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Promoting fruit set and increasing yield of cherry tomatoes with gibberellin

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Abstract

Background and Objective: High summer temperatures can reduce cherry tomato yield. Gibberellic acid (GA_3) has been shown to improve fruit sets in some plants. This study aimed to compare the effects of GA_3 on fruit set and yield in two cherry tomato cultivars, 'Sweet Boy' and 'Sweet Girl,' grown in a greenhouse during the summer months with high temperatures.

Methodology: A 2 × 5 factorial experiment in a randomized complete block design (RCBD) was conducted to assess the responses of the two cherry tomato cultivars to five different GA_3 concentrations (0, 50, 100, 150, and 200 mg/L) (n = 15). Flower inflorescences were sprayed with GA_3 at 0, 2, and 4 days after anthesis (DAA). Data were analyzed to determine means and standard deviations. Statistical analysis was performed using ANOVA, followed by Duncan's Multiple Range Test at a 95% confidence level.

Main Results: Applying 50 and 100 mg/L GA_3 increased the fruit set of 'Sweet Boy' cherry tomato from 72.9 ± 5.9% to 90.6 ± 2.3% and 93.6 ± 2.0%, respectively ($P < 0.05$), but GA_3 did not affect 'Sweet Girl' cherry tomato fruit set, which remained consistently around 91.7 ± 1.9%. The highest yield was obtained by applying 100 mg/L of GA_3 to the 'Sweet Boy' cherry tomato, reaching an average of 291.2 ± 113.1 g/cluster. In contrast, the yield of the 'Sweet Girl' cherry tomato remained relatively consistent across different GA_3 concentrations at 187.6 ± 17.6 g/cluster.

Conclusions: The application of GA_3 can enhance fruit set and yield in greenhouse-grown cherry tomatoes during the summer when applied at appropriate concentrations. Cultivar responses to GA_3 may differ. In this study, spraying 100 mg/L GA_3 on 0, 2, and 4 DAA significantly increased fruit set and yield in the 'Sweet Boy' cherry tomato.

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INTRODUCTION

The increasing health consciousness among Thai consumers has led to a surge in demand for fresh and nutritious produce, including cherry tomatoes (*Solanum lycopersicum* var. *cerasiforme*). In the past 5 years, tomato cultivation areas in Thailand remained relatively stable at approximately 39,130 rai or 62.6 square kilometers. Approximately 40% of this land was dedicated to growing table tomatoes, primarily consumed fresh (Office of Agricultural Economics, 2024). While table tomatoes can be produced year-round, production typically peaks during the cooler months of December to March and significantly declines during the summer and rainy seasons. According to the Office of Agricultural Economics (2024), table tomato production in 2023 peaked in January at over 8,500 tons and reached its lowest point in July at 600 tons. The seasonal fluctuations in tomato production are mainly influenced by environmental factors, including high temperatures and limited water availability during the summer, as well as pest and disease outbreaks during the rainy season. Cherry tomato production often takes place in greenhouses to protect against pests and diseases, although these controlled environments can pose challenges related to high temperatures.

Sitathani (2002) suggested optimal temperature ranges for tomato growth and development at different stages. Seed germination thrives at 28–30°C, while vegetative development prefers temperatures ranging between 20–30°C. For fruit sets, the optimal day and night temperatures are 25–30°C and 15–20°C, respectively. Sitathani (2012) also indicated that the cherry tomato fruit set requires higher temperatures, with optimal daytime and overnight conditions of 28–30°C and 17–20°C, respectively. Nevertheless, greenhouses in tropical regions often experience temperatures significantly higher than these optimal levels. A previous study by Chomphu *et al*. (2023) showed that the average daily temperature in a net-covered greenhouse located at Suranaree University of Technology, Nakhon Ratchasima, Thailand, reached 37.4°C during April–May 2022, with a peak of 39.7°C. These results are consistent with other studies; for example, Ajwang and Tantau (2005) reported that under hot and humid tropical climate conditions, the air temperature inside a greenhouse can rise to 38°C. Sato *et al*. (2002) and Zhou *et al*. (2017) indicated that high air temperatures cause tomato flowers and fruits to shed as well as abnormal fruit development. As global warming intensifies, extremely high temperatures within greenhouses are projected to occur more frequently and with greater severity, especially in tropical regions. This intensified thermal stress poses a significant threat to plant growth, development, and overall yield, necessitating adaptive strategies to mitigate the adverse effects of climate change on greenhouse cultivation.

Plant growth regulators (PGRs) have demonstrated potential in ameliorating high-temperature stress and enhancing fruit retention in greenhouse tomato production.

Studies have indicated that specific PGRs, such as auxins and gibberellins, can effectively reduce premature flower and fruit drops induced by elevated temperatures. Gibberellins have been shown to positively influence various aspects of fruit set, fruit growth, and overall yield. By enhancing pollen tube growth and germination, it promotes fertilization, especially under suboptimal conditions. Additionally, GA_3 regulates hormonal balance, stimulating floral organ development and fruit initiation. Furthermore, it stimulates cell division and elongation, leading to increased fruit size. By enhancing nutrient uptake and transport to the developing fruit, GA_3 promotes faster growth and development of developing fruit. Moreover, it can delay fruit senescence, extending the harvest period and improving overall yield (Quinet *et al*., 2019).

Luitel *et al*. (2015) demonstrated that applying GA_3 at 10–15 mg/L, 2,4-D at 5–10 mg/L, or a combination of both PGRs at 50 days after transplanting significantly increased fruit set in 'Adoration' tomato compared to untreated plants ($P < 0.05$). These treatments also increased the overall fruit yield per plant. Moreover, 15 mg/L GA_3 applications alone or in combination with 2,4-D (5:10 or 15:5 mg/L ratios) led to longer fruits with higher soluble solids content. A study by Pattanachatchai *et al*. (2020) observed that spraying GA_3 on 'Ranger' tomato inflorescences at concentrations of 50–100 mg/L resulted in increased fruit production. In this experiment, researchers evaluated three different PGR application dates (0, 2, and 4 days after full bloom, DAFB). They found that applying PGRs at 2 DAFB significantly increased the number of fruits per inflorescence compared to the application at 4 DAFB ($P < 0.05$). However, there was no significant difference between the application at 2 DAFB and 0 DAFB ($P > 0.05$). Interestingly, applying PGRs at 4 DAFB resulted in the highest fruit weight per inflorescence, which was significantly higher than the other two application times. In cherry tomatoes, a study by Jinagool *et al*. (2020) revealed that NAA at concentrations of 50 and 100 mg/L and 2,4-D at 10 and 50 mg/L significantly enhanced fruit set and yield of 'Tony TA 104' cherry tomatoes cultivated in a greenhouse under high summer temperatures. Meanwhile, Chomphu *et al*. (2023) reported that applying 100 mg/L of GA_3 to 'Sweet Princess' cherry tomato inflorescences four days after blooming stimulated fruit set, increased fruit size, and boosted overall yield when grown in a greenhouse during the summer.

These findings suggest that while PGRs offer potential benefits, optimal PGR type, concentration, and timing require further investigation for different tomato cultivars and greenhouse conditions. 'Sweet Boy' and 'Sweet Girl' are commercialized F1 hybrid cherry tomatoes that are popular among Thai growers. Therefore, this study aimed to compare the effects of different concentrations of GA_3 on fruit set and yield in 'Sweet Boy' and 'Sweet Girl' cherry tomatoes grown under greenhouse conditions during the summer season.

MATERIALS AND METHODS

Preparation of Plant Materials and Experimental Design

The experiment was conducted from February to June 2022 at Suranaree University of Technology in Nakhon Ratchasima, Thailand. Seeds of 'Sweet Boy' and 'Sweet Girl' cherry tomatoes were sown in peat moss-filled germination trays, sprouted in a shaded nursery, and watered daily. At 25 days old, seedlings were transplanted into 10 L pots filled with a growing medium consisting of a 4:4:1 volumetric ratio of soil, manure, and black rice husk, with one seedling in each pot. The pots were arranged in six rows of 25 pots, spaced 40 cm apart and 70 cm between rows, within a plastic-covered greenhouse equipped with a drip irrigation system. Cherry tomato plants were irrigated daily and fertilized according to recommendations from the Highland Research and Development Institute (2015). The experimental design

was a 2 × 5 factorial experiment in a randomized complete block design (RCBD). Factor A included two cherry tomato cultivars ('Sweet Boy' and 'Sweet Girl'), while Factor B consisted of five GA_3 concentrations (0 (water), 50, 100, 150, and 200 mg/L), resulting in a total of 10 treatment combinations. The six rows were divided into three blocks, each with two consecutive rows. Within each block, treatments were randomly assigned to groups of five consecutive pots, resulting in 15 plants per treatment.

Data Collection

Average daily temperature and relative humidity inside the plastic-covered greenhouse were recorded from February 25th (transplant) to June 5th, 2022 (harvest). Fourteen days after transplanting (DAT), plant height (from the soil surface to the apical bud) was measured for all plants. Additionally, three leaves from the midpoint of plant height were selected, and their leaf greenness was measured using the Chlorophyll Meter SPAD-502Plus (Konica Minolta). Each leaf was measured three times, and the average values were recorded. These measurements were repeated every 14 days until 70 DAT.

The two cherry tomatoes produced inflorescences between 30 and 45 DAT. During this period, five inflorescences per plant were tagged. They were monitored for the number of flowers per inflorescence and the number of fruit sets, which were used for the calculation of fruit set percentage. All inflorescences were monitored for blooming. When 50% of the flowers on an inflorescence opened, that day was considered full bloom. GA_3 or water was then sprayed on the inflorescence according to the assigned treatment, followed by two additional applications two and four days after full bloom. The three application times were carried out to ensure that most of the flowers in the inflorescence received PGRs within 0–4 days after anthesis, a crucial period for triggering the developmental transition of ovaries into fruits following pollination (Hu *et al*., 2018; Shinozaki *et al*., 2020). Subsequently, the number of flowers on the tagged inflorescences was recorded.

At 80 DAT, fruit ripening commenced. Clusters were harvested when 90% of the fruits reached full maturity, indicated by a yellow for 'Sweet Boy' and red for 'Sweet Girl'. Harvesting occurred once a week until 100 DAT, with fresh yield recorded at each harvest. At the end of the experiment, the fruit weights recorded at each harvest were summed to calculate the yield, which was expressed as fruit weight per cluster (g/cluster). Fruit numbers on tagged inflorescences were counted to calculate fruit set percentage based on previously recorded flower counts. In addition, 10 fruits were randomly selected from each treatment at every harvest for measurement of fruit size (length and width) using a vernier caliper, individual fruit weight, fruit firmness using a DFGS-R-200 Texture Analyzer (Chatillon), and total soluble solids (TSS) using a hand refractometer.

Data Analysis

The collected data were analyzed for means and standard deviations. Statistical analysis was performed using ANOVA followed by Duncan's Multiple Range Test at a 95% confidence level.

RESULTS AND DISCUSSION

Temperature and Relative Humidity in the Greenhouse

Greenhouse temperature and relative humidity were monitored daily from February 25th to June 5th, 2022. The average daily temperature fluctuated between 23.9 and 44.8°C, with a mean of 34.2°C, while relative humidity ranged from 30.1 to 89.8%, averaging 42.9%. Monthly averages (Figure 1) revealed that April, May, and June temperatures exceeded the optimal ranges suggested by Sitathani

(2002; 2012). During inflorescence development (30–45 DAT), temperatures fell within a range of 32.1 to 38.2°C.

Plant Height and Leaf Greenness

Table 1 presents the plant height of two cherry tomatoes, 'Sweet Boy' and 'Sweet Girl', across different GA_3 concentrations over 56 days following transplanting (14–70 DAT). Throughout the observation period, a general increasing trend in plant height was observed. However, no significant differences in plant height were observed between the two cherry tomatoes or GA_3 concentrations ($P > 0.05$). Furthermore, no interactive effects were observed between the factors studied. The maximum height was attained at 70 DAT with an average of 245.2 ± 86.2 cm. Given that GA_3 was exclusively applied to cherry tomato inflorescences, the absence of significant alterations in plant height for both 'Sweet Boy' and 'Sweet Girl' cherry tomatoes is notable. While GA_3 is recognized for its role in various plant growth processes (Bagale *et al*., 2022; Shah *et al*., 2023), including stem elongation (Prasad *et al*., 2013), the data suggested that its impact on vegetative growth may be limited when applied specifically to inflorescences in these cherry tomatoes.

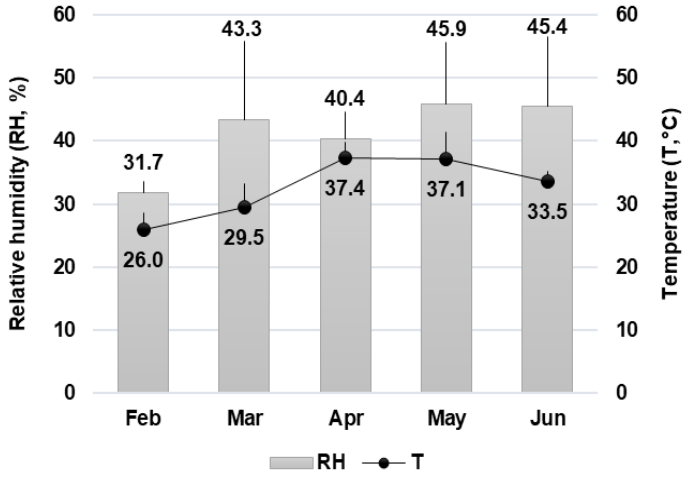

Figure 1 Monthly average temperature (T, °C) and relative humidity (RH, %) inside the greenhouse located at Suranaree University of Technology, Nakhon Ratchasima, Thailand, recorded from February 25th to June 5th, 2022.

Both cherry tomatoes exhibited similar leaf greenness throughout the studied period ($P > 0.05$). Leaf greenness increased from 35.7 SPAD units at 14 DAT, reaching a maximum of 47.9 SPAD units at 56 DAT. At 70 DAT, leaf greenness slightly decreased to 45.5 SPAD unit. The average leaf greenness of the two cherry tomatoes throughout the studied period was 42.4 ± 4.4 and 43.0 ± 5.3 SPAD units, respectively. Leaf greenness found in this study was in a range of previous studies on other cherry tomatoes (Chomphu *et al*., 2023; Nie *et al*., 2023). Normal leaf greenness, as measured by the SPAD unit, generally indicates normal photosynthesis, growth, and yield in plants (de Oliveira *et al*., 2017). Therefore, it can be assumed that both studied tomato cultivars will have similar potential for yield production.

When comparing leaf greenness among cherry tomato plants receiving different GA_3 concentrations, similar values were observed at 14 and 28 DAT before hormone application. The average leaf greenness was 35.7 ± 1.4 and 43.2 ± 1.1 SPAD units, respectively. At 42 DAT, GA_3-treated plants exhibited significantly

lower leaf greenness than the control ($P < 0.05$). Leaf greenness of GA_3-treated plants ranged from 37.1 to 41.7 SPAD units, whereas untreated plants had an average leaf greenness of 49.8 SPAD units. At 56 DAT, only cherry tomato plants treated with 50 mg/L GA_3 had a significantly lower leaf greenness than the control. In comparison, at 70 DAT, all GA_3-treated plants again exhibited significantly lower leaf greenness than untreated plants ($P < 0.05$). A declining trend in leaf greenness was also observed in GA_3-treated plants when considering the interaction between cherry tomatoes and GA_3 concentrations (Table 2).

A previous study by Sandoval-Villa *et al*. (2002) reported that tomato leaf greenness typically increases during vegetative development, peaking around 40 DAT, before decreasing at 49 DAT upon reproductive stage onset. The transition from vegetative to reproductive growth is characterized by a shift in resource allocation within the plant. As developing fruits and seeds emerge as strong sinks for nutrients and photosynthates, older leaves experience accelerated senescence. This process is driven by the redistribution of essential elements, such as nitrogen and phosphorus, from senescent leaves to the growing reproductive

Table 1 Plant height of 'Sweet Boy' (SB) and 'Sweet Girl' (SG) cherry tomatoes during 14–70 days after transplanting (DAT)

Factors		Plant height (cm)				
		14 DAT	**28 DAT**	**42 DAT**	**56 DAT**	**70 DAT**
A: cultivar	SB	23.9 ± 3.3	81.9 ± 7.1	143.3 ± 11.6	199.9 ± 22.3	243.5 ± 36.3
	SG	23.2 ± 4.2	81.5 ± 6.7	133.4 ± 14.4	198.1 ± 21.2	246.9 ± 28.8
	P-value	0.62	0.88	0.05	0.83	0.78
B: GA_3	0 mg/L	22.2 ± 4.6	83.3 ± 5.9	127.5 ± 7.4	178.8 ± 28.5	235.8 ± 76.5
	50 mg/L	23.0 ± 1.7	81.2 ± 6.6	142.0 ± 9.9	197.7 ± 17.3	252.8 ± 84.0
	100 mg/L	23.0 ± 2.4	82.7 ± 4.6	141.7 ± 10.0	209.3 ± 46.1	259.5 ± 88.9
	150 mg/L	22.1 ± 4.6	80.5 ± 10.3	145.2 ± 15.1	207.4 ± 36.0	247.8 ± 84.4
	200 mg/L	23.4 ± 4.0	81.1 ± 7.6	135.5 ± 19.8	201.8 ± 28.1	229.8 ± 79.0
	P-value	0.37	0.96	0.18	0.08	0.51
A × B	SB, 0 mg/L	24.0 ± 3.5	87.5 ± 1.3	133.0 ± 5.2	178.7 ± 18.9	233.0 ± 28.3
	SB, 50 mg/L	23.9 ± 1.9	84.0 ± 7.8	149.0 ± 9.8	208.3 ± 20.2	264.7 ± 13.0
	SB, 100 mg/L	22.8 ± 3.1	83.3 ± 5.7	147.0 ± 2.6	214.7 ± 15.0	256.3 ± 17.8
	SB, 150 mg/L	28.2 ± 1.5	79.3 ± 10.8	146.0 ± 10.0	199.0 ± 18.8	227.0 ± 14.4
	SB, 200 mg/L	20.5 ± 0.8	75.5 ± 4.1	141.0 ± 11.0	199.0 ± 23.1	236.3 ± 17.2
	SG, 0 mg/L	20.3 ± 5.5	79.0 ± 5.6	122.0 ± 4.4	179.0 ± 6.1	238.7 ± 23.2
	SG, 50 mg/L	22.0 ± 1.0	78.3 ± 5.0	135.0 ± 1.0	187.0 ± 19.3	241.0 ± 12.5
	SG, 100 mg/L	23.1 ± 2.3	82.0 ± 4.4	136.3 ± 12.5	204.7 ± 10.5	262.7 ± 14.1
	SG, 150 mg/L	24.4 ± 6.3	81.7 ± 12.1	144.0 ± 11.4	215.7 ± 9.1	223.3 ± 3.5
	SG, 200 mg/L	26.2 ± 4.0	86.7 ± 5.7	129.7 ± 15.5	204.7 ± 10.2	233.0 ± 13.2
	P-value	0.24	0.55	0.30	0.29	0.69

structures, thereby accelerating chlorophyll breakdown and reduction of leaf greenness (Guo *et al*., 2021). The application of GA_3 to tomato inflorescences to induce fruit set can lead to a reduction in leaf greenness as a trade-off for increased fruit development. GA_3 alters the hormonal balance by promoting the

synthesis of auxin and inhibiting the synthesis of ethylene. This hormonal shift, coupled with increased GA_3 levels, redirects nutrients and photosynthetic resources from vegetative growth to reproductive development (de Jong *et al*., 2009). As a result, the plant may allocate more resources to developing fruits, potentially leading to a decline in chlorophyll content and reduced greenness of leaves (Khan *et al*., 2007; Ritonga *et al*., 2023). This phenomenon is evident in previous studies on plants like *Camellia sinensis* (Li *et al*., 2021) and tobacco (Falcioni *et al*., 2017), which exhibited chlorophyll degradation in response to GA_3 application and the production of new sinks.

Table 2 Leaf greenness of 'Sweet Boy' (SB) and 'Sweet Girl' (SG) cherry tomatoes during 14–70 days after transplanting (DAT).

Factors		Leaf greenness (SPAD unit)				
		14 DAT	28 DAT	42 DAT	56 DAT	70 DAT
A: cultivar	SB	35.4 ± 2.8	45.3 ± 3.5	41.2 ± 4.8	46.2 ± 6.7	44.0 ± 6.0
	SG	36.0 ± 3.8	41.1 ± 3.4	41.8 ± 4.6	49.5 ± 5.9	46.8 ± 6.5
	P-value	0.58	0.20	0.91	0.18	0.24
B: GA_3	0 mg/L	35.1 ± 3.6	44.3 ± 5.9	49.8 ± 0.4^{a}	52.3 ± 3.2^{a}	54.3 ± 2.7^{a}
	50 mg/L	34.5 ± 2.7	42.5 ± 3.6	40.9 ± 0.8^{b}	43.4 ± 2.7^{b}	43.3 ± 3.1^{b}
	100 mg/L	37.6 ± 2.8	41.9 ± 3.7	41.7 ± 2.1^{b}	45.3 ± 4.9^{ab}	42.4 ± 6.4^{b}
	150 mg/L	36.9 ± 2.6	43.1 ± 3.1	37.1 ± 2.8^{c}	45.5 ± 4.4^{ab}	42.2 ± 3.8^{b}
	200 mg/L	34.6 ± 4.4	44.3 ± 3.8	39.6 ± 2.0^{bc}	48.3 ± 7.8^{ab}	44.8 ± 5.7^{b}
	P-value	0.36	0.81	0.00	0.01	0.00
A × B	SB, 0 mg/L	35.2 ± 2.8	40.9 ± 2.5	48.8 ± 0.5^{a}	54.8 ± 3.2^{ab}	53.2 ± 3.7^{ab}
	SB, 50 mg/L	35.8 ± 0.5	45.4 ± 2.2	46.3 ± 0.9^{a}	42.5 ± 2.3^{c}	40.8 ± 2.1^{c}
	SB, 100 mg/L	36.9 ± 0.8	43.0 ± 5.3	41.7 ± 2.3^{b}	43.6 ± 6.7^{c}	43.5 ± 5.3^{c}
	SB, 150 mg/L	36.2 ± 0.7	45.1 ± 3.1	38.2 ± 3.2^{c}	46.7 ± 4.9^{bc}	41.6 ± 3.1^{c}
	SB, 200 mg/L	33.0 ± 5.6	44.1 ± 2.4	39.1 ± 2.3^{bc}	43.6 ± 9.0^{c}	40.9 ± 5.2^{c}
	SG, 0 mg/L	35.0 ± 5.0	39.7 ± 4.5	49.8 ± 0.5^{a}	58.9 ± 1.5^{a}	55.4 ± 0.9^{a}
	SG, 50 mg/L	33.2 ± 3.5	39.6 ± 1.5	41.5 ± 0.9^{b}	44.3 ± 3.2^{c}	45.7 ± 1.5^{bc}
	SG, 100 mg/L	38.4 ± 4.1	40.8 ± 1.4	42.7 ± 2.3^{ab}	47.0 ± 2.6^{bc}	41.6 ± 8.3^{c}
	SG, 150 mg/L	37.5 ± 3.9	41.1 ± 1.3	37.1 ± 3.2^{c}	44.3 ± 4.6^{c}	42.8 ± 5.0^{c}
	SG, 200 mg/L	36.1 ± 3.0	44.4 ± 5.5	39.6 ± 2.3^{bc}	43.0 ± 2.6^{c}	41.7 ± 2.9^{c}
	P-value	0.66	0.06	0.00	0.00	0.00

Note: Means within the same column followed by different superscript letters (a, b, c) are significantly different ($P < 0.05$). Values are presented as mean ± standard deviation.

Flower and Fruit Production

'Sweet Boy' cherry tomato produced a significantly greater number of flowers per inflorescence than 'Sweet Girl', with an average of 17.3 ± 3.2 and 15.2 ± 2.0 flowers/inflorescence, respectively ($P < 0.05$). Both cultivars maintained similar fruit numbers per inflorescence (14.1 ± 5.8 fruits/inflorescence). Consequently, the 'Sweet Boy' cherry tomato exhibited a significantly lower fruit set percentage of 84.2 ± 8.4% compared with Sweet Girl, 91.7 ± 4.7% ($P < 0.05$, Table 3). Notably, the fruit set percentages of both studied

cultivars were higher than those in a previous study on 'Sweet Princess' cherry tomato by Chomphu *et al*. (2023), conducted simultaneously in an adjacent greenhouse. The 'Sweet Princess' cherry tomato yielded only 32.2% fruit set without GA_3 treatment, whereas 100 mg/L GA_3 increased fruit set to 64.6%. These differences might be attributed to cultivar sensitivity.

Table 3 Number of flowers per inflorescence recorded at 30–45 days after transplanting (DAT) and number of fruits per inflorescence and fruit set percentage at 80–100 DAT for 'Sweet Boy' (SB) and 'Sweet Girl' (SG) cherry tomatoes

Factors		No. flowers/inflorescence	No. fruits/inflorescence	Fruit set (%)
A: cultivar	SB	17.1 ± 3.2^{a}	14.4 ± 6.7	84.5 ± 8.4^{b}
	SG	15.4 ± 2.0^{b}	14.0 ± 4.7	91.5 ± 4.7^{a}
	P-value	0.00	0.64	0.02
B: GA_3	0 mg/L	20.4 ± 9.1^{a}	16.1 ± 6.1^{a}	82.5 ± 5.6^{b}
	50 mg/L	15.0 ± 6.5^{b}	13.7 ± 6.9^{b}	91.1 ± 3.9^{a}
	100 mg/L	14.1 ± 4.6^{b}	13.1 ± 4.3^{b}	93.5 ± 1.2^{a}
	150 mg/L	16.7 ± 6.3^{b}	14.6 ± 6.4^{ab}	88.0 ± 9.6^{ab}
	200 mg/L	15.1 ± 4.9^{b}	12.7 ± 4.3^{b}	84.7 ± 5.8^{b}
	P-value	0.00	0.03	0.00
A × B	SB, 0 mg/L	24.9 ± 10.0^{a}	17.7 ± 7.0^{a}	72.9 ± 5.9^{d}
	SB, 50 mg/L	16.3 ± 7.9^{bc}	15.0 ± 8.3^{ab}	90.6 ± 2.3^{ab}
	SB, 100 mg/L	13.2 ± 4.5^{c}	12.0 ± 3.3^{b}	93.6 ± 2.0^{a}
	SB, 150 mg/L	17.4 ± 7.4^{b}	14.6 ± 8.3^{ab}	83.0 ± 4.5^{bc}
	SB, 200 mg/L	14.8 ± 4.6^{bc}	11.7 ± 3.6^{b}	80.7 ± 8.1^{cd}
	SG, 0 mg/L	15.8 ± 5.2^{bc}	14.6 ± 4.8^{ab}	92.1 ± 7.5^{ab}
	SG, 50 mg/L	13.6 ± 4.6^{bc}	12.5 ± 5.0^{b}	91.5 ± 5.6^{ab}
	SG, 100 mg/L	14.9 ± 4.7^{bc}	14.1 ± 5.0^{b}	93.3 ± 4.5^{a}
	SG, 150 mg/L	16.0 ± 5.0^{bc}	14.6 ± 4.0^{ab}	93.1 ± 3.4^{ab}
	SG, 200 mg/L	15.5 ± 5.3^{bc}	13.6 ± 4.8^{b}	88.6 ± 2.4^{abc}
	P-value	0.00	0.02	0.00

Note: Means within the same column followed by different superscript letters (a, b, c) are significantly different ($P < 0.05$). Values are presented as mean ± standard deviation.

GA_3 application significantly reduced flower numbers ($P < 0.05$). The number of flowers in GA_3-treated plants dropped from 20.4 ± 9.1 flowers per inflorescence in untreated plants to 15.4 ± 1.8 flowers per inflorescence. This is also the case for 'Sweet Boy', where the number of flowers per inflorescence dropped from 24.9 ± 10.0 flowers per inflorescence to an average of 15.4 ± 1.8 flowers per inflorescence in GA_3-treated plants. However, GA_3 application positively influenced fruit retention, as fruit set percentages were significantly higher in plants treated with GA_3 ($P < 0.05$). In the case of 'Sweet Boy', the application of 50–150 mg/L GA_3 yielded a higher fruit set (88.8 ± 5.4%) than in the control (72.9 ± 5.9%, $P < 0.05$). The 200 mg/L GA_3 treatment did not enhance the fruit set of Sweet Boy (80.3 ± 8.1%) compared to the control ($P < 0.05$). Conversely, the 'Sweet Girl' cherry tomato exhibited no response to GA_3 application in terms of flower

number (16.2 ± 0.9 flowers per inflorescence), fruit per inflorescence (13.8 ± 0.9 fruits per inflorescence), or fruit set (91.2 ± 2.4%) as shown in Table 3. Increasing fruit retention in 'Sweet Boy' cherry tomato is consistent with studies by Gelmesa *et al*. (2010) and Luitel *et al*. (2015), which indicated that the increased fruit set is attributed to GA_3's ability to prevent flower and fruit abscission in tomatoes, particularly under high-temperature conditions. The shedding of flowers and fruits under high temperatures is often caused by a decrease in the levels of PGRs within developing flowers and fruits, specifically a reduction in auxin and gibberellin (Kuo and Tsai, 1984; Su *et al*., 2001).

Yield and Yield Quality

Table 4 presents the effects of cultivar and GA_3 application on fruit fresh weight, fruit size (width and length), fruit firmness, TSS, and yield of 'Sweet Boy' and 'Sweet Girl' cherry tomatoes. The 'Sweet Girl' cherry tomato showed significantly superior fruit fresh weight, fruit size (length and width), TSS, and yield compared with the 'Sweet Boy' cherry tomato; only fruit firmness of the 'Sweet Boy' cherry tomato was significantly higher ($P < 0.05$). According to the cultivar company, the two cultivars produce small, oval-shaped fruit. When ripe, the fruit turns yellow for 'Sweet Boy' cherry tomatoes and red for 'Sweet Girl' cherry tomatoes, with an average fruit fresh weight of 18 g/fruit (Home Garden, 2022). In this experiment, the fruits obtained from the two cultivars were smaller than the standard sizes identified by the company. This can be attributed to the high temperature in the greenhouse used in this experiment (Figure 1). A previous study by Park *et al*. (2023) suggested that cherry tomato fruit size can be significantly impacted by high-temperature stress, resulting in smaller fruit size due to a combination of physiological mechanisms such as reduced plant photosynthesis, impaired reproductive processes, hormonal imbalance, accelerated ripening, or impaired nutrient uptake and transport.

The application of different concentrations of GA_3 did not affect fruit fresh weight, fruit length, and fruit width ($P > 0.05$). However, fruit quality in terms of fruit firmness and TSS was enhanced. GA_3 at 100 mg/L gave the highest fruit firmness, followed by 150, 200, and 50 mg/L, respectively. The fruit firmness of these treatments was significantly higher than the control, whereas TSS was significantly induced when 150 and 200 mg/L of GA_3 were applied ($P < 0.05$). The application of GA_3 to inflorescence can have lasting effects on fruit development and post-harvest characteristics (Mesbah Uddin *et al*., 2024). It can influence cell wall metabolism by reducing the activity of cell wall-degrading enzymes, leading to firmer fruit texture (Kazemi, 2014). Additionally, GA_3 can interact antagonistically with ethylene, which delays ripening and maintains fruit firmness (Park and Malka, 2022). The delay in ripening allows for extended photosynthate accumulation, potentially increasing TSS levels, which are indicative of sugar content in the fruit (Kazemi, 2014; Mesbah Uddin *et al*., 2024). As a result of the high fruit set (Table 3) observed from the application of 100 mg/L GA_3, the yield obtained from this treatment was significantly higher than other treatments (251.9 ± 101.4 g/cluster; $P < 0.05$).

When considering the interaction effects, GA_3 at 50–150 mg/L enhanced fruit fresh weight for both cultivars compared with the control ($P < 0.05$), with averages of 11.9 ± 0.6 and 14.3 ± 0.5 g/fruit for 'Sweet Boy' and 'Sweet Girl' cherry tomatoes, respectively. No significant difference was observed among the three concentrations of each cultivar. While GA_3 at 200 mg/L did not increase fruit fresh weight like the other lower concentrations.

For the 'Sweet Boy' cherry tomato, GA_3 significantly increased fruit size, particularly fruit width, leading to a significant increase in fruit fresh weight. The increase in fruit size with GA_3 application was likely due to the promotion of cell division and expansion (Serrani *et al*., 2007). GA_3 can activate the cell cycle

Table 4 Fruit fresh weight, fruit size, fruit firmness, total soluble solid (TSS), and yield of Sweet Boy (SB) and Sweet Girl (SG) cherry tomatoes harvested between 80–100 days after transplanting (DAT)

Factors		Fruit fresh weight (g/fruit)	Fruit width (mm)	Fruit length (mm)	Fruit firmness (N mm^{-1})	TSS (°Brix)	Yield (g/cluster)
A: cultivar	SB	11.3 ± 1.5^{b}	24.2 ± 1.9^{b}	34.5 ± 2.4^{b}	2.0 ± 0.3^{a}	7.8 ± 0.9^{b}	180.1 ± 121.7^{b}
	SG	13.4 ± 0.7^{a}	25.1 ± 2.0^{a}	40.2 ± 3.0^{a}	1.5 ± 0.4^{b}	8.3 ± 0.7^{a}	187.6 ± 64.3^{a}
	P-value	0.00	0.01	0.00	0.00	0.00	0.04
B: GA_3	0 mg/L	11.1 ± 1.9	24.7 ± 2.6	38.0 ± 5.4	1.4 ± 0.3^{c}	7.9 ± 0.9^{b}	143.2 ± 58.4^{c}
	50 mg/L	12.9 ± 2.0	24.6 ± 1.5	37.0 ± 3.4	1.7 ± 0.5^{b}	7.7 ± 1.0^{b}	155.5 ± 55.9^{bc}
	100 mg/L	13.5 ± 1.7	25.1 ± 1.3	38.2 ± 3.4	2.0 ± 0.2^{a}	7.6 ± 0.6^{b}	251.9 ± 101.4^{a}
	150 mg/L	12.5 ± 1.8	25.1 ± 2.4	36.9 ± 3.4	1.8 ± 0.4^{b}	8.5 ± 0.5^{a}	182.5 ± 77.9^{b}
	200 mg/L	11.8 ± 1.6	23.7 ± 1.6	36.5 ± 3.9	1.8 ± 0.4^{b}	8.6 ± 0.5^{a}	151.0 ± 56.2^{c}
	P-value	0.06	0.09	0.13	0.00	0.00	0.00
A × B	SB, 0 mg/L	9.9 ± 1.3^{e}	22.4 ± 1.5^{d}	32.9 ± 1.5^{d}	1.7 ± 0.3^{bc}	7.4 ± 0.5^{c}	107.3 ± 27.2^{f}
	SB, 50 mg/L	12.0 ± 0.9^{cd}	24.8 ± 1.3^{bc}	35.1 ± 1.3^{cd}	1.9 ± 0.4^{ab}	7.1 ± 0.7^{c}	138.7 ± 32.5^{def}
	SB, 100 mg/L	12.4 ± 1.2^{bc}	25.3 ± 1.5^{b}	35.6 ± 1.5^{c}	2.0 ± 0.2^{ab}	7.4 ± 0.7^{c}	291.2 ± 113.1^{a}
	SB, 150 mg/L	11.3 ± 1.0^{cd}	25.2 ± 1.5^{b}	34.2 ± 1.5^{cd}	2.1 ± 0.2^{a}	8.5 ± 0.5^{a}	165.4 ± 93.3^{cde}
	SB, 200 mg/L	10.9 ± 1.7^{de}	23.2 ± 2.0^{cd}	34.5 ± 2.0^{cd}	2.2 ± 0.4^{a}	8.6 ± 0.5^{a}	127.3 ± 39.4^{ef}
	SG, 0 mg/L	12.3 ± 1.5^{c}	26.9 ± 1.0^{a}	43.1 ± 1.0^{a}	1.2 ± 0.2^{e}	8.4 ± 0.8^{a}	179.1 ± 59.5^{bcd}
	SG, 50 mg/L	13.8 ± 2.4^{ab}	24.5 ± 1.8^{bc}	39.0 ± 1.8^{b}	1.4 ± 0.5^{de}	8.2 ± 0.9^{ab}	172.2 ± 68.8^{bcd}
	SG, 100 mg/L	14.6 ± 1.4^{a}	24.9 ± 1.1^{b}	40.9 ± 1.1^{b}	2.1 ± 0.2^{a}	7.7 ± 0.5^{bc}	212.6 ± 70.7^{b}
	SG, 150 mg/L	13.7 ± 1.5^{ab}	25.0 ± 3.1^{b}	39.5 ± 3.1^{b}	1.5 ± 0.2^{cd}	8.5 ± 0.5^{a}	199.5 ± 55.4^{bc}
	SG, 200 mg/L	12.8 ± 0.7^{bc}	24.1 ± 1.0^{bc}	38.5 ± 1.0^{b}	1.4 ± 0.3^{de}	8.6 ± 0.5^{a}	174.6 ± 61.0^{bcd}
	P-value	0.00	0.00	0.00	0.00	0.00	0.00

Note: Means within the same column followed by different superscript letters (a, b, c, d, e, f) are significantly different ($P < 0.05$). Values are presented as mean ± standard deviation.

and thus is able to stimulate cell division and increase the number of cells. GA_3 stimulates the elongation of cells primarily by enhancing the plasticity of cell walls via activation of enzymes like expansions and promoting the uptake of water, leading to larger cells and more cells per fruit (Kappel and MacDonald, 2002). GA_3 applications at 100 and 150 mg/L significantly increased the yield of 'Sweet Boy' cherry tomato, with the highest yield of 291.2 ± 113.1 g/cluster obtained from the 100 mg/L treatment, followed by 165.4 ± 93.3 g/cluster from the 150 mg/L GA_3 treatment. This increase in yield is attributed to the high fruit set and fruit fresh weight observed in these treatments.

In addition to increasing fruit size, GA_3 increased fruit firmness in the 'Sweet Boy' cherry tomato. This can be due to the ability of GA_3 to enhance the synthesis of cell wall components like cellulose and hemicellulose, which provide structural support and contribute to firmness (He and Yamamuro, 2022). At a higher concentration level of GA_3 (150 and 200 mg/L), the TSS of the 'Sweet Boy' cherry tomato was significantly increased compared with the control and lower concentrations ($P < 0.05$). This increase in TSS is primarily attributed to the delayed ripening effect of GA_3 by suppressing ethylene biosynthesis (Wu *et al*., 2024). As a result, plants have more time to synthesize and accumulate sugars, such as glucose and fructose, within the fruit. This increased sugar accumulation directly contributes to higher TSS. In addition, GA_3 can also enhance the efficiency of sugar transport from source to sink, which supplies increased TSS (Iqbal *et al*., 2011; Seymour *et al*., 2013).

Despite an increase in fruit fresh weight in 'Sweet Girl' cherry tomatoes treated with 50–150 mg/L GA_3, the application of GA_3 resulted in a reduction in both fruit width and length. This suggests that the increased fresh weight may be attributed to factors other than size increase, such as higher water content within the fruit. Notably, the 'Sweet Girl' cherry tomato exhibited a larger initial fruit size than the 'Sweet Boy' cherry tomato, which might have masked potential size-enhancing effects of GA_3 on this cultivar. Regarding fruit quality parameters, the influence of GA_3 on the 'Sweet Girl' cherry tomato differed from that observed in the 'Sweet Boy' cherry tomato. Fruit firmness was significantly increased only at 100 and 150 mg/L GA_3 compared to the control ($P < 0.05$). In general, the GA_3 application did not significantly alter TSS in the 'Sweet Girl' cherry tomato. However, the observed decrease in TSS at 100 mg/L GA_3 treatment might be associated with increased water content within the fruit. For the 'Sweet Girl' cherry tomato, the highest yield was observed at 100 mg/L GA_3 (212.6 ± 70.7 g/cluster). However, there was no significant difference in yield across GA_3 concentration. This lack of significant variation in yield can be explained by the consistent fruit set observed across all GA_3 treatments for this cultivar (Table 3).

The differential fruit set and yield induction observed between 'Sweet Boy' and 'Sweet Girl' cherry tomatoes following similar GA_3 treatments can be attributed to inherent genetic and physiological variations influencing their hormonal responses and pollination efficiency. Studies have shown that the efficacy of GA_3 in enhancing fruit sets varies among tomato cultivars due to differences in genetic makeup, affecting hormone sensitivity, metabolic pathways, and gibberellin biosynthesis and signaling. Additionally, these cultivars may differ in floral structures, pollen viability, or receptivity, impacting pollination success. For instance, 'Sweet Boy' may exhibit a more pronounced response to GA_3-induced parthenocarpy (fruit development without fertilization) than 'Sweet Girl,' leading to differences in fruit set outcomes and yield. Further research is needed to clarify the mechanisms underlying these cultivar-specific responses to GA_3 and their impact on fruit production.

CONCLUSIONS

The study demonstrated the potential of GA_3 to enhance fruit yield and quality in greenhouse-grown cherry tomatoes during the summer months, especially in the 'Sweet Boy' cherry tomato. Applying 100 mg/L of GA_3 on 0, 2, and 4 DAA was optimal for increasing the fruit set and yield in the 'Sweet Boy' cherry tomato. As responses to GA_3 varied between the cherry tomatoes studied, it is essential to consider cultivar-specific characteristics when applying this growth regulator commercially. Additionally, the economic feasibility of the GA_3 application should be carefully evaluated by weighing the increased yield against the cost of the PGRs application.

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