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Original Article

Impact of GA_3 Application at Different Times and Methods on Tomato Growth and Fruit Shelf Life

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ABSTRACT

Gibberellic acids (GAs) are vital plant growth regulators that significantly influence plant growth, development, and responses to stress. This study examined the effects of applying gibberellic acid (GA_3) to tomato plants and their growing medium at various intervals. The focus was on plant growth, fruit development, and postharvest quality. The results indicated that applying GA_3 every two weeks notably enhanced plant height and stem diameter. However, more frequent applications had a negative impact on fruit size, overall yield, and root fresh weight. Regarding postharvest quality, tomatoes treated with GA_3 every four weeks experienced less weight loss and decay, mainly when GA_3 was applied through the growing medium. Furthermore, plant applications helped maintain the brightness of the fruit peel color. These findings underscore the importance of optimizing the timing and method of GA_3 application to balance growth promotion, yield, and postharvest quality effectively. Future research should investigate alternative application strategies to maximize the benefits of GA_3 while minimizing potential drawbacks.

Key words: Gibberellic acid, *Solanum lycopersicum* L., plant development, plant growth regulators, postharvest

GA_3 Uygulamasının Farklı Zaman ve Yöntemlerle Domates Bitkisi Büyümesi ve Meyve Raf Ömrü Üzerindeki Etkisi

ÖZ

Gibberellik asitler, bitki büyümesini, gelişimini ve strese verdiği tepkileri önemli ölçüde etkileyen hayati bitki büyüme düzenleyicileridir. Bu çalışma, çeşitli aralıklarla domates bitkilerine ve yetiştirme ortamlarına gibberellik asit (GA_3) uygulamasının etkilerini incelemiştir. Odak noktası olarak bitki büyümesi, meyve gelişimi ve hasat sonrası kalitedeki etkiler incelendi. Sonuçlar, GA_3'ün iki haftada bir uygulanmasının bitki boyunu ve gövde çapını önemli ölçüde artırdığını göstermiştir. Ancak, daha sık uygulamalar meyve boyutu, genel verim ve kök taze ağırlığı üzerinde olumsuz bir etki göstermiştir. Hasat sonrası kalite açısından, her dört haftada bir GA_3 ile muamele edilen domatesler, özellikle GA_3 yetiştirme ortamı yoluyla uygulandığında daha az ağırlık kaybı ve çürüme göstermiştir. Ayrıca, bitki uygulamaları kabuk renginin parlaklığının korunmasına yardımcı olmuştur. Bu bulgular, büyüme teşviki, verim ve hasat sonrası kaliteyi etkili bir şekilde dengelemek için GA_3 uygulamasının zamanlamasını ve yöntemini optimize etmenin önemini vurgulamaktadır. Gelecekteki araştırmalar, GA_3'ün faydalarını en üst düzeye çıkarırken olası dezavantajlarını en aza indirmek için alternatif uygulama stratejilerini araştırmalıdır.

Anahtar kelimeler: Giberellik asit, *Solanum lycopersicum* L., bitki gelişimi, bitki büyümeyi düzenleyicileri, hasat sonrası

INTRODUCTION

The growing demand for efficient and sustainable agricultural practices has increased interest in plant growth regulation to enhance crop productivity and quality (Pérez-Jiménez et al., 2015). One promising approach involves using plant growth regulators (PGRs), organic compounds that influence various physiological processes even at low concentrations (Pérez-Jiménez et al., 2015; Rostami and Azhdarpoor, 2019). According to the Environmental Protection Agency (EPA), PGRs can modulate plant growth by altering key physiological mechanisms (Fishel, 2006). Their widespread adoption in commercial agriculture is attributed to their cost-effectiveness and environmentally sustainable nature (Cassina et al., 2011). However, the effectiveness of PGRs depends on several factors, including concentration, application method, environmental conditions, and plant-specific physiological responses (Singh et al., 2018; Rostami and Azhdarpoor, 2019).

Among the various classes of PGRs, gibberellins (GAs) are particularly important due to their ability to regulate key developmental processes such as seed germination, stem elongation, flowering, and root formation (Plackett and Wilson, 2016; Rostami and Azhdarpoor, 2019; Alharby et al., 2021). Additionally, GAs influence physiological functions such as stomatal conductance and photosynthesis while mediating plant responses to environmental stressors, including temperature fluctuations, light availability, and water scarcity (Iqbal et al., 2011; Gupta and Chakrabarty, 2013). While over 250 gibberellins have been identified, only a subset exhibit significant biological activity (El Sabagh et al., 2022). Among them, gibberellic acid (GA_3) is the most widely utilized in commercial agriculture, recognized for its role in stimulating cell elongation and division, thereby enhancing fruit growth and yield (Serrani et al., 2007; Li et al., 2011; Ben Rhouma et al., 2020). Furthermore, GA_3 has been reported to improve crop productivity under suboptimal growing conditions (Khalloufia et al., 2017; Rahman et al., 2019).

Tomato (*Solanum lycopersicum*), a globally significant horticultural crop, is cultivated over 4 million hectares worldwide (FAOSTAT, 2022). Given the increasing consumer demand for high-yield, long-lasting produce, optimizing the use of GA_3 in tomato production is of considerable interest. Research indicates that GA_3 application promotes stem elongation (Bukovac and Witter, 1956), increases fresh weight (Bukovac and Witter, 1956; Rappaport, 1956), and enhances flowering and fruit set (Witter and Bukovac, 1957). Additionally, it has been linked to improved photosynthetic capacity, shoot elongation, leaf expansion, and extended postharvest shelf life (Moncada et al., 2020; Vetrano et al., 2020). However, GA_3 effects vary depending on species, cultivar, and environmental factors. For instance, while GA_3 increases fruit weight in pineapples (Li et al., 2011) and facilitates root development in peas through mycorrhizal associations (Yaxley et al., 2001), it promotes vegetative growth in strawberries. However, it may reduce fruit size and yield (Qureshi et al., 2013). These inconsistencies underscore the need for further research to refine GA_3 application strategies tailored to specific crops and growing conditions.

Despite its known benefits, the optimal timing and method of GA_3 application in tomato production remain unclear due to variability in cultivar responses and environmental interactions. This study investigates the effects of different GA_3 application intervals on tomato plant growth, fruit development, and postharvest shelf life. By examining these physiological and postharvest responses, this research seeks to optimize GA_3 application strategies to enhance yield, fruit quality, and storage longevity, thereby contributing to improved tomato production practices.

MATERIALS AND METHODS

Plant Growing Conditions

The experiment was conducted in a gothic-style, climate-controlled, automated hydroponic research greenhouse at the Department of Horticulture, Faculty of Agriculture, Kırşehir Ahi Evran University. The greenhouse maintained a daytime temperature of 24°C and a nighttime temperature of 16°C, with humidity levels ranging from 60% to 65%.

On May 18, 2018, tomato seedlings of the Altess variety (De Ruiter-Bayer, F1 hybrid) were planted in 8-liter pots positioned on 4-meter-long gutters, using cocopeat as the growing medium. The first and last plants in each gutter were excluded from measurements and analyses to minimize edge effects. An automated system was utilized to control the irrigation and fertilization's pH and electrical conductivity (EC) throughout the experiment. The tomato plants were irrigated with a modified Hoagland nutrient solution tailored to their developmental needs.

The application of gibberellic acid (GA_3) at a concentration of 100 mg L^{-1} began on May 30, 2018. Two application methods were used: GA_3 was applied directly to the plants (P) and the growing medium (M). Both treatment groups received GA_3 at five different intervals, while a control group consisted of plants that did not receive any treatment. Table 1 provides a detailed overview of the treatments.

Table 1. GA_3 treatments

Treatment Method (TM)	Treatment Period (TP)
Control (C)	Control (0)
Plant (P)	Once at the beginning (1)
Medium (M)	Once in every week (2)
	Once in every 2 weeks (3)
	Once in every 3 weeks (4)
	Once in every 4 weeks (5)

Plant Height and Stem Diameter

The plants' heights were measured on three different dates: July 6, July 25, and August 31, 2018. The measurements were taken from the pot level to the tip of the top shoot. The stem diameter was also recorded as 5 cm above the pot level.

Leaf Pigment Content

Leaf tissue pigment levels, including chlorophyll a, chlorophyll b, total chlorophyll, and carotenoids, were measured following the method described by Arnon (1949). Leaf samples weighing 0.2 grams were homogenized in 8 milliliters of 80% acetone and then centrifuged at 10,000 rpm at 4 °C. The supernatants were analyzed using a spectrophotometer at 470 nm, 645 nm, 652 nm, and 663 nm. The amounts of pigments were calculated using the formulas provided by Lichtenthaler (1983).

$$\text{Total chlorophyll} = \frac{\text{A652} \times 27.8 \times 20}{\text{Sample weight}}$$

$$\text{Chlorophyll a} = \frac{(11.75 \times \text{A663} - 2.35 \times \text{A645}) \times 20}{\text{Sample weight}}$$

$$\text{Chlorophyll b} = \frac{(18.61 \times \text{A645} - 3.96 \times \text{A663}) \times 20}{\text{Sample weight}}$$

$$\text{Carotenoid} = \frac{((1000 \times \text{A470}) - (2.27 \times \text{Klo.a}) - (81.4 \times \text{Klo.b}) / 227) \times 20}{\text{Sample weight}}$$

Fruit Dimensions and Yield

During the research period, tomatoes were harvested on seven different dates. The fruits from each plant were weighed and recorded to determine the yield per plant. In addition, the dimensions (width and length in millimeters) and weight of the fruits for each treatment were measured.

Stem and Rroot Fresh Weight

To determine the weight of the stems and roots, the plants' stems were cut at the same level as the root collar. Their fresh weight was then measured by weighing them. Next, the roots were cleaned of cocopeat, washed, and dried before measuring their fresh weight.

Shelf-Life Parameters

Measurements taken included weight loss, color (L*, a*, b*), titratable acidity (expressed as a percentage of citric acid), soluble solid content (SSC), and the percentage of rotten fruit. Peel color measurements of the tomato fruits were obtained using a CR-200 Minolta colorimeter in the CIE L*, a*, and b* color space. SSC was measured as a percentage using a Leica refractometer. To determine titratable acidity, 5 mL of fruit juice was extracted and diluted with 50 mL of pure water, which was then titrated with a 0.1 N NaOH solution using an automatic titrator (Mettler Toledo DL 50 Graphix). The results were reported as a percentage of citric acid. Additionally, the weight of the tomatoes was recorded on days 0 and 7 to assess weight loss.

Statistical Analyses

The study was conducted with three replicates, each consisting of 14 plants, following a randomized complete block experimental design. Additionally, each replicate included shelf-life studies using 10 tomato

fruits. The collected data were analyzed using ANOVA with the MINITAB software package at a significance level of $P \leq 0.05$. After conducting the ANOVA, the Duncan Multiple Range Test was applied using the MSTAT-C software package to identify significant differences from the variance analysis.

RESULTS AND DISCUSSION

Plant Height and Stem Diameter

No significant interactions were observed between the treatment methods and treatment intervals for plant height and stem diameter, suggesting that each variable acted independently (Table 2). However, GA_3 application consistently resulted in taller plants compared to the control group, with the most pronounced effect observed when applied every two weeks. Similarly, stem diameter measurements were significantly greater in both plant and medium treatments compared to the control, which exhibited consistently lower stem diameters throughout the study.

The observed increases in plant height and stem diameter following GA_3 application can be attributed to its role in stimulating cell division and elongation, fundamental processes in plant growth (Pérez-Jiménez et al., 2015; Chen et al., 2020; Rana et al., 2020). Similar growth-promoting effects of GA_3 have been documented in various crops, including tomatoes (Mukati et al., 2019), peppers (Singh and Singh, 2019), chickpeas (Iqbal et al., 2001), cowpeas (Emongor, 2007), and peas (Singh et al., 2015). Furthermore, findings by Islam et al. (2023) corroborate these results, demonstrating that multiple GA_3 applications effectively enhance plant height in mung beans.

Overall, these results highlight the effectiveness of GA_3 in promoting vegetative growth, particularly when applied biweekly. Further research is warranted to explore the long-term effects of different application frequencies on overall yield and physiological development.

Table 2. The impact of GA_3 on the height of plants and the diameter of stems.

Factors	Plant Height (cm)	Stem Diameter (mm)
Treatment Method (TM)		
Control	290.07±2.64 c[1]	12.74±0.12 b[1]
Plant	311.19±4.83 a	14.26±0.23 a
Medium	300.42±4.87 b	13.81±0.24 a
Treatment Period (TP)		
0*	290.07±3.85 b[2]	12.74±0.18 b[2]
1	298.59±5.46 b	13.59±0.28 a
2	303.31±6.74 b	13.84±0.37 a
3	317.93±8.31 a	13.96±0.44 a
4	304.24±5.01 ab	13.55±0.33 a
5	289.21±5.52 b	13.93±0.39 a
Significant effects		
TM	0.000	0.000
TP	0.002	0.012
TM × TP	0.087	0.132

[1]Letters indicate differences between treatment methods. [2]Letters indicate differences between treatment periods. *Once at the beginning (1), once in every week (2), once in every 2 weeks (3), once in every 3 weeks (4), once in every 4 weeks (5)

Leaf Pigment Content

A significant interaction between treatment methods and treatment periods was observed for leaf pigment content ($P = 0.000$). As illustrated in Figure 1, the analysis of chlorophyll a, b, and total chlorophyll values across treatment methods and periods indicated that plants in treatment group 5 exhibited the highest leaf pigment content. Additionally, when comparing application methods within each treatment period, the control group generally showed elevated chlorophyll values; however, during treatment period 5, no significant differences were observed among treatments. This suggests that GA_3 application had a limited effect on enhancing chlorophyll content in this study, a trend also reflected in carotenoid values.

These findings contrast with previous studies reporting increased chlorophyll content following GA application. Datta (2009) observed higher chlorophyll levels and enhanced photosynthesis rates in soybeans, while Chauhan et al. (2018) reported a similar effect in oats. Furthermore, Matos et al. (2020) found that carotenoid content increased with higher GA concentrations. Although GA_3 is known to promote plant

elongation, it can also lead to tissue lightening, potentially due to dilution effects from increased water uptake (Kacar et al., 2006; Shah, 2007). In the present study, the observed decline in chlorophyll content with more frequent GA_3 applications may be attributed to accelerated growth, supporting the hypothesis that rapid elongation can result in pigment dilution.

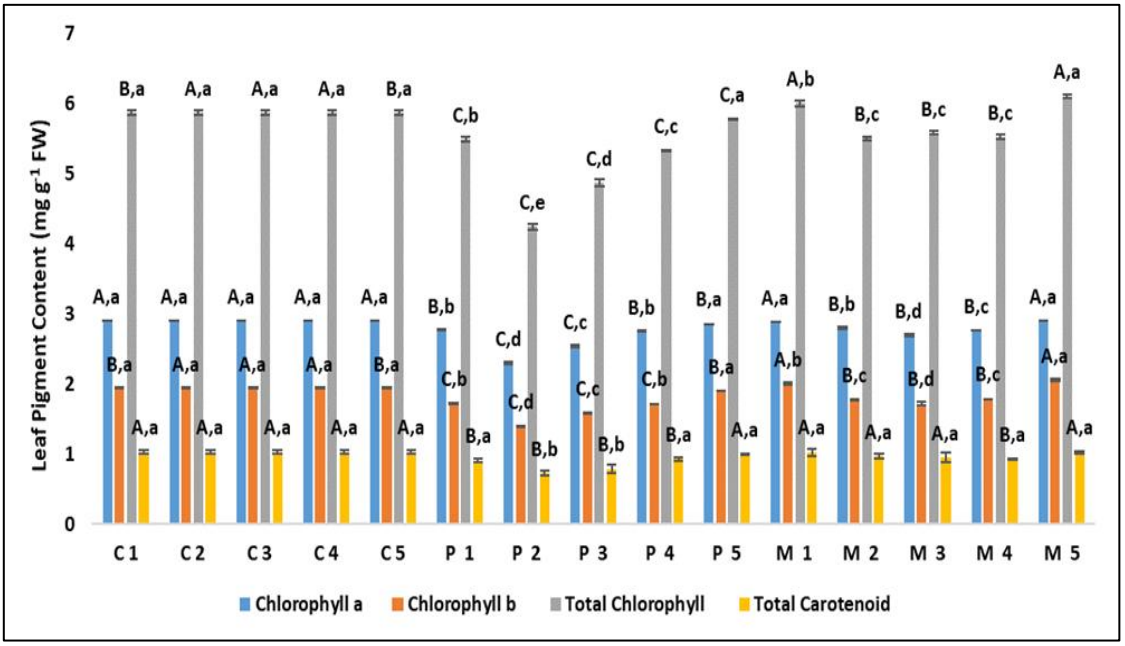

Figure 1. Effect of GA_3 on chlorophyll a, chlorophyll b, total chlorophyll and total carotenoid content. Capital letters represent the differences between treatment methods for each treatment period and the lower letters represent the differences between treatment periods for each treatment method. C: Control, P: Plant, M: Medium. Once at the beginning (1), once in every week (2), once in every 2 weeks (3), once in every 3 weeks (4), once in every 4 weeks (5).

Fruit Dimensions and Yield

The interaction between treatment methods and treatment periods significantly influenced yield, fruit weight, width, and length ($P < 0.05$) (Table 3). Among all treatment periods, period 1 was the most effective in enhancing yield. The control group consistently produced the highest values for all measured parameters when analyzed separately. Notably, only the medium application proved effective in treatment period 1. A similar trend was observed for fruit weight, width, and length, with the control group displaying superior results across all treatments.

Furthermore, increasing the frequency of GA_3 applications was associated with reduced fruit weight, width, and length. While GA_3 enhances fruit set and promotes parthenocarpic fruit production, the resulting fruits are often smaller (Serrani et al., 2007; Mariotti et al., 2011). These findings align with previous studies, which reported that gibberellin-treated fruits tend to be smaller (Jong et al., 2009; Kim et al., 2020). Additionally, yield decreased as GA_3 application frequency increased, supporting observations by Abdel et al. (2011), who found that although GA_3 application in mung beans promoted plant height, it concurrently reduced yield.

These results suggest that while GA_3 may enhance certain aspects of fruit development, its excessive application can negatively impact overall fruit size and yield. Future studies should explore optimal application frequencies to balance growth promotion and fruit quality.

Stem and Root Fresh Weight

A significant interaction was observed between treatment methods and treatment periods regarding the fresh weight of stems and roots (Table 3). While no significant differences in plant fresh weight were noted between the various treatments and the control group, the control group exhibited the highest root fresh weight. Root development is essential for nutrient absorption and plant growth (Araya et al., 2016). A well-coordinated relationship between the shoot and root systems is crucial for maintaining healthy plant growth (Yang et al., 2004; Chu et al., 2014). Both root size and activity influence the efficiency of the photosynthetic process, while the growth and development of the root system depend on photoassimilates produced by the shoots (Zhang et al., 2009; Araya et al., 2016).

Table 3. Impact of GA_3 on yield, fruit weight, fruit width, fruit length, plant fresh weight, and root fresh weight.

Factors	Yield (g)	Fruit Weight (g)	Fruit Width (mm)	Fruit Length (mm)	Plant Fresh Weight (g)	Root Fresh Weight (g)
C × 1	3640±89.7 B,a*	142.02±0.63 A,a	65.77±0.16 A,a	54.86±0.37 A,a	1389±28.7 A,a	348.74±0.35 A,a
C × 2	3640±89.7 A,a	142.02±0.63 A,a	65.77±0.16 A,a	54.86±0.37 A,a	1389±28.7 A,a	348.74±0.35 A,a
C × 3	3640±89.7 A,a	142.02±0.63 A,a	65.77±0.16 A,a	54.86±0.37 A,a	1389±28.7 A,a	348.74±0.35 A,a
C × 4	3640±89.7 A,a	142.02±0.63 A,a	65.77±0.16 A,a	54.86±0.37 A,a	1389±28.7 A,a	348.74±0.35 A,a
C × 5	3640±89.7 A,a	142.02±0.63 A,a	65.77±0.16 A,a	54.86±0.37 A,a	1389±28.7 A,a	348.74±0.35 A,a
P × 1	3661±26.4 B,a	137.69±6.57 A,a	66.45±0.92 A,a	51.83±0.62 B,a	1422±48.2 A,a	318.88±0.35 B,a
P × 2	2166±56.8 B,d	65.31±7.42 C,d	51.64±2.23 C,d	39.77±1.91 C,c	1021±42.6 B,b	242.77±0.35 C,c
P × 3	2716±44.0 C,c	94.10±6.01 C,c	58.78±1.30 B,c	44.93±1.18 B,b	1285±6.43 A,a	195.17±0.35 C,e
P × 4	3431±76.8 AB,b	94.10±6.01 B,c	58.78±1.30 B,c	44.93±1.18 B,b	1369±45.0 A,a	231.74±0.35 C,d
P × 5	3316±112.0 B,b	116.57±9.08 B,b	62.57±1.71 B,b	49.38±1.15 B,a	1063±28.5 B,b	249.56±0.35 B,b
M × 1	4156±133.0 A,a	135.49±6.18 A,a	65.50±1.09 A,a	50.15±0.59 B,a	1386±102.0 A,a	228.04±0.35 C,d
M × 2	3652±20.3 A,b	116.75±7.40 B,b	62.95±1.42 B,ab	48.35±1.37 B,ab	1386±119 A,a	336.38±0.35 B,a
M × 3	3411±66.0 B,c	108.34±4.62 B,bc	60.72±0.89 B,bc	46.99±1.21 B,b	1340±36.0 A,a	269.46±0.35 B,b
M × 4	3297±8.59 B,c	106.12±2.73 B,bc	59.92±0.14 B,c	46.75±0.51 B,b	1361±47.1 A,a	254.63±0.35 B,c
M × 5	3363±36.1 B,c	95.30±4.38 C,c	57.93±0.86 C,c	47.09±1.08 B,b	1270±84.3 A,a	219.44±0.35 C,e
Significant effects						
TM	0.000	0.000	0.000	0.000	0.000	0.000
TP	0.000	0.000	0.000	0.000	0.002	0.000
TM × TP	0.000	0.000	0.000	0.000	0.003	0.000

*Capital letters represent the differences between treatment methods for each treatment period and the lower letters represent the differences between treatment periods for each treatment method. C: Control, P: Plant, M: Medium. Once at the beginning (1), once in every week (2), once in every 2 weeks (3), once in every 3 weeks (4), once in every 4 weeks (5)

The root system's structure is vital not only for its functional capabilities but also for supporting proper shoot function (Wang et al., 2009). Bidadi et al. (2010) found that increased gibberellic acid (GA) application resulted in greater shoot biomass but inhibited root growth. This effect may be attributed to the heightened sensitivity of roots to GA concentrations (Barboza-Barquero et al., 2015). While gibberellins are critical for promoting root elongation, high concentrations can have inhibitory effects (Tanimoto, 2012; Hedden and Sponsel, 2015).

These findings highlight the complex relationship between GA application, root development, and shoot growth, suggesting that optimal GA concentrations are necessary to promote balanced plant development. Future research should further investigate the effects of GA concentrations on root and shoot dynamics to enhance our understanding of plant growth regulation.

Shelf-Life Parameters

Tomato fruit is highly susceptible to water loss during storage, leading to increased weight loss and negatively impacting fruit quality. Our study revealed significant interactions between treatment type, treatment period, and shelf life regarding weight loss in tomatoes (P = 0.000) (Figure 2). As shelf life progressed, weight loss increased.

When analyzing plant and medium treatments separately, the lowest weight loss values were observed in tomatoes treated with GA_3 once every four weeks. For treatment methods, both plant and medium treatments exhibited weight loss values comparable to those of the control group. However, tomatoes treated with GA_3 every four weeks showed lower weight loss during the 7-day shelf life compared to the control group for both application methods. These findings align with research by Bagnazari et al. (2018), which indicated that pre-harvest GA_3 application reduced weight loss during the storage of bell peppers. The application of GA_3 influences the size of epidermal cells and reduces the activity of enzymes that hydrolyze cell walls, thereby affecting tissue water permeability (Gang et al., 2015). Consequently, the reduced weight loss observed in GA_3-treated tomatoes may be linked to decreased enzyme activity and alterations in water permeability.

Furthermore, the effects of treatment method, treatment period, and shelf life duration on the rate of fruit rot were statistically significant (P = 0.000) (Figure 3). The treatment method significantly influenced the rate of fruit spoilage over the 7-day shelf life, with GA_3 applied to the medium proving to be the most effective. Analysis of treatment periods for each application type revealed that applying GA_3 once every four weeks resulted in the lowest rate of fruit spoilage.

These results suggest that optimizing GA_3 application frequency and method can effectively reduce water loss and decay in tomatoes during storage, thereby enhancing postharvest quality. Future research should further explore the underlying mechanisms by which GA_3 influences fruit tissue properties to improve storage outcomes.

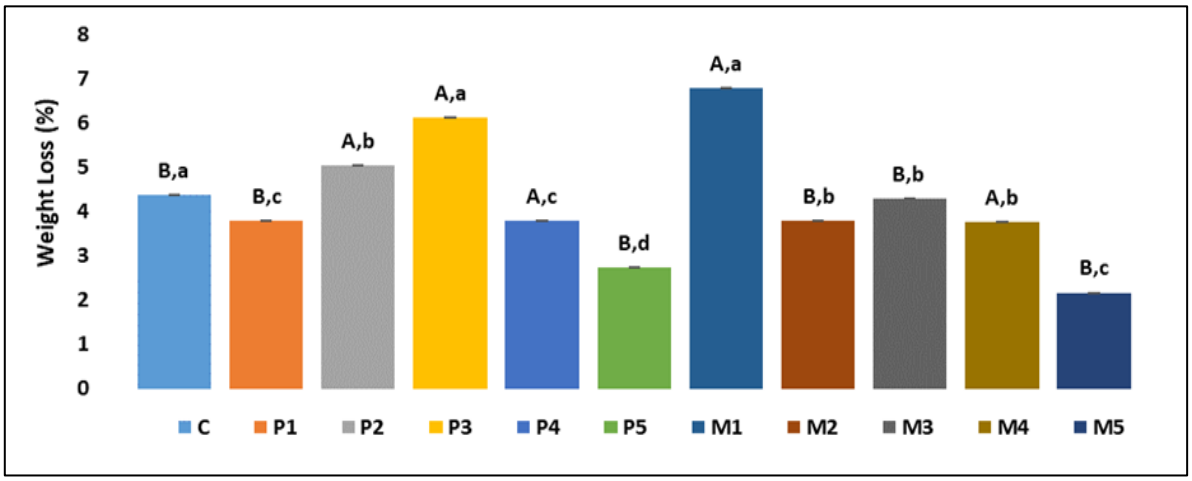

Figure 2. The impact of GA_3 on the weight loss of tomatoes at 7-day shelf life.
Capital letters represent the differences between treatment methods for each treatment period and the lower letters represent the differences between treatment periods for each treatment method. C: Control, P: Plant, M: Medium. Once at the beginning (1), once in every week (2), once in every 2 weeks (3), once in every 3 weeks (4), once in every 4 weeks (5)

In the medium treatment, tomatoes treated with gibberellic acid (GA_3) once every four weeks exhibited the lowest rate of fruit decay. This finding aligns with research by Kirmani et al. (2013), which indicates that pre-harvest GA_3 application can effectively delay fruit decay and extend shelf life. Gibberellins enhance the fruit's resistance to decay by preventing cellular breakdown, contributing to the reduced decay percentage observed with GA3 treatment (Rokaya et al., 2016).

However, the effectiveness of this treatment may vary based on the application method and timing of GA_3, whether applied through foliar spraying or via the growing medium. Understanding these variables is crucial for optimizing GA_3 usage in tomato cultivation to maximize shelf life and minimize decay.

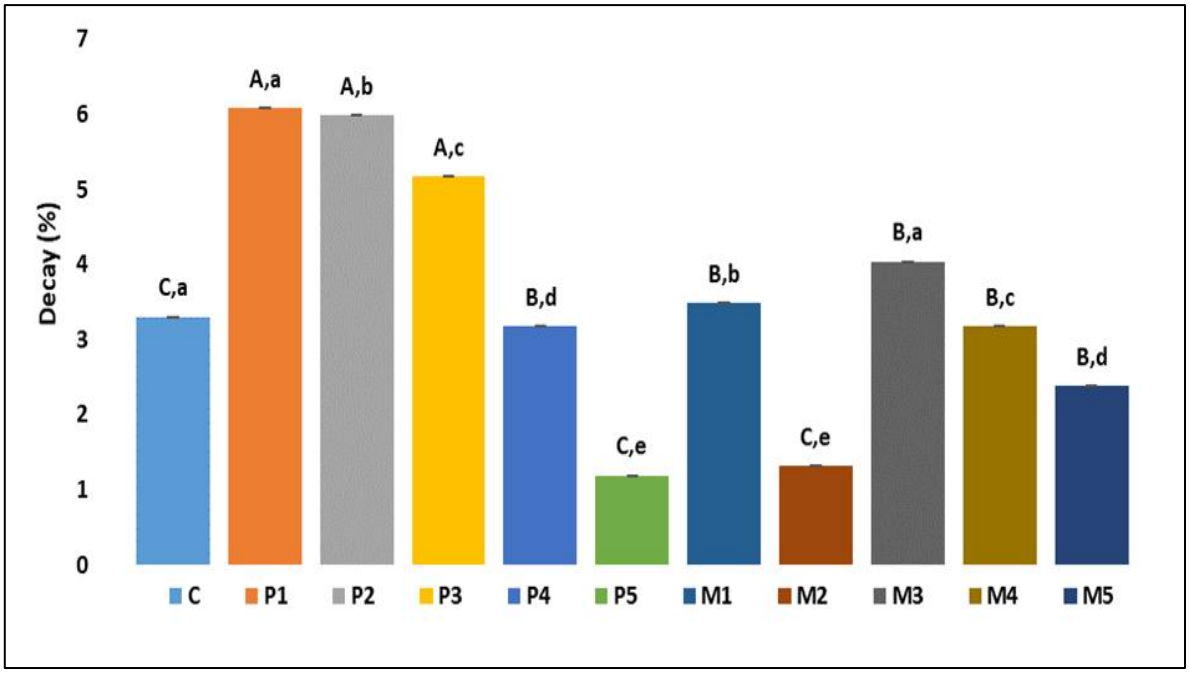

Figure 3. Effect of GA_3 on the percentage of rotten tomatoes at 7-days of shelf life.
Capital letters represent the differences between treatment methods for each treatment period and the lower letters represent the differences between treatment periods for each treatment method. C: Control, P: Plant, M: Medium. Once at the beginning (1), once in every week (2), once in every 2 weeks (3), once in every 3 weeks (4), once in every 4 weeks (5)

After evaluating the color values of tomato fruit peels over 7 days, the interaction between treatment type and shelf-life duration significantly affected the L value, which indicates brightness (see Table 4). Notably, plant treatments were more effective in maintaining peel color brightness throughout the shelf life. In contrast, the L value decreased over time in the control group, while it remained stable in both the medium and plant treatment groups. Previous studies have shown that pre-harvest application of GA_3 can help maintain the L value in kumquats and okra (Cai et al., 2021; Xiao et al., 2022).

The a and b values of tomato peels did not show significant variation, except across different shelf-life periods (see Table 4). As shelf life progressed, the a value increased while the b value decreased. Similar trends in the a and b color values of tomato fruits have been reported by da Costa de Quadros et al. (2020).

Soluble solid content (SSC), which measures the sugars present in fruits and vegetables and is essential for quality assessment (Niu et al., 2019), was significantly influenced by the interaction of treatment methods, durations, and shelf life (see Table 4). SSC levels were higher in plant treatments than in medium treatments, although these levels were statistically like those in the control tomatoes. Additionally, SSC increased with extended shelf life, likely due to increased weight loss over time. This trend aligns with findings from several other studies (Akan et al., 2022; Akan and Horzum, 2023).

Titratable acidity (TA) is a critical quality factor that significantly influences the taste of tomato fruits (Duguma et al., 2022). Treatment methods, durations, and shelf-life periods influenced TA values (see Table 4). Mean value analysis indicated that both the control group and plant treatments exhibited higher TA values than medium treatments. Moreover, significant statistical differences in TA were observed across treatment periods; however, TA levels decreased as shelf life progressed.

Table 4. Impact of GA_3 application on L, a, b values and soluble solid and titratable acidity content.

Factors	L	a	b	SSC	TA
Treatment Method (TM)					
Control (C)	43.80±0.50 ns	27.95±0.64 ns	29.59±0.97 ns	4.60±0.02 A[1]	0.64±0.01 A[1]
Plant (P)	44.35±0.35 ns	28.02±0.37 ns	30.52±0.61 ns	4.48±0.02 B	0.64±0.01 A
Medium (M)	43.36±0.24 ns	27.84±0.35 ns	28.36±0.47 ns	4.09±0.06 C	0.60±0.01 B
Treatment Period (TP)					
0	43.80±0.72 ns	27.95±0.92 ns	29.59±1.40 ns	4.60±0.03 A[2]	0.64±0.01 A[2]
1	43.09±0.48 ns	27.24±0.63 ns	28.30±0.90 ns	4.30±0.09 C	0.59±0.01 B
2	44.99±0.57 ns	28.56±0.60 ns	31.42±1.05 ns	4.46±0.03 B	0.63±0.01 A
3	43.77±0.49 ns	27.73±0.60 ns	29.26±0.94 ns	4.30±0.09 C	0.64±0.02 A
4	43.50±0.46 ns	27.30±0.58 ns	28.75±0.88 ns	4.31±0.11 C	0.63±0.01 A
5	43.87±0.45 ns	28.83±0.59 ns	29.64±0.86 ns	4.36±0.06 BC	0.62±0.01 AB
Shelf Life (SL)					
0. day	44.23±0.40 ns	27.16±0.45 B[3]	30.43±0.77 A[3]	4.31±0.04 B[3]	0.64±0.01 A[3]
7. day	43.44±0.18 ns	28.71±0.27 A	28.56±0.30 B	4.46±0.05 A	0.61±0.01 B
TM × TP					
C × 1	43.80±1.33 ns	27.95±1.70 ns	29.59±2.58 ns	4.60±0.06 A,a[4]	0.64±0.01 ns
C × 2	43.80±1.33 ns	27.95±1.70 ns	29.59±2.58 ns	4.60±0.06 A,a	0.64±0.01 ns
C × 3	43.80±1.33 ns	27.95±1.70 ns	29.59±2.58 ns	4.60±0.06 A,a	0.64±0.01 ns
C × 4	43.80±1.33 ns	27.95±1.70 ns	29.59±2.58 ns	4.60±0.06 A,a	0.64±0.01 ns
C × 5	43.80±1.33 ns	27.95±1.70 ns	29.59±2.58 ns	4.60±0.06 A,a	0.64±0.01 ns
P × 1	41.96±0.31 ns	26.57±0.86 ns	26.85±0.82 ns	4.47±0.02 A,a	0.59±0.04 ns
P × 2	47.14±0.35 ns	29.04±0.74 ns	35.11±0.59 ns	4.43±0.02 AB,a	0.65±0.01 ns
P × 3	44.88±0.31 ns	28.40±0.39 ns	31.24±0.34 ns	4.42±0.07 A,a	0.64±0.06 ns
P × 4	44.00±0.38 ns	27.02±0.31 ns	29.76±0.49 ns	4.55±0.06 A,a	0.65±0.03 ns
P × 5	44.32±0.37 ns	29.12±0.52 ns	30.60±0.69 ns	4.40±0.05 A,a	0.63±0.02 ns
M × 1	43.52±0.32 ns	27.19±0.50 ns	28.45±0.41 ns	3.83±0.13 B,c	0.53±0.02 ns
M × 2	44.04±0.25 ns	28.68±0.38 ns	29.56±0.45 ns	4.33±0.02 B,a	0.59±0.02 ns
M × 3	42.61±0.29 ns	26.83±0.57 ns	26.95±0.63 ns	3.89±0.17 B,bc	0.64±0.03 ns
M × 4	42.71±0.21 ns	26.93±0.58 ns	26.91±0.37 ns	3.79±0.17 B,c	0.60±0.03 ns
M × 5	43.49±0.24 ns	29.43±0.35 ns	28.71±0.36 ns	4.08±0.06 B,b	0.59±0.02 ns
TM × SL					
C × 0. day	44.98±0.93 A,a[5]	26.50±1.11 ns	31.62±1.84 ns	4.47±0.01 ns	0.65±0.01 ns
C × 7. day	42.62±0.09 B,b	29.40±0.47 ns	27.57±0.17 ns	4.73±0.01 ns	0.63±0.00 ns
P × 0. day	44.39±0.59 AB,a	27.75±0.56 ns	31.09±1.02 ns	4.45±0.01 ns	0.65±0.02 ns
P × 7. day	44.31±0.41 A,a	28.29±0.49 ns	29.96±0.68 ns	4.51±0.04 ns	0.62±0.02 ns
M × 0.day	43.32±0.44 B,a	27.23±0.56 ns	28.58±0.87 ns	4.02±0.09 ns	0.61±0.01 ns
M × 7. day	43.40±0.20 AB,a	28.44±0.39 ns	28.15±0.37 ns	4.15±0.09 ns	0.58±0.01 ns
Significant effects					
TM	0.190	0.968	0.132	0.000	0.002
TP	0.240	0.534	0.411	0.000	0.032
SL	0.077	0.010	0.035	0.000	0.007
TM × TP	0.348	0.979	0.650	0.000	0.369
TM × SL	0.046	0.242	0.202	0.061	0.941
TP × SL	0.737	0.918	0.921	0.599	0.125
TM × TP × SL	0.996	0.999	0.999	0.958	0.222

[1]Letters indicate differences between treatment methods. [2]Letters indicate differences between treatment periods. [3]Letters indicate differences between shelf-life periods. [4]First letters represent the differences between treatment methods for each treatment period and the second letters represent the differences between treatment periods for each shelf-life treatment methods. [5]First letters represent the differences between treatment methods for each treatment period and the second letters represent the differences between treatment periods for each shelf life treatment methods. ns: non-significant. C: Control, P: Plant, M: Medium.

CONCLUSION

This study underscores the significant effects of the application method and timing of gibberellic acid (GA_3) on plant growth, yield, and post-harvest quality in tomatoes. Applying GA_3 every two weeks effectively increased plant height and stem diameter; however, more frequent applications adversely impacted fruit size,

overall yield, and root fresh weight. Regarding shelf life, GA_3 treatments applied every four weeks resulted in the least weight loss, with moderate applications being the most effective in reducing fruit rot. Furthermore, applying GA_3 to the plants helped maintain peel color brightness and increased soluble solid content (SSC) and titratable acidity (TA). However, these values remained statistically like those of the control group. These findings highlight the importance of optimizing the frequency and method of GA_3 application to balance growth promotion, yield, and post-harvest quality. Future research should explore application strategies that maximize benefits while minimizing adverse effects.

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

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Hakan Başak: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; review and editing.
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