flower production did not consistently translate into higher
578 productivity, making individual fruit mass a more reliable predictor of yield than reproductive
579 quantity in this specific stress environment. As hypothesized, vegetative vigor emerged as the
580 primary determinant of yield stability. Parallel to our results, Zannat et al. (2023) also found
581 highly significant positive correlations of fruit length, fruit diameter, number of fruits/plants,
582 and fruit weight with fruit yield/plant as well as fruit yield/hectare. Sanam et al. (2022), in their
583 study of tomato plant growth with bacterial inoculant, claimed that the number of fruits per
584 plant has the strongest relationship with tomato development and yield characteristics.

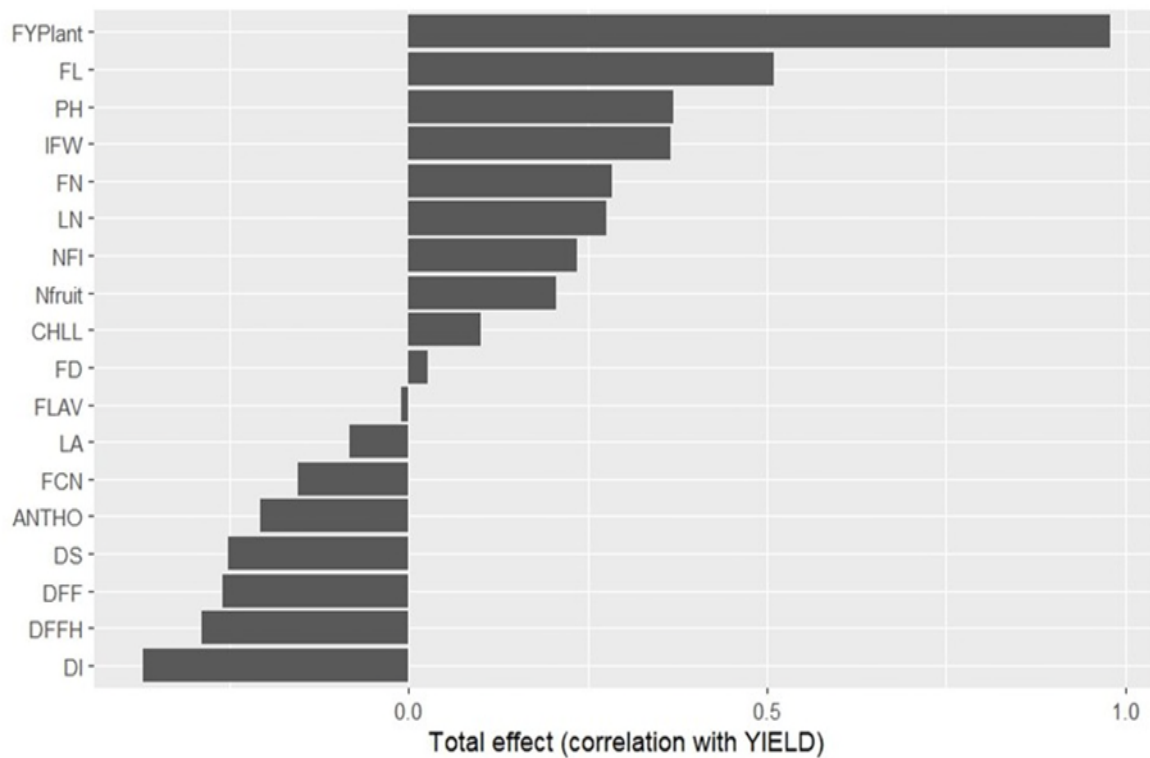


Figure 12. Correlation of morpho-physiological, phenological, and yield-contributing traits with yield under summer cultivation conditions. Abbreviations: PH, plant height (cm); LN, number of leaves per plant; LA, individual leaf area (cm²); CHLL, chlorophyll content per leaf (μmol m⁻²); FLAV, flavanol content per leaf (μmol m⁻²); ANTHO, anthocyanin content per leaf (μmol m⁻²); NFI, nitrogen flavanol index; DFF, days to first flowering; FCN, number of flower clusters per plant; FN, number of flowers per plant; DFFruit, days to first fruiting; Nfruit, number of fruits per plant; DI, disease incidence (%); DS, disease severity (%); FL, fruit length (cm); FD, fruit diameter (cm); IFW, individual fruit weight (g); FYPlant, yield per plant (kg); YIELD, yield per hectare (t ha⁻¹). Days to first fruit harvest (DFFH) and yield per plot (FYPlot) were excluded from the figure because they showed near-identical or perfect correlations with YIELD ($r = 1$), as presented in Supplementary Table S2.

4. Conclusion

This study provides robust evidence validating the hypothesis that tomato cultivars exhibit significant variation in vegetative stability and reproductive success under high-temperature stress (exceeding 32°C). As hypothesized, vegetative vigor emerged as a primary prerequisite for yield stability. This is evidenced by the superior growth of cultivars like Raja Super, Beer Super, and Binatomato-6, which contributed to the high productivity seen in Beer Super. Pearson correlation analysis confirmed this link, showing a significant positive association between plant height and total yield. The study further confirms the predicted link between vigor and disease resistance. Cultivars that maintained vegetative stability showed higher resilience. In contrast, sensitive genotypes like Pusa Rubi, Black Tomato, and Pomodoro succumbed to the synergistic pressure of heat and humidity, resulting in complete reproductive failure as predicted. The strong negative correlation between disease incidence and yield highlights biotic stress as a major limiting factor in this environment. Our findings highlight two distinct strategies for successful summer production: vegetative resilience (as seen in Beer Super) and heat escape through earliness (exhibited by Udayan and Unnayan), statistically supported by the negative relationship between yield and days to first fruit harvesting, confirming that maturity timing is a critical survival trait. For future breeding and commercial off-season production, selecting early-maturing cultivars with robust vegetative Vigor and a

high capacity for photo-assimilate accumulation, exemplified by Beer Super and Udayan, is recommended to mitigate the combined impacts of hydrothermal stress.

Authors contribution

All listed authors have significantly contributed to the work both intellectually and directly, and have given their approval for its publication.

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Conflict of interest

The authors did this research and wrote the article, and there is no conflict of interest with other people.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. (Supporting Information)

Table S1: This table provides a comprehensive daily record of climatological variables including maximum, minimum, and mean air temperatures, precipitation, and relative humidity. These data document specific hydrothermal stress events such as thermal peaks reaching 38.2°C and significant precipitation events influencing cultivar phenology and limiting reproductive success in sensitive cultivars.

Table S2: This table elucidates the associations between vegetative vigor, reproductive success, and final productivity. Specifically, it highlights significant positive correlations between vegetative stability and reproductive parameters and total yield. Conversely, a strong negative association was observed between yield and both phenological timing, such as days to first flowering and harvesting, and biotic stress indicators like disease incidence.

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