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RESEARCH ARTICLES

Growth, Physiological, and Yield Responses of 'Micro-Tom' and Commercial Tomato Varieties Under High Temperature Conditions

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Abstract

Tomato, a nutrient-rich horticultural crop, is widely cultivated and consumed worldwide, with the 'Micro-Tom' cultivar commonly used as a model plant for its compact size and rapid life cycle. In tropical regions, rising temperatures caused by climate change intensify heat stress, which disrupts pollen viability and reduces fruit set, thereby limiting tomato productivity. This study aimed to evaluate the growth, physiology, and production responses of 'Micro-Tom' and three commercial tomato varieties 'Bareto' F1, 'Gustavi' F1, 'Tymoti' F1) under high-temperature (HT) conditions. The experiment was conducted from March to November 2023 at the Leuwikopo Experimental Field, IPB Bogor, using a randomized complete block design with two factors (temperature and variety) and three replicates. For the HT treatment, plants were placed in a UV-protected plastic house, resulting in a minimum temperature of 18.7 °C and a maximum temperature of 46.2 °C. In contrast, the standard temperature (ST) treatment had a minimum temperature of 17 °C and a maximum temperature of 40.2 °C. The treatments lasted approximately three months, from transplanting to harvest. The standard temperature (ST) treatment outperformed the high-temperature (HT) treatment across all measured parameters, including plant height, leaf number, flower number, chlorophyll content, glucose and fructose levels, and fruit production. Among the varieties, 'Bareto' F1 exhibited superior performance across most parameters. Limitations of this study include its implementation in a controlled field setting over a single season. These findings highlight the need for further investigation into heat-tolerant genotypes and the physiological mechanisms that enhance tomato resilience under climate-induced stress.

Keywords: abiotic stress, chlorophyll, climate change, glucose-fructose, pollen sterility

Introduction

The tomato (*Solanum lycopersicum* L.) is a significant horticultural crop within the Solanaceae family worldwide. Tomatoes are a primary nutritional source, providing vitamins A, B, and C, as well as calcium, potassium, magnesium, sodium, and iron. They are also rich in antioxidants, including phenolics, flavonoids, lycopene, and ascorbic acid (Anas et al., 2022; Mubarok et al., 2023a). The 'Micro-Tom' (*Solanum lycopersicum* cv. 'Micro-Tom') is a model tomato plant characterized by its small size and short life cycle. The traits of this 'Micro-Tom' cultivar make it a valuable source of genetic diversity in research aimed at improving tomato quality (Wahyudi et al., 2021). The small-fruited 'Micro-Tom' cultivar is a result of a cross between the 'Florida Basket' and 'Ohio 4013-3'

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cultivars. Its phenotypic characteristics, based on its lineage, include mutations in central recessive genes dwarf (d) and miniature (mnt), as well as a mutation in the SELF-PRUNING (SP) gene, which causes its determinate phenotype (Watanabe et al., 2007). 'Micro-Tom' has two mutant types, iaa9-3 and iaa9-5, which are characterized by strong parthenocarpy. ‘Micro-Tom’ is a mutant due to its mutation in the specific gene IAA9 from the auxin/IAA (indole-3-acetic acid) gene family. This gene plays a role in suppressing the endogenous auxin signal transcription pathway (Mubarok et al., 2020; Ningrum et al., 2020).

Global tomato consumption reaches 180 million tons annually (Rajametov et al., 2021). In the future, climate change will likely be one of the primary concerns for tomato production. Climate change increases air and soil temperatures, significantly affecting the productivity of tomato plants and other temperature-sensitive crops (Silva et al., 2017). Daytime temperatures exceeding 26 °C and nighttime temperatures exceeding 20 °C significantly reduce tomato yields due to pollen infertility, flower drop, reduced fruit set, and disruptions in the photosynthesis process (Qi et al., 2013).

Several factors, including genetics, nutrition, cultivation methods, and environmental factors such as temperature, influence tomato production. Temperature is a crucial environmental factor for the growth and development of tomato plants. Heat stress is an external factor that often challenges tomato cultivation. Generally, heat stress occurs when temperatures are 10-15 °C above the optimal temperature for cultivation. For tomato growth, the optimal temperature is 26 °C, and heat stress occurs when air temperatures exceed 32 °C (Pham et al., 2020).

Heat stress is one of the primary abiotic stresses in tropical countries, with impacts that can limit plant growth and development and affect production. Failure in pollen development and increased pollen sterility are significant issues in tomato production under heat stress, leading to low fruit set (Ezura et al., 2019). The Intergovernmental Panel on Climate Change reported in 2014 that the average global temperature had increased by 0.3 °C due to global warming and is predicted to rise by 3 °C by 2,100.

Another research shows that exposure to temperatures above 35 °C, particularly when sustained around 38 ± 2 °C for 20 days during the flowering to fruit maturation stage (50-70 days after sowing), can significantly impair tomato development, including pollen viability, fruit set, and photosynthetic efficiency (Rahmat et al., 2023). Parthenocarpy tomato genotypes, such as iaa9-3 and iaa9-5, which can set fruit without fertilization, offer a promising solution to mitigate reduced fruit formation under heat stress, which commonly causes pollen sterility (Mubarok et al., 2024). Several popular commercial tomato varieties widely cultivated in Indonesia, including 'Bareto' F1, 'Tymoti' F1 and 'Gustavi' F1, are known for their high productivity (Evidayanti et al., 2022; Sakya et al., 2020; Wulandhari et al., 2024). However, studies examining the heat tolerance of these superior varieties remain limited. Therefore, in this study, we evaluated the responses of three commercial tomato varieties ('Bareto' F1, 'Tymoti' F1, and 'Gustavi' F1) and one cultivar ('Micro-Tom') to high-temperature stress with respect to growth, physiology, and yield.

Materials and Methods

The experiment was conducted from March to November 2023 under the screen house at the Leuwikopo Experimental Station, Department of Agronomy and Horticulture, IPB, Dramaga, Bogor, Indonesia (6°33′51.99″ S, 106°43′29.14″ E, 250 m above sea level). Physiological and post-harvest observations were conducted in the Integrated Laboratory Seed Center, Department of Agronomy and Horticulture, IPB.

The experiment employed a completely randomized block design with two factors and three replications. The first factor was temperature condition, consisting of two levels: standard temperature (ST) and high temperature (HT). The 4 m x 4 m screen house is designed for high-temperature treatment and is divided

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into two parts: standard temperature (ST) and high temperature (HT). The high-temperature part features UV plastic installed to retain heat. The second factor was the tomato varieties, consisting of four levels: 'Bareto' F1, 'Gustavi' F1, 'Tymoti' F1, and 'Micro-Tom'. These commercial varieties were selected for their diverse growth characteristics and altitudinal adaptation: 'Bareto', 'Tymoti', and 'Gustavi' are commercial F1 hybrids commonly cultivated across different altitude zones, while 'Micro-Tom' is a well-known dwarf model cultivar used extensively in physiological and genetic studies. As climate change increases the frequency of heat waves, it is crucial to understand cultivar-specific tolerance mechanisms to ensure sustainable tomato production under elevated temperatures.

Experimental Procedures

The plant materials used were seeds from three commercial tomato varieties ('Bareto' F1, 'Gustavi' F1, and 'Tymoti' F1), while the 'Micro-Tom' seeds were obtained from the University of Tsukuba, Japan. These seeds germinated for two weeks in seed trays before being transplanted into polybags. The growing medium consists of a mixture of soil and rice husk charcoal in a 1:1 ratio. The seeds are sown at a rate of 1 seed per tray hole at a depth of 1 cm. Seedlings are transplanted 14 days after sowing (DAS) with the criteria of being taller than 2 cm, having four perfect leaves, an upright stem, and being disease-free. The seedlings are transplanted into 15-cm-diameter polybags using the same medium used during sowing. Subsequently, the plant material was placed in a screen house, and half of it was fitted with UV-resistant plastic to retain heat. Plants were irrigated daily with 120 ml of water per plant. Fertilization was performed weekly via fertigation using NPK Growmore 20-20-20 (1 g/L) in the growing media. Pest control was managed using two insecticides: Decis 25 EC (active ingredient: deltamethrin) at 1 ml/L and Curacron 500 EC (active ingredient: profenofos) at 1 ml/L. The pests that attacked were mealybugs from the Pseudococcidae family.

General Condition Measurement

The temperature and relative humidity inside the screen house were measured using an Elitech Data Logger RC-4HC and a GSP-6 digital thermometer for a 14-week period of high-temperature application.

Plant Growth and Production Measurements

Vegetative growth was measured weekly from 0 to 5 weeks, i.e., at the maximum vegetative stage. Plant height, leaf number, and canopy diameter were measured weekly. Generative growth measurements include flowering time, the number of flowers, and fruit production, which involves counting fruits and measuring fruit weight.

Physiological Measurements

The leaf chlorophyll content was quantified using the Warren method (2008) at 6, 10, and 14 weeks. A 0.56 cm^2 leaf was homogenized using a mortar with 2 ml of absolute methanol. The solution was then transferred to a 2 ml microtube and centrifuged at 16940 relative centrifugal force (RCF) for 2 min. The supernatant solution was transferred to a new microtube and then washed again with 1 ml of fresh methanol before centrifugation. The remaining supernatant was transferred to the microtube from the previous supernatant. Subsequently, 200 µl of the supernatant was transferred to a 96-well flat-bottom polystyrene plate. The absorbance value was then measured using a Multiskan Sky Microplate Spectrophotometer at wavelengths of 652 nm and 665 nm.

The glucose and fructose content in the leaves was measured at 6, 10, and 14 weeks following the method by Lanoue et al. (2019). A total of 0.56 cm^2 of the sample was transferred to a 2 ml microtube, then boiled in 1 ml of 80% ethanol in a water bath until the ethanol had evaporated; this process was repeated twice. The samples were then dried at 50 °C for 3 hr. The ethanol-soluble fraction was then mixed with a solution of distilled water and 99% chloroform

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(1000 µl: 500 µl, v/v) and centrifuged at 2200 × g for 3 min. Subsequently, the supernatant was analyzed using the D-Fructose/D-Glucose Assay Kit (Megazyme K-FRGLQR). The absorbance of the solution at 340 nm was measured using the Multiskan Sky Microplate Spectrophotometer.

The fruit quality testing included measuring the TSS (total soluble solids, expressed as % Brix) and TAT (total titratable acidity, expressed as % acidity) values using the ATAGO PAL-BX/ACID1 (Pocket Brix-Acidity Meter Master Kit). Additionally, the glucose-fructose content in the fruit was tested using the D-Fructose/D-Glucose Assay Kit K-FRGLQR (Megazyme), and the organic acid testing, specifically malic acid, was conducted using the L-Malic Acid Assay Kit K-LMALQR (Megazyme).

Data Analysis

The data were analyzed using analysis of variance at a 5% significance level. Variables showing significant effects were further tested using Duncan's multiple range test (DMRT) at a 5% significance level. Data processing was conducted using The SAS System for Windows 9.0.

Results and Discussion

Temperature and Relative Humidity

Based on the temperature and relative humidity recordings during the 14-week application period, the average daily temperature in the high-temperature (HT) environment was 29.14 °C, with a minimum of 18.7 °C and a maximum of 46.2 °C (Table 1). The average relative humidity (RH) was 52.98%. In the standard temperature (ST) environment, the average daily temperature was 27.17 °C, with a minimum temperature of 17.9 °C and a maximum temperature of 39.9 °C. The average relative humidity was 77.31%. The difference in peak daytime temperatures between the High Temperature (HT) and Standard temperature (ST) environments over the 14-week application period averaged 6.47 °C. Global climate change leads to rising temperatures, necessitating efforts to address this in crop production, including experiments under high-temperature conditions to assess plant tolerance. High-temperature conditions can alter morphology, physiology, and biochemistry, leading to reduced photosynthetic activity and plant growth and productivity (Nievola et al., 2017).

Plant Growth and Production Measurement

The research results indicate that the plant growth parameters, specifically plant height at 3-5 weeks under the standard temperature (ST) treatment for all varieties, namely 'Bareto' (B), 'Gustavi' (G), 'Tymoti' (T), and 'Micro-Tom' (M), were significantly higher compared to the High Temperature (HT) treatment (Figure 1). The tallest plants were observed under the B-NT treatment during the 3-5 WAA period, although they were not significantly different from those under the G-ST treatment. This trend also applies to the leaf number per plant parameter (Figure 2) and the plant canopy diameter (Figure 3). The vegetative growth of plants under stress can be observed through changes in plant phenotype. The parameters described earlier reflect the phenotypic condition of the plants under stress. Canopy diameter is one of the plant growth variables that can indicate a response to stress conditions. Heat stress significantly affects plant growth, as indicated by reduced vegetative development, resulting in smaller plant size, such as shorter plant height compared to conditions with normal temperatures (Mubarok et al., 2023b).

Table 2 shows the data on flowering time, number of flowers, number of fruits per tree, and fruit weight per fruit. The 'Micro-Tom' initiated flowering significantly earlier than other commercial tomato varieties. However, there were no differences in flowering time between NT and HT treatments in each variety. The flowering time of the 'Micro-Tom' cultivar was 19–23 days after transplanting, followed by the 'Tymoti' F1 variety at 49–50 days after transplanting, then the 'Bareto' F1 and 'Gustavi' F1 varieties at 54–56 days after transplanting.

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Table 1

Temperatures and Relative Humidity of the Standard and High Temperature Environments

Week	Standard temperature (ST) (°C)	High temperature (HT) (°C)	Peak standard temperature (°C)	Peak high temperature (°C)	Temperature differences (°C)	Relative humidity at the standard temperature (%)	Relative humidity at the high temperature (%)
1	27.40	28.46	36.50	42.30	5.80	74.89	42.64
2	27.16	29.10	36.90	43.40	6.50	77.17	44.92
3	26.49	28.53	37.50	43.70	6.20	73.54	49.43
4	26.99	29.03	37.40	44.10	6.70	77.53	53.10
5	26.78	28.82	37.80	44.60	6.80	83.11	47.33
6	26.80	28.78	37.80	44.70	6.90	78.19	48.30
7	26.84	28.74	38.70	44.90	6.20	78.20	51.56
8	27.04	29.11	38.60	45.00	6.40	80.25	44.23
9	26.97	29.02	38.70	45.10	6.40	73.15	57.43
10	27.44	29.23	39.10	45.50	6.40	75.39	68.69
11	27.94	30.06	38.80	45.10	6.30	77.56	76.10
12	27.79	29.83	39.10	45.50	6.40	74.92	55.63
13	27.35	29.57	38.90	46.20	7.30	79.99	52.16
14	27.42	29.62	39.90	46.20	6.30	78.46	50.18
Average	27.17	29.14	38.26	44.74	6.47	77.31	52.98

Notes. Temperatures and relative humidity (RH) are the average over 24 hr. Temperature differences refer to the differences between the average high and the standard temperature.

The number of flowers produced between the standard (ST) and high temperature (HT) treatments did not differ significantly (Table 2). Similarly, comparisons among the varieties showed no significant differences. The ‘Micro-Tom’-Normal Temperature (M-NT) treatment yielded the highest number of flowers. However, most of the flowers failed to set fruit under both standard- and high-temperature treatments. This was hypothetical due to the high maximum temperatures during reproductive growth in the NT treatment, as shown in Table 1, with peak midday temperatures exceeding 35 °C. The ‘Bareto’ F1 variety also failed to set fruit at high temperatures, likely because it is a mid-altitude variety; when planted in low-altitude areas with higher temperatures, it tends to produce no fruit. Environmental temperatures above 35 °C in tomato cultivation can damage plant growth and development, including seed germination, vegetative and reproductive growth, fruit formation, and photosynthetic activity (Rahmat et al., 2023). Yang et al. (2019) reported that fruit set was reduced under short periods of high temperature during the flowering phenophase in Rabbit Eye blueberry due to impairment of pollen tube growth following pollen germination and ovule degeneration.

On the other hand, 'Tymoti' F1 variety produced a higher number of fruits under the standard temperature (ST) treatment compared to the high temperature (HT) treatment, which indicates that 'Tymoti' F1 variety is slightly sensitive to heat stress. In contrast, 'Gustavi' F1 variety appeared to be more tolerant to heat stress than all other varieties, as shown by the data in Table 2, which indicates that there were no significant differences in the number of fruits between 'Gustavi'-standard temperature and ‘Gustavi’-high temperature.

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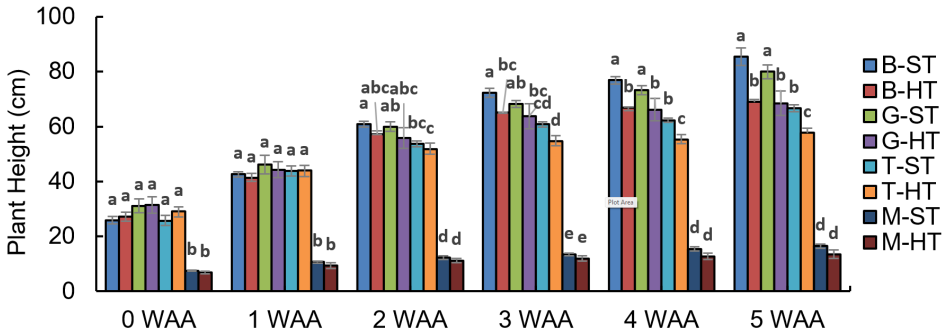
Figure 1

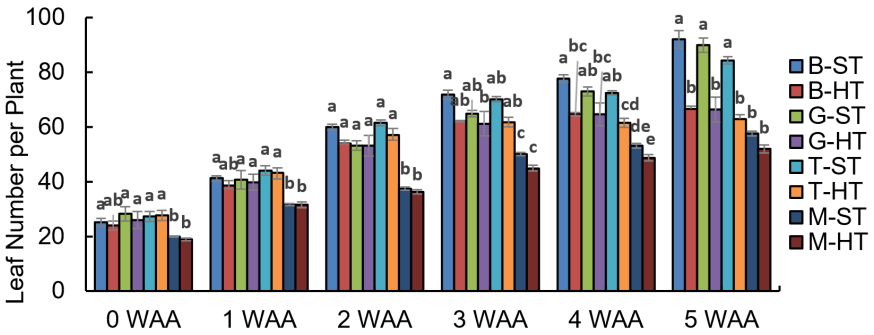
The Height of the Tomato Plant Under High-Temperature Treatment for 5 Weeks of Application



Notes. Values followed by the same letter within the same week are not significantly different according to DMRT at the 5% level. B = 'Bareto', G = 'Gustavi', T = 'Tymoti', M = 'Micro-Tom', ST = standard temperature, HT = high temperature.

Figure 2

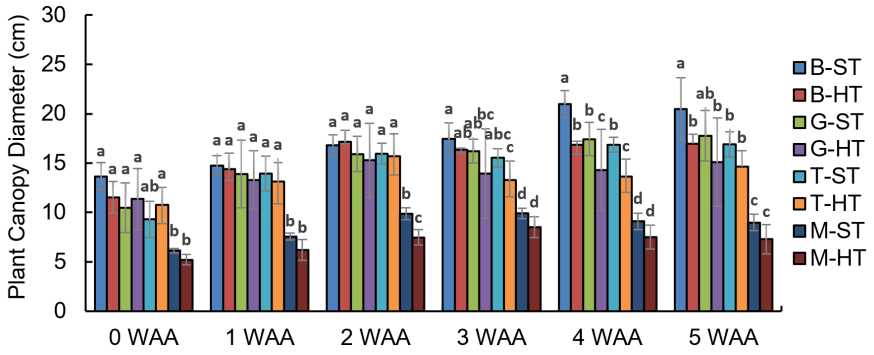
Tomato Leaf Number Under High-Temperature Treatment for 5 Weeks of Application



Notes. Values followed by the same letter within the same week are not significantly different according to DMRT at the 5% level. B = 'Bareto', G = 'Gustavi', T = 'Tymoti', M = 'Micro-Tom', ST = standard temperature, HT = high temperature.

Figure 3

Average of Plant Canopy Diameter Under High-Temperature Treatment for 5 Weeks of Application



Notes. Values followed by the same letter are not significantly different at the 5% level according to the DMRT. B = 'Bareto', G = 'Gustavi', T = 'Tymoti', M = 'Micro-Tom', ST = standard temperature, HT = high temperature.

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Table 2

Reproductive Growth and Tomato Production in the Standard and High Temperature Environments

Treatments	Flowering time (DAT)	Number of flowers	Number of fruits	Fruit weight (g)
'Bareto'-ST	54.11 ± 2.06 ab	4.56 ± 0.29 a	4.58 ± 1.65 a	15.49 ± 5.19 a
'Bareto'-HT	54.67 ± 2.33 ab	4.00 ± 0.51 a	0.00 ± 0.00 c	00.00 ± 0.00 b
'Gustavi'-ST	56.56 ± 3.27 a	4.67 ± 0.19 a	4.42 ± 0.46 a	15.71 ± 2.72 a
'Gustavi'-HT	56.67 ± 0.44 a	5.44 ± 0.78 a	4.94 ± 0.47 a	14.04 ± 0.42 a
'Tymoti'-ST	50.11 ± 0.48 bc	4.44 ± 0.87 a	5.22 ± 0.11 a	15.07 ± 4.17 a
'Tymoti'-HT	49.17 ± 1.17 c	6.89 ± 1.66 a	2.67 ± 0.33 b	09.96 ± 3.22 a
'Micro-Tom'-ST	19.50 ± 0.50 d	7.11 ± 1.97 a	1.00 ± 0.33 c	00.00 ± 0.00 b
'Micro-Tom'-HT	23.33 ± 0.33 d	5.44 ± 0.56 a	0.00 ± 0.00 c	00.00 ± 0.00 b

Notes. Values followed by the same letter within the same column are not significantly different according to DMRT at the 5% level. DAT: days after transplanting, ST: standard temperature, HT: high temperature.

Heat stress is a major abiotic stressor in tropical regions that can limit plant growth and development and affect crop production. Failure of pollen development and increased pollen sterility are significant issues in tomato production under heat stress, resulting in reduced fruit set (Ezura et al., 2019). Tomato productivity is strongly influenced by heat stress. Heat stress-induced abortion of the male gametophyte reduces fruit set (Alsamir et al., 2021). Kumar et al. (2022) stated that exposure to extremely high temperatures can limit plants' ability to produce fruit due to disruption of the pollination process. The increase in flower numbers under heat stress, as reported by Park et al. (2016), results from high temperatures that can trigger flower growth as a plant adaptation to maintain its generation. The number of lateral shoots influences the number of flowers produced under both normal conditions and heat stress; a decrease in lateral shoots due to high temperatures also reduces the number of flowers. High-temperature stress can significantly reduce tomato yield by decreasing fruit set and altering flower morphology and physiology, thereby altering metabolite production under stress conditions, including carbohydrates, polyamines, and proline (Masouleh & Sassine, 2020).

Leaf Chlorophyll Content

The chlorophyll a content (Figure 4a) and chlorophyll b content (Figure 4b) in the high-temperature (HT) and standard-temperature (ST) treatments did not differ significantly. However, differences were observed among the varieties at 2 and 10 weeks after application (WAA). The chlorophyll a and b contents in the 'Micro-Tom'-ST and 'Micro-Tom'-HT treatments were the highest compared to 'Bareto'-HT and 'Tymoti'-HT treatments, but not significantly different from other treatments at 2 WAA. The highest chlorophyll a content was observed at 6 WAA in the 'Tymoti'-ST treatment, which was significantly different from the 'Tymoti'-HT treatment but not from the others. The highest chlorophyll a and b content at 10 WAA was found in the 'Tymoti'-ST treatment, which was significantly different from 'Bareto'-ST and 'Bareto'-HT treatments, but not significantly different from other treatments.

The total chlorophyll content tends to be lower under high-temperature conditions than under normal conditions. Under stress, plants produce ROS (Reactive Oxygen Species) due to excess energy absorbed in the photosynthetic apparatus, thereby reducing the number of absorbed pigments (Herbinger et al., 2002; Purnama et al., 2018). High temperatures can also inhibit chlorophyll synthesis, resulting in

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reduced chlorophyll content in leaves. High-temperature stress is sensitive to chlorophyll synthesis, so that chlorophyll damage can indicate high-temperature stress (Hu et al., 2020).

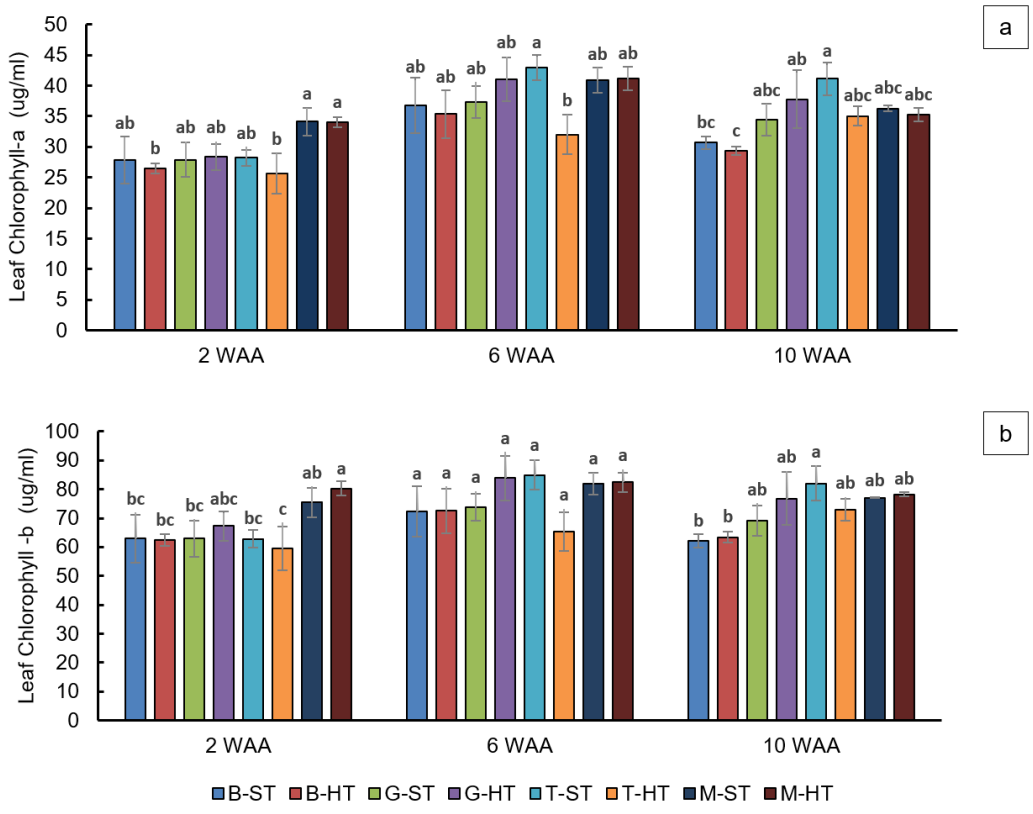
Leaf Glucose and Fructose

The leaf glucose content from 2 WAA to 6 WAA (Figure 5a) showed no difference. An increase was observed at 10 WAA, with significant differences among the varieties. The highest glucose content was observed at 10 weeks in the 'Tymoti'-ST treatment, which was significantly higher than the 'Bareto'-ST and 'Bareto'-HT treatments but not significantly different from the 'Tymoti'-HT and other treatments. Although fructose content fluctuated at the beginning of the observation, the leaf fructose content (Figure 5b) remained stable from 2 WAA to 10 WAA, showing no significant differences among the temperature conditions and tomato varieties.

Chen et al. (2007) reported that one of the fundamental strategies for plant survival under heat stress is the accumulation of proline, sugars, and polyols. Environmental changes can also significantly alter the phenolic and flavonoid content of tomatoes (Ilahy et al., 2016). Zhou et al. (2017) found that the soluble sugar content increased in the leaves of heat-tolerant tomato plants compared to those of sensitive plants during the flowering and blooming stages. This is primarily because sensitive plants are unable to regulate carbohydrate synthesis under heat stress.

Figure 4

Leaf Chlorophyll a (a) and Chlorophyll b (b)



Notes. Values followed by the same letter within the same week are not significantly different according to DMRT at the 5% level. B = 'Bareto', G = 'Gustavi', T = 'Tymoti', M = 'Micro-Tom', ST = standard temperature, HT = high temperature.

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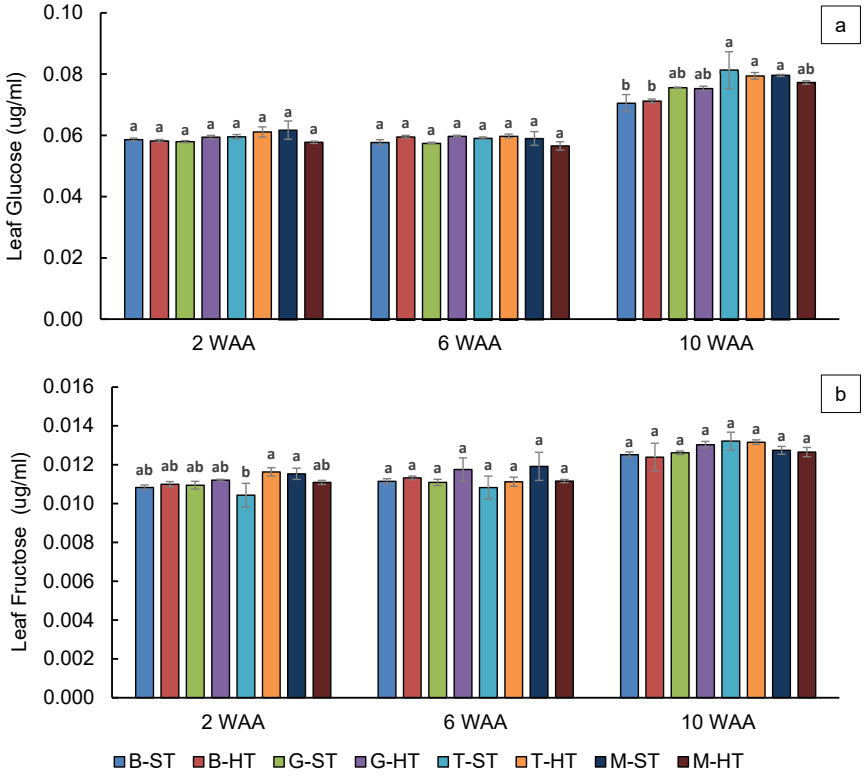
Figure 5

Leaf Glucose (a) and Fructose Content (b)



Notes. Values followed by the same letter within the same week are not significantly different according to DMRT at the 5% level. B = 'Bareto', G = 'Gustavi', T = 'Tymoti', M = 'Micro-Tom', ST = standard temperature, HT = high temperature.

Fruit Quality Analysis (TSS, TTA, Glucose-Fructose, and Malic Acid)

The total soluble solids (TSS), total titratable acidity (TTA), and malic acid content in the fruit showed no significant differences under various temperature conditions and tomato varieties. Still, there was a significant difference among treatments for glucose and fructose content (Table 3). However, fluctuations occurred between the HT and ST treatments, suggesting that glucose content was higher in the HT treatment than in the ST treatment. Conversely, the fructose content tended to be higher in the ST treatment than in the HT treatment.

Lokesha et al. (2019) reported that most tolerant tomato genotypes increase sugar accumulation in their fruits. Alsamir et al. (2021) stated that increasing sugar content aims to improve the cell's osmotic potential, thereby protecting its components from damage. On the other hand, research by Zheng et al. (2023) demonstrated that nitrogen fertilizer can help tomato plants cope with heat stress by improving sugar metabolism, specifically sucrose, glucose, and fructose. The tolerant response of tomato to heat stress, characterized by a decrease in sucrose, is accompanied by increases in glucose and fructose. This suggests that sucrose degradation predominates over its synthesis as a strategy for tomato resistance to heat stress. However, in this research, the increase was observed only in glucose content, while fructose levels decreased. It might be because the fructose was transported or converted to another form of antioxidant or secondary metabolites related to the synthesis of erythrose-4-P (Rosa et al., 2009).

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Table 3

Glucose-fructose Content, Total Soluble Solids, Titratable Acidity, and Malic Acid Content in Tomato Fruits

Treatments	Fruit glucose (µg/ml)	Fruit fructose (µg/ml)	Total soluble solids (% Brix)	Total titratable acidity (% Acidity)	Fruit malic acid (mg/ml)
'Bareto'-ST	1.54 ± 0.02 c	1.27 ± 0.08 a	5.17 ± 0.12 a	2.40 ± 0.18 a	0.57 ± 0.17 a
'Bareto'-HT	-	-	-	-	-
'Gustavi'-ST	1.63 ± 0.11 c	1.21 ± 0.01 a	5.19 ± 0.06 a	2.43 ± 0.26 a	0.51 ± 0.02 a
'Gustavi'-HT	2.03 ± 0.17 ab	0.92 ± 0.10 bc	5.82 ± 0.20 a	2.72 ± 0.08 a	0.54 ± 0.03 a
'Tymoti'-ST	1.73 ± 0.06 bc	1.12 ± 0.08 ab	5.42 ± 0.14 a	2.42 ± 0.17 a	0.55 ± 0.05 a
'Tymoti'-HT	2.13 ± 0.16 a	0.76 ± 0.20 c	5.60 ± 0.50 a	2.21 ± 0.26 a	0.37 ± 0.08 a
'Micro-Tom'-ST	-	-	-	-	-
'Micro-Tom'-HT	-	-	-	-	-

Note. Values followed by the same letter within the same column are not significantly different at the 5% level according to the DMRT. ST: standard temperature, HT: high temperature.

Conclusions

This study demonstrated that high-temperature stress adversely affected vegetative growth and productivity in tomatoes compared with normal-temperature conditions. A peak temperature difference of 6.47 °C was sufficient to induce heat stress, resulting in reduced plant height, leaf number, and canopy diameter across all varieties. However, even in the standard temperature treatment, the maximum temperature exceeded 35 °C, which may have contributed to fruit set failure in the 'Micro-Tom' cultivar and 'Bareto' F1 variety. Flower production remained relatively unaffected, but fruit set dropped sharply under heat in most varieties, except for the 'Gustavi' F1 variety, indicating it is more tolerant to heat stress. Chlorophyll a and b levels were unaffected by temperature but varied among the different varieties. Fruit quality traits, including total soluble solids (TSS), total titratable acidity (TTA), and malic acid, showed no significant changes. However, a slight increase in glucose and a decrease in fructose under heat stress suggested some metabolic response. In summary, most of the tested tomato varieties exhibited sensitivity to heat stress, as indicated by declines in both vegetative growth and fruit yield. The 'Gustavi' F1 variety showed promising tolerance to heat stress. Nevertheless, further research is necessary to confirm its performance under varied environmental conditions. These findings highlight the importance of identifying and developing heat-tolerant tomato varieties to ensure crop resilience in the face of ongoing climate change.

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