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Manipulating Growth, Yield, and Quality of Tomato Fruit (*Solanum lycopersicum* L.): Influences of Gibberellin and Paclobutrazol

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ABSTRACT

The decline in tomato productivity is often attributed to climate change, as it disrupts the flowering and fruit formation processes. Gibberellin (GA_3) and paclobutrazol (PBZ) function to stimulate flowering in plants. This research aimed to analyze the influences of GA_3 and PBZ on the growth, yield, and quality of Tymoti F_1 tomato fruits. The experiment was conducted from June to September 2022. A randomized complete block design (RCBD) was used consisting of the control (0 ppm), GA_3 (50 ppm, 100 ppm, and 150 ppm), and PBZ (50 ppm, 100 ppm, and 150 ppm) treatments. The results showed that GA3 at 100 ppm increased plant height, number of flowers and fruits, fruit weight, Hue° value, and vitamin C content. The GA_3 treatment at 150 ppm enhanced lycopene, β-carotene, and total carotenoid content. Paclobutrazol at 50 ppm improved the peel color (L* and b*). PBZ at 100 ppm increased the fruit diameter, and at 150 ppm increased the leaf chlorophyll index, flowering age, fruit set, soluble solids content (SSC), fructose, glucose, and total sweetness index (TSI) in the fruits.

Introduction

Tomato (*Solanum lycopersicum* L.) is highly regarded for its fresh taste and is a rich source of nutrients, including vitamins, minerals, phenolic compounds such as phenolic acids and flavonoids, and carotenoids like lycopene and β-carotene. These compounds serve as potent antioxidants, offering numerous health benefits (Chaudhary et al., 2018; Kusumiyati et al., 2022; Kusumiyati & Putri, 2023). Growing awareness of the importance of a healthy lifestyle has led to an increased demand for nutritious foods, with tomatoes being sought after worldwide (Dehnavard et al., 2017). However, achieving high-quality tomato production is challenging due to various environmental factors and abiotic stresses. Despite these challenges, greenhouse tomato production has been steadily increasing on a global scale (Quinet et al., 2019; Souri & Tohidloo, 2019).

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One of the primary environmental challenges is high-temperature stress caused by climate change. Temperature is crucial to the growth of tomato plants, which typically thrive in a range of 21 °C to 29 °C. In Indonesia, however, temperatures can rise to 35 °C during the day and 24 °C at night (Nuraini et al., 2021). Over the past 134 years, data analyses have shown a maximum daily temperature increase of 2.12 °C per century, which has disrupted tomato growth and development (Siswanto et al., 2016). Elevated temperatures can cause pollen to become sticky and inactive, leading to pollination failure, reduced flower numbers, decreased fruit set ratios, and ultimately, reduced fruit formation (Arthanari & Dhanapalan, 2019). These conditions hinder the growth, flowering, and fruit development of tomatoes, resulting in decreased production.

To mitigate these challenges, one effective approach is the manipulation of plant nutrition, particularly through the application of plant growth regulators (PGRs). Exogenous application of PGRs, even in low concentrations, can either stimulate or inhibit plant growth and development, making it essential to apply them at the appropriate concentrations. Proper PGR application can enhance yield, tolerance to abiotic stress, and physiological traits (Desta & Amare, 2021). PGRs also influence secondary metabolite production (Lv et al., 2021). For instance, gibberellin (GA_3) and paclobutrazol (PBZ) are often used to regulate plant growth conditions. GA_3 stimulates cell division and elongation, thereby increasing stem height. It also plays a key role in stem elongation, flower formation, and fruit ripening. The application of GA_3 in tomato plants enhances protein synthesis, shoot elongation, and photosynthesis activity (Pramanik et al., 2017). GA_3 has also been found to influence the synthesis of primary and secondary metabolites in grapevine organs (Murcia et al., 2017). A concentration of 100 ppm of GA_3 significantly increased tomato plant height by 42%, stem diameter by 0.18%, leaf count by 1.34%, branch count by 20.67%, and fruit weight by 1.42% compared to the control treatment (0 ppm) (Ning et al., 2018).

PBZ, in contrast, is an anti-gibberellin that inhibits the biosynthesis of GA_3, thereby preventing cell elongation (Desta & Amare, 2021). It is particularly useful in controlling plant height, especially in fruit-bearing crops, and is widely used by farmers to enhance crop productivity (Kumari et al., 2018). PBZ can either delay or accelerate flowering, depending on the plant variety (Desta & Amare, 2021). A study reported that applying PBZ at a concentration of 100 ppm combined with 150 mL of banana peel fertilizer increased the number of fruits per plant, fresh fruit weight per plant, and fruit set in tomato plants (Jayanti et al., 2022). PBZ is recommended for improving growth, yield, and quality (Desta & Amare, 2021). The response of tomato plants to different PGRs and concentrations varies, as previous research has shown significant effects on plant height, fruit shape, pericarp cell structure, flowering time, and fruit production (Chen et al., 2020; Li et al., 2022).

This study, therefore, investigates the effects of GA_3 and PBZ on the growth, yield, and quality of tomato fruits, particularly focusing on the Tymoti F_1 variety. The use of the Tymoti F_1 tomato is expected to contribute to the success of the research and provide a viable recommendation for improving tomato production in Indonesia.

Material and Methods

This research was conducted in a screen house at Ciparanje, Faculty of Agriculture, Universitas Padjadjaran, Indonesia, from June to September 2022. The altitude of the location was approximately 750 m above sea level (m asl) at coordinates 6°54'50.9"S 107°46'17.3"E. The maximum temperature was 28.19 °C, and the minimum was 12.83 °C. The average daily temperature was 22.43 °C, with a humidity of 88.70%, while laboratory analysis was carried out at the Horticulture Laboratory, Faculty of Agriculture, Universitas Padjadjaran, Indonesia. Tomato variety used was Tomat Tymoti F_1, known for the resistance to geminiviruses, blossom end rot, and high yield potential (Savitri et al., 2019).

A randomized complete block design (RCBD) with seven treatments was used including control (0 ppm), GA_3 (50, 100, 150 ppm), and PBZ (50, 100, 150 ppm). Each treatment was replicated four times, resulting in 28 experimental units. Each unit consisted of three plants, being 84 in total. Data analysis was performed using an F-test ($P \leq 0.05$) to determine the influences of the given treatments. When the analysis of variance (ANOVA) showed significant differences, further testing was conducted with Duncan's Multiple Range Test (DMRT) ($P \leq 0.05$). All data analyses were performed using Statistical Product and Service Solutions (SPSS) version 16.0.

The planting preparation started by sowing Tomat Tymoti F_1 seeds in a tray for approximately 21 d. Subsequently, the screen house area was cleaned, and the planting medium, a mixture of soil: charcoal husk: and chicken manure (1:2:3) with Dazomet 98% as a soil sterilizer, was prepared. The medium was then placed in polybags sized 35 x 40 cm (3 kg polybag^{-1}).

Polybags were arranged based on the experimental plots, and the medium was incubated for a week. Furthermore, the medium was moistened with water, and tomato seedlings were transplanted 14 d after planting (DAP). Bamboo stakes were used to support the upright growth of plant. Fertilizer was applied three times (14 DAP, 28 DAP, 42 DAP) using NPK fertilizer (16:16:16) (11.7 g polybag^{-1}). Plant growth regulators (PGR) were applied at 21 DAP (15 mL volume) and 42 DAP (30 mL volume) through morning spray. Harvesting of Tymoti F_1 tomato fruits was accomplished at breaker + 4 stages.

Growth observation
Plant height (cm)
Measurements were directed at the plant stem base above the ground to the apical growth point. Plant height was measured weekly from 28 to 42 DAP.

Chlorophyll content index (CCI)
CCI observation on leaf was conducted in the morning using a chlorophyll meter SPAD CCM-200 Plus (Konika Minolta, Inc, Japan). The third leaf from the apex was selected as the sample, and measurements were taken every 2 weeks at 28 DAP and 42 DAP.

Yield observation
Days to first flower appearance (DAP)
The time of the first flower appearance was calculated when the first flower appeared on the observed plant. The recording was performed when the flower was fully bloomed or reached anthesis.

Number of flowers per plant
The flower count was observed by counting each fully-bloomed flower. Observations continued until no more flowers appeared, and the total number of flowers per plant was calculated and averaged.

Number of fruits per plant
Observations on the number of fruits per plant were conducted when plants entered the final generative phase. The total count of tomato produced per plant was recorded.

Fruit set (%)
The fruit set ratio was calculated by comparing the data of number of fruits per plant with number of flowers per plant. Fruit set represents the transformation of the ovary from a flower to a fruit. The calculation of the value can be performed using the formula:

$$\text{Fruit set (\%)} = \frac{\Sigma \text{ fruit formed}}{\Sigma \text{ total flowers}} \text{ x } 100\%$$

Fruit weight per plant (g)
Tomato fruits were harvested at the appropriate criteria (breaker + 4) followed by weighing using a digital scale. Fruit weight per plant was obtained by summing the weights of all fruits from the same treatment and dividing them by the number of plants.

Fruit quality observation
Fruit diameter (cm)
Measurements of fruit diameter were conducted on the horizontal and vertical sides. Fruit diameter was obtained by averaging the measurements from both sides.

Peel color analysis
Peel color analysis of tomato fruits was performed immediately after harvesting. Quantitative measurements were taken using the CM-600d color spectrophotometer (Konica Minolta, Inc, Japan), and the displayed color values included L*, a*, and b*. The L* value represented lightness, with 100 indicating the brightest color and 0 implying the darkest. The a* value showed green (negative a*) or red (positive a*), while the b* value signified blue (negative b*) or yellow (positive b*) hues (Kusumiyati et al., 2019; Mendoza et al., 2007). Saturation or color purity intensity was determined by measuring chroma (C*) and the central angle of the primary color pair was assessed by measuring Hue (h°). Measurements of C* and h° were performed using a relevant formula (Pathare et al., 2013):

$$\text{Chroma (C*)} = \sqrt{(a^*)^2 + (b^*)^2}$$

$$\text{Hue (h°)} = \tan^{-1}\frac{b^*}{a^*}$$

Fruit firmness
Fruit firmness was measured using a texture analyzer (Stable Micro Systems, Surrey, UK). The probe for measurement was a stainless steel cylinder with a diameter of 2 mm (Kusumiyati et al., 2021; Suhaimi et al., 2021).

Water content
Water content was obtained from fruit samples harvested under the same criteria without storage using the gravimetric method (Kusumiyati et al., 2018a; 2019b; 2021c). Small cuts were made in the samples, which were then sliced and placed in aluminum foil. Subsequently,

the cuts were weighed to 3 g and placed into an oven at 105 °C for 3 h. The samples were removed from the oven and cooled in a desiccator for 5-10 min, followed by reweighing via an analytical balance. The drying process was repeated until reaching a constant sample weight. The water content was calculated using the formula:

$$\% \text{ Water content} = \frac{\text{W1-W2}}{\text{W1}} \text{ x } 100\%$$

Where:
W1 = Weight of the cup + initial sample weight (Before oven drying)
W2 = Weight of the cup + sample after oven drying

Total soluble solids (TSS)

TSS value in tomato fruit was measured through a refractometer (Atago, Japan) (Huang et al., 2018; Kusumiyati et al., 2020a; 2021b). Small cuts were made in the samples, which were then blended and centrifuged. A volume of 5 mL was placed into a centrifuge (Corona 80-2 Centrifuge) and operated at 4000 rpm for 10 min. The supernatant was collected using a micropipette (Thermo Fisher Scientific, Waltham, USA) and dropped onto the refractometer. Values on the instrument were expressed in % Brix.

Fructose, sucrose, glucose, and total sweetness index

High-Performance Liquid Chromatography (HPLC) enabled measurements of sucrose, fructose, and glucose levels (Shimadzu, LC 20AT Prominence, Japan) (Kusumiyati et al., 2022). The samples were centrifuged to obtain the homogenate, and then the homogenate was diluted to 1:1 with acetonitrile and homogenized using a vortex. About 1 mL of the mixture was placed into an HPLC vial and analyzed using a refractive index detector (RID). The results of fructose, glucose, and sucrose levels enabled calculations of Total Sweetness Index (TSI) (Amin et al., 2018):

$$TSI = [(1{,}00 \times sucrose) + (0{,}76 \times glucose) + (1{,}50 \times fructose)]$$

Vitamin C

Vitamin C test followed the procedure outlined by Kumar et al. (2011), and HPLC analysis conditions were as follows: UV detector with a wavelength of 264 nm, flow rate of approximately 1 mL min^{-1} with methanol, column (C18/Phenomenek with a length of 150 mm and a diameter of 4.6 mm, with an injection volume (20 µL). The mobile phase used was 0.1% acetic acid and methanol in a ratio of 95:5 (v/v).

Preparation of dry samples

Dry samples were prepared by slicing small pieces and placing on aluminum foil arranged on a baking sheet. The sliced samples were then placed in an oven (Memmert Schutzart DIN 40050-IP 20, Germany) at a temperature of 60 °C for approximately 15 h. Once dried, the samples were ground using a grinder and further placed in a ziplock plastic bag, labeled, and stored in a refrigerator.
An amount of 95-105 mg of the dry sample was placed in a 10 mL volumetric flask. Subsequently, methanol was added, and the mixture was placed in a sonicator (Baku BK-2000, China) for 30 min at room temperature. The solution was transferred to a centrifuge tube and the sample was centrifuged for 10 min at a speed of 4000 rpm. The resulting supernatant was transferred to vial bottles for analysis of total phenolic content, total flavonoid, and antioxidants.

Total phenolic content

The measurement of total phenolic content was performed using the Folin Ciocalteu method (Sytar et al., 2018), with the dry extracted sample. An aliquot of 0.1 mL extraction was placed into a reaction tube, to which 0.4 mL methanol and 2.5 mL Folin reagent were added. The mixture was incubated at room temperature for 3-5 min. Subsequently, 2 mL of a 7.5% sodium bicarbonate solution was added, homogenized, and incubated again at room temperature for 60 min. Absorbance values were measured at 765 nm with a spectrophotometer (UV-Vis Shimadzu UV-1601, Japan).
Standard solutions were prepared at various concentrations of 2, 4, 8, 16, 32, 64, and 128 mg L^{-1}. The absorbance measurements of the standard were used to create a calibration curve. The total phenolic content in the sample was converted to GAE mg 100 g^{-1} using the formula:

$$\text{Total phenolic (mg GAE } 100 g^{-1}) = \frac{\text{C.V}}{\text{W}} \text{ x } 100$$

Description:
C = Quercetin concentration (mg L^{-1})
V = Volume test solution (L)
W = Weight of sample (g)

Total flavonoid content

The measurement of total flavonoid content followed a procedure by Sytar et al. (2018) using a dry extracted sample. An aliquot of 0.5 mL extraction was placed into a reaction tube, then

1.5 mL methanol, 0.1 mL aluminum chloride, 0.1 mL of acetate, and 2.8 mL distilled water were added. The solution was homogenized and incubated for 30 min at room temperature. Absorbance was measured at a wavelength of 432 nm using a UV-Vis spectrophotometer. Standard solutions were prepared at various concentrations: 2, 4, 8, 16, 32, 64, and 128 mg $^{L-1}$. Furthermore, the sample and standards were measured at 432 nm. The absorbance measurements of the standard were used to create a calibration curve. Total flavonoid content in the sample was converted to QE mg 100 g^{-1} using the formula.

$$\text{Total Flavonoid (mg QE } 100g^{-1}) = \frac{\text{C.V}}{\text{W}} \text{x } 100$$

Description:
C = Quercetin concentration (mg L^{-1})
V = Volume test solution (L)
W = Weight of sample (g)

Antioxidant activity and capacity

Antioxidant activity and capacity were measured using a modified procedure (Kusumiyati et al., 2022; Lim and Murtijaya, 2007), with the dry extracted sample. The test was carried out with the 2,2-diphenyl-1-picrylhydrazyl (DPPH) method. The sample and DPPH were then incubated in the dark for 30 min at room temperature. Absorbance values were measured at 515 nm. The percentage of inhibition was calculated as follows:

$$\%\ Inhibition\ = \frac{blank\ -\ sample}{blank} \times\ 100$$

The $_{IC50}$ of the sample was determined from the inhibition curve (50% inhibition), and ascorbic acid was used as the standard. Ascorbic Acid Equivalent Antioxidant Capacity (AEAC) in the dry sample (mg) 100 g^{-1} was determined based on the equation:

$$\text{AEAC} = \frac{\text{IC50 (ascorbic acid)}}{\text{IC50 (sample)}} \times\ 100.000$$

Results

Plant height (cm)

At 28 DAP, 35 DAP, and 42 DAP, both GA_3 and PBZ concentrations significantly influenced plant height. Duncan's Multiple Range Test ($P \leq 0.05$) determined significant differences for plant height (Table 1). Based on measurements at DAP 28, the treatment with GA_3 at 100 ppm showed a significant difference in plant height (84.00 cm) compared to several other treatments, particularly PBZ at 150 ppm, which yielded 66.20 cm. However, the GA_3 treatment at 100 ppm did not differ from 150 ppm. The final measurement at 42 DAP yielded the same results, with the GA_3 treatment at a concentration of 100 ppm resulting in a plant height of 100.00 cm. This treatment showed the most significant difference compared to the plant height of PBZ at 150 ppm, yielding 67.18 cm.

Table 1. The influence of various concentrations of GA_3 and PBZ on tomato plant height.

Treatment	Plant Height (cm)		
	28 DAP	35 DAP	42 DAP
C	76,05^{bc}	78,78^{bc}	83,10^{bc}
G50	74,08^{abc}	75,08^{ab}	78,08^{abc}
G100	84,00^{d}	88,30^{d}	100,00^{d}
G150	81,35^{cd}	86,80^{cd}	87,50^{c}
P50	73,60^{abc}	74,45^{ab}	74,55^{ab}
P100	72,45^{ab}	73,90^{ab}	74,48^{ab}
P150	66,20^{a}	67,05^{a}	67,18^{a}

Description: numbers followed by the same letter do not indicate a significant difference according to Duncan's Multiple Range Test ($P \leq 0.05$). C = control, G50 = GA_3 50 ppm, G100 = GA_3 100 ppm, G150 = GA_3 150 ppm and P50 = PBZ 50 ppm, P100 = PBZ 100 ppm, P150 = PBZ 150 ppm.

Chlorophyll content index (CCI)

A crucial parameter reflecting the chlorophyll content in leaf is CCI. Leaf chlorophyll index measures the amount contained in leaf which is a vital green pigment for the process of photosynthesis. The level of chlorophyll index can provide clues about nutrient uptake, lighting, and other environmental conditions that generally and on most influence leaf photosynthesis activity (Serri et al., 2021). This measurement is usually conducted via a non-destructive evaluation tool to monitor the nutritional status. A higher chlorophyll index value indicates greater efficiency in capturing solar energy and producing food through photosynthesis. Therefore, monitoring CCI value in tomato plant can be a crucial parameter in maximizing harvest yields and fruit quality. At 28 DAP and 42 DAP, there was a significant influence by several treatments. Further examination using the 5% DMRT test (Table 2) enabled measurements using a chlorophyll meter, an instrument that reads chlorophyll content and assesses the nitrogen status in leaf tissues. The chlorophyll content is closely related to the essential element nitrogen because the green pigment in leaf tissues is composed of nitrogen.

Table 2. Influence of various concentrations of GA_3 and PBZ on the chlorophyll index of tomato leaf.

Treatment	Chlorophyll content index	
	28 DAP	42 DAP
C	46,88^{bc}	47,98^{ab}
G50	40,20^{a}	48,75^{abc}
G100	44,23^{ab}	48,00^{ab}
G150	31,33^{a}	43,50^{a}
P50	49,53^{bc}	50,25^{bc}
P100	50,13^{c}	54,05^{cd}
P150	52,33^{c}	57,00^{d}

Description: numbers followed by the same letter do not show a significant difference according to Duncan Multiple Range Test (P≤0.05). C = control, G50 = GA_3 50 ppm, G100 = GA_3 100 ppm, G150 = GA_3 150 ppm and P50 = PBZ 50 ppm, P100 = PBZ 100 ppm, P150 = PBZ 150 ppm.

Time of first flower appearance

The time of first flower appearance in tomato plants depends on several factors, such as the variety, environmental conditions, and cultivation techniques. Generally, plants start producing flowers after reaching a certain growth stage, namely, the end of the vegetative phase. Factors including temperature, light, and nutrition also have significant influences on the time of the first flower appearance. Understanding when flowers appear on tomato plants becomes crucial in managing harvest timing and maximizing fruit yield. The applied treatments significantly influenced the time of the first flower appearance. The results of further examination using the 5% DMRT test are presented in Table 3.

Table 3. The influence of various concentrations of GA_3 and PBZ on the time of the first flower appearance in tomato plants.

Treatment	Time of first flower appearance (DAP)
C	23,98^{d}
G50	23,65^{bcd}
G100	23,25^{abc}
G150	23,93^{cd}
P50	23,58^{bcd}
P100	23,00^{ab}
P150	22,83^{a}

Description: numbers followed by the same letter do not indicate a significant difference according to Duncan's Multiple Range Test (P≤0.05). C = control, G50 = GA_3 50 ppm, G100 = GA_3 100 ppm, G150 = GA_3 150 ppm and P50 = PBZ 50 ppm, P100 = PBZ 100 ppm, P150 = PBZ 150 ppm.

Number of flowers, number of fruits, and fruit set (%)

The various treatments had significant impacts on the number of flowers, fruits, and fruit set per plant. The results of further testing using the 5% DMRT test are presented in Table 4. As shown in Table 4, GA_3 and PBZ treatments at various concentrations had a significantly different influence on the number of flowers. Plants treated with GA_3 at 100 ppm had the highest number of flowers (53.75). This treatment significantly differed from PBZ at 150 ppm, with 33.08 flowers. The application of GA_3 at 100 ppm also impacted the number of fruits (44.50). This was consistent with Garmendia et al. (2019) stating that the use of GA resulted in a significant increase in fruit set. Number of fruits produced by GA_3 treatment at 100 ppm differed significantly from PBZ treatments at 50, 100, and 150 ppm, namely 29.75, 31.75, and 32.43 fruits, respectively. PBZ is recognized for its ability to reduce the rate of vegetative growth by inducing early growth cessation, thus leading to carbohydrate buildup and a minor decrease in total nitrogen within terminal shoots. These changes promote blooming by maintaining a high carbon-to-nitrogen ratio (Gollagi et al., 2019).

Fruit weight

Fruit weight in tomato plant is a crucial parameter reflecting harvest yield and production quality. This parameter influences the economic value and consumer satisfaction with tomato products. Fruit weight can be influenced by various factors, including plant nutrition, water management, weather conditions, and the type of variety planted. Monitoring and measuring fruit weight can help farmers evaluate the effectiveness of farming practices and provide useful information for harvest planning. In this context, optimizing fruit weight in tomato plants is a primary target to enhance production yields and ensure that the produced fruits fulfill the quality standards desired by the market and consumers (Table 5).

Fruit diameter

The diameter of tomato fruit is one of the crucial factors in determining the quality and maturity. The size might vary depending on the type of tomato variety being cultivated. In the growth and development process, the diameter continues to increase over time. In the early stages, fruits typically have a smaller diameter and continue to

enlarge. Furthermore, the diameter can also be affected by factors such as environmental conditions, nutrient availability, and proper plant management. Tomato plants receiving sufficient nutrients, and with the ability to maintain moisture, tend to produce fruit with a larger diameter. Diameter size also affects crop use, for example, tomato with smaller diameter is often used as raw materials for making sauces, pasta, or juice. Meanwhile, those with larger diameters are commonly used for direct consumption or as ingredients in dishes including salads (Table 6).

Table 4. Influence of various concentrations of GA_3 and PBZ on the number of flowers, number of fruits, and fruit set (%) in tomato plants.

Treatment	Number of flowers per plant	Number of fruits per plant	Fruit set (%)
C	45,28^{c}	36,15^{b}	79,98^{a}
G50	48,75^{c}	40,50^{c}	83,40^{ab}
G100	53,75^{d}	44,50^{d}	83,58^{ab}
G150	46,45^{c}	41,43^{c}	89,15^{bc}
P50	38,75^{b}	32,43^{a}	83,75^{ab}
P100	38,00^{b}	31,75^{a}	83,75^{ab}
P150	33,08^{a}	29,75^{a}	90,35^{c}

Description: numbers followed by the same letter do not indicate a significant difference according to Duncan's Multiple Range Test ($P \leq 0.05$). C = control, G50 = GA_3 50 ppm, G100 = GA_3 100 ppm, G150 = GA_3 150 ppm and P50 = PBZ 50 ppm, P100 = PBZ 100 ppm, P150 = PBZ 150 ppm.

Table 5. Influence of various concentrations of GA_3 and PBZ on weight of tomato fruit.

Treatment	Fruit weight per plant (g)
C	1260,13^{ab}
G50	1389,18^{bc}
G100	1498,30^{c}
G150	1369,35^{abc}
P50	1245,43^{ab}
P100	1288,08^{ab}
P150	1225,23^{a}

Description: numbers followed by the same letter do not show significant differences according to Duncan's Multiple Range Test ($P \leq 0.05$). C = control, G50 = GA_3 50 ppm, G100 = GA_3 100 ppm, G150 = GA_3 150 ppm and P50 = PBZ 50 ppm, P100 = PBZ 100 ppm, P150 = PBZ 150 ppm.

Table 6. Influence of various concentrations of GA3 and PBZ on diameter of tomato fruit.

Treatment	Fruit Diameter (mm)
C	40,48^{a}
G50	41,50^{ab}
G100	40,80^{ab}
G150	40,35^{a}
P50	41,78^{b}
P100	43,28^{c}
P150	43,25^{c}

Description: numbers followed by the same letter do not show significant differences according to Duncan's Multiple Range Test ($P \leq 0.05$). C = control, G50 = GA_3 50 ppm, G100 = GA_3 100 ppm, G150 = GA_3 150 ppm and P50 = PBZ 50 ppm, P100 = PBZ 100 ppm, P150 = PBZ 150 ppm.

Color of fruit peel

The color of fruit peel with values of a* and C* did not differ significantly among the treatments. Certain treatments had a significant effect on peel color with values of L*, b*, and h°. Further testing using DMRT (P≤0.05) (Table 7) helped pinpoint which specific treatments resulted in significant changes in the peel color parameters, contributing to a better understanding of how these treatments influence the overall fruit appearance.

Fruit Firmness

The firmness of tomato fruit has a significant influence on its quality and durability during the postharvest process. The level of fruit firmness can affect the duration of transportation, storage time, resistance to diseases, and mechanical damage. The method for measuring fruit firmness involves using specific tools that allow for objective firmness values, providing a reliable assessment of this important quality parameter. A deep understanding of tomato fruit firmness is key to maintaining quality during marketing. ANOVA results showed that the application of GA_3 and PBZ had no significant influence on the fruit firmness of *Tymoti* F_1 tomato (Table 8).

Water content

The treatments did not significantly influence the water content of *Tymoti* F_1 tomato fruit. Based on Table 9, the water content for each treatment showed no significant differences (78-79%). Meanwhile, this water content is smaller than the normal limit of typical tomato fruit. *Tymoti* F_1 tomato harvested at breaker + 4 maturity criteria remained physically dense, so the water content was smaller compared to fully ripened fruits.

Table 7. Influence of various concentrations of GA_3 and PBZ on color of tomato fruit peel.

Treatment	Color of the Fruit Peel				
	L*	a*	b*	C*	h°
C	43,28^{abc}	29,82^{a}	35,31^{bc}	46,33^{a}	49,78^{ab}
G50	43,60^{bc}	29,79^{a}	35,91^{cd}	46,75^{a}	50,18^{abc}
G100	43,85^{bc}	29,09^{a}	36,16^{cd}	46,48^{a}	51,10^{c}
G150	42,50^{a}	30,14^{a}	34,75^{ab}	46,10^{a}	49,03^{a}
P50	44,08^{c}	29,40^{a}	36,39^{d}	46,88^{a}	51,00^{bc}
P100	42,85^{ab}	29,76^{a}	34,27^{a}	45,45^{a}	49,00^{a}
P150	43,68^{bc}	29,50^{a}	36,15^{cd}	46,78^{a}	50,73^{bc}

Description: numbers followed by the same letter do not show significant differences according to the Duncan Multiple Range Test (P≤0.05). C = control, G50 = GA_3 50 ppm, G100 = GA_3 100 ppm, G150 = GA_3 150 ppm and P50 = PBZ 50 ppm, P100 = PBZ 100 ppm, P150 = PBZ 150 ppm.

Table 8. Influence of various concentrations of GA_3 and PBZ on firmness of tomato fruit.

Treatment	Fruit Firmness (N)
C	6,94^{a}
G50	8,65^{a}
G100	7,21^{a}
G150	7,02^{a}
P50	7,58^{a}
P100	7,12^{a}
P150	7,72^{a}

Description: numbers followed by the same letter do not show significant differences according to Duncan's Multiple Range Test (P≤0.05). C = control, G50 = GA_3 50 ppm, G100 = GA_3 100 ppm, G150 = GA_3 150 ppm and P50 = PBZ 50 ppm, P100 = PBZ 100 ppm, P150 = PBZ 150 ppm.

Table 9. Influence of various concentrations of GA_3 and PBZ on water content of tomato fruit.

Treatment	Water content
C	78,52[a]
G50	78,82[a]
G100	78,78[a]
G150	79,10[a]
P50	79,13[a]
P100	79,49[a]
P150	79,01[a]

Description: numbers followed by the same letter do not show significant differences according to Duncan's Multiple Range Test (P≤0.05). C = control, G50 = GA_3 50 ppm, G100 = GA_3 100 ppm, G150 = GA_3 150 ppm and P50 = PBZ 50 ppm, P100 = PBZ 100 ppm, P150 = PBZ 150 ppm.

Table 10. Influence of various concentrations of GA_3 and PBZ on TSS of tomato fruit.

Treatment	Total Soluble Solids (%Brix)
C	3,94[b]
G50	3,93[b]
G100	3,49[a]
G150	3,81[b]
P50	3,78[b]
P100	4,23[c]
P150	4,26[c]

Description: numbers followed by the same letter do not show significant differences according to Duncan's Multiple Range Test (P≤0.05). C = control, G50 = GA_3 50 ppm, G100 = GA_3 100 ppm, G150 = GA_3 150 ppm and P50 = PBZ 50 ppm, P100 = PBZ 100 ppm, P150 = PBZ 150 ppm.

TSS, fructose, glucose, sucrose, and total sweetness index

Based on Table 10, TSS measurement of tomato fruit in this research yielded significantly different results. TSS produced with PBZ concentrations of 100 and 150 ppm was 4.23 and 4.26% Brix, respectively. This was significantly different from other treatments, specifically those treated with GA_3 at 100 ppm, yielding 3.49% Brix. Higher PBZ concentrations resulted in greater TSS levels. TSS values serve as an indicator of sweetness in fruits.

Table 11 shows ANOVA results for fructose, glucose, sucrose, and the total sweetness index (TSI) in tomato fruit. Each treatment had a significant influence on the fructose, glucose, and TSI parameters, but no effect was observed on sucrose. The fructose content in *Tymoti* F_1 tomato fruit produced by PBZ concentration of 150 ppm and GA_3 at 100 ppm treatments differed significantly from the control treatment, yielding 0.94%. However, this treatment did not differ substantially from PBZ concentrations of 50 and 100 ppm. There was a significant difference in glucose content among treatments, with GA_3 and PBZ at 100 and 150 ppm, each causing the highest values.

Table 11. Influence of various concentrations of GA_3 and PBZ on fructose, glucose, sucrose, and TSI.

Treatment	Fructose (%)	Glucose (%)	Sucrose (%)	TSI(%)
C	0,94[a]	1,20[a]	0,05[a]	2,37[a]
G50	1,90[b]	2,52[b]	0,06[a]	4,81[b]
G100	2,40[c]	3,52[c]	0,05[a]	6,32[c]
G150	1,95[b]	3,11[c]	0,04[a]	5,32[b]
P50	2,12[bc]	2,54[b]	0,05[a]	5,16[b]
P100	2,07[bc]	3,26[c]	0,04[a]	5,55[b]
P150	2,40[c]	3,56[c]	0,06[a]	6,37[c]

Description: numbers followed by the same letter do not show significant differences according to Duncan's Multiple Range Test (P≤0.05). C = control, G50 = GA_3 50 ppm, G100 = GA_3 100 ppm, G150 = GA_3 150 ppm and P50 = PBZ 50 ppm, P100 = PBZ 100 ppm, P150 = PBZ 150 ppm.

Total phenolic, total flavonoid, antioxidant activity, and antioxidant capacity

ANOVA results showed that the application of treatments did not affect the total phenolic, total flavonoid, antioxidant activity, and antioxidant capacity of tomato fruit (Table 12). Phenolic and flavonoid compounds function as antioxidants or free radical scavengers when consumed by humans. In this research, antioxidant activity was determined by examining IC_{50} value through

DPPH method. IC_{50} value is inversely proportional to the antioxidant capacity value. Thus, when the value is low, the antioxidant activity of the tested sample will be high and vice versa. The antioxidant activity and capacity values showed the level of antioxidant compounds in the tomato fruits. Based on previous reports, the application of GA_3 and PBZ increased the levels of total phenolic compounds, total flavonoids, and antioxidants. However, in this research, the given concentrations did not produce significant differences between the treatments.

Table 12. Influence of various concentrations of GA_3 and PBZ on total phenolic, total flavonoid, antioxidant activity, and antioxidant capacity.

Treatment	Total Phenolic (mg 100 g^{-1})	Total Flavonoid (mg 100 g^{-1})	IC_{50} (mg L^{-1})	AEAC (mg 100 g^{-1})
C	196,85[a]	183,89[a]	1075,10[a]	296,00[a]
G50	185,03[a]	163,84[a]	1018,02[a]	311,00[a]
G100	185,44[a]	190,10[a]	1090,38[a]	292,75[a]
G150	211,91[a]	215,04[a]	1011,66[a]	321,75[a]
P50	199,28[a]	170,86[a]	1076,04[a]	297,00[a]
P100	199,28[a]	184,59[a]	1069,18[a]	298,50[a]
P150	218,19[a]	195,86[a]	1076,08[a]	298,00[a]

Description: numbers followed by the same letter do not show significant differences according to Duncan's Multiple Range Test (P≤0.05). C = control, G50 = GA_3 50 ppm, G100 = GA_3 100 ppm, G150 = GA_3 150 ppm and P50 = PBZ 50 ppm, P100 = PBZ 100 ppm, P150 = PBZ 150 ppm.

Vitamin C

Vitamin C is an essential nutrient that plays a crucial role in collagen production, which is vital for maintaining skin health and the integrity of connective tissues. It also enhances the body's ability to absorb iron from plant-based foods, helping to prevent anemia. Moreover, vitamin C acts as a powerful antioxidant, protecting body cells from damage caused by free radicals, which are harmful molecules that can contribute to chronic diseases and aging. The vitamin C content in tomato fruits was significantly affected by the treatments. Further testing using DMRT (P≤0.05) is depicted in Table 13.

Table 13. Influence of various concentrations of GA_3 and PBZ on vitamin C content.

Treatment	Vitamin C (mg 100 g^{-1})
C	2,35[b]
G50	1,58[a]
G100	3,55[c]
G150	2,97[bc]
P50	3,01[bc]
P100	3,05[bc]
P150	2,84[bc]

Description: numbers followed by the same letter do not show significant differences according to Duncan's Multiple Range Test (P≤0.05). C = control, G50 = GA_3 50 ppm, G100 = GA_3 100 ppm, G150 = GA_3 150 ppm and P50 = PBZ 50 ppm, P100 = PBZ 100 ppm, P150 = PBZ 150 ppm.

Discussion

GA_3 plays a crucial role in tomato plants, accumulating during fruit cell division and cell expansion in the early growth phase (Chen et al., 2016). This hormone stimulates stem growth and enhances cell enlargement and multiplication, leading to maximum plant height. A concentration of 100 ppm GA_3 was identified as the most suitable for achieving optimal height growth in *Tymoti* F_1 tomato plants (Table 1). However, higher concentrations, particularly of PBZ, suppress plant height. Previous research has shown that PBZ application helps control plant height, preventing lodging (Desta and Amare, 2021).

As shown in Table 2, the Chlorophyll Content Index (CCI) at 28 DAP with PBZ application at 100 and 150 ppm significantly differed from other treatments, except for 50 ppm and the control. The lowest chlorophyll index was observed in GA_3 treatments at 50, 100, and 150 ppm, with values of 40.20, 44.23, and 31.33, respectively. By 42 DAP, the CCI showed significant differences, with PBZ treatment at 150 ppm reaching 57.00, significantly higher than the GA_3 treatment at 150 ppm, which had a CCI value of 43.50. According to Mansuroglu et al. (2009), PBZ application to *Consolida orientalis* significantly improved leaf greenness. PBZ enhances chlorophyll content by producing precursors for chlorophyll formation (Nuraini et al., 2021).

As illustrated in Table 3, tomato plants treated

with varying concentrations of GA_3 and PBZ showed distinct responses to each treatment. Observations revealed that PBZ at 150 and 100 ppm, and GA_3 at 100 ppm, resulted in the earliest flowering at 22.83, 23.00, and 23.25 DAP, respectively, significantly earlier than the control at 23.98 DAP. PBZ suppresses cell division during vegetative growth, redirecting nutrients to stimulate generative organ development, notably flowers. The plants in this experiment entered the generative phase earlier than usual, as indicated by the appearance of the first flowers at 22–23 DAP. PBZ may enhance flowering by inhibiting the conversion of kaurene into kaurenoic acid due to its anti-gibberellin activity (Desta and Amare, 2021).

The treatments also impacted fruit set, as detailed in Table 6. Plants treated with GA_3 and PBZ at 150 ppm achieved fruit set rates of 89.15% and 90.35%, respectively, significantly higher than the control treatment at 79.98%. Fruit set, which refers to the percentage of formed fruits relative to the number of new flowers, was best with GA_3 and PBZ at 150 ppm. While the number of flowers produced by GA_3 at 100 ppm was greater than PBZ at 150 ppm, PBZ-treated plants were better able to retain flowers, leading to fruit development.

ANOVA results indicated that the treatments significantly affected fruit weight per plant. Further analysis using DMRT at a 5% significance level (Table 5) showed that GA_3 and PBZ treatments yielded different responses in terms of fruit weight per plant. The most significant increase was observed in plants treated with GA_3 at 100 ppm, which produced 1498.30 g of fruit per plant, significantly higher than the 1225.23 g from PBZ treatment at 150 ppm. However, the result from GA_3 at 100 ppm did not significantly differ from concentrations of 50 and 150 ppm. Plants treated with GA_3 at 100 ppm showed better vegetative growth, consistent with Chang and Lin (2006), who noted that GA_3 increases fruit weight. Balanced vegetative growth is crucial for enhancing fruit production compared to plants with inhibited growth.

The ANOVA results also revealed that treatments significantly affected fruit diameter per plant (Table 6). PBZ concentrations of 100 and 150 ppm produced the largest fruit diameters, both measuring 43.25 mm. These values significantly differed from those of GA_3 at 100 ppm (40.35 mm) and the control (40.48 mm). Additionally, the fruit diameter in GA_3 at 100 ppm did not significantly differ from treatments at 50 and 150 ppm. While PBZ-treated plants produced fewer fruits, they had larger diameters, as seen in prior research on *Malpighia emarginata*, where PBZ application increased fruit size (Sousa et al., 2020).

The ANOVA results indicated that the application of GA_3 and PBZ did not significantly affect the fruit firmness of *Tymoti* F_1 tomatoes (Table 8), with values 6-8 N across treatments. This consistency can be attributed to the uniform maturity stage of the harvested fruits, identified as breaker + 4. Tomato fruit quality, including factors like color, shape, and texture, is crucial for post-harvest longevity. Firmness, in particular, influences the shelf life and post-harvest quality of tomatoes (Huang et al., 2018). During ripening, firmness decreases as the fruit transitions from green to red, highlighting the importance of understanding these changes for optimizing storage and transportation conditions to maintain tomato quality for consumers.

The ANOVA results indicated that the treatments had no significant effect on the water content of *Tymoti* F_1 tomato fruit (Table 9). The tomatoes were harvested at the breaker + 4 maturity stage, meaning they were at an intermediate stage of ripeness, neither fully ripe nor immature. At this stage, tomatoes are physically denser and less mature than fully ripened fruit, likely contributing to lower water content. The firmness and density at this stage of development also support the observed lower moisture levels. This maturity stage likely explains the differences in moisture levels, reflecting the physical characteristics of tomatoes at various ripeness stages. Understanding water content at different ripening stages is essential for post-harvest handling and storage, as it affects both shelf life and quality during transportation.

A notable result was the increase in total soluble solids (TSS), which is a key indicator of sweetness in fruit (Table 10). Higher TSS levels generally correspond with sweeter taste, a desirable trait for both fresh consumption and processing. These findings suggest that manipulating PBZ concentrations can effectively enhance tomato sweetness, making the fruit more appealing to consumers and competitive in the market. This result is particularly relevant for tomato breeders and growers seeking to improve fruit quality through precise agricultural practices. The significant variation in TSS across treatments underscores the impact of growth regulators, such as PBZ and GA_3, on the compositional quality of tomatoes. Specifically, treatments with GA_3 and PBZ at 100 and 150 ppm, respectively, were effective in increasing glucose content (Table 11). The results also showed significant differences in the TSI among the treatments. TSI is a calculated measure that combines the concentrations of

sucrose, glucose, and fructose, with GA_3 at 100 ppm and PBZ at 150 ppm yielding the highest values. Measurements of fructose, glucose, and sucrose were used to calculate the TSI, which serves as another indicator of sweetness in the sample. Analysis indicated that tomatoes treated with 150 ppm PBZ and 100 ppm GA_3 differed significantly from the control, yielding a TSI value of 2.37%.

Conversely, ANOVA results showed that the treatments had no significant effect on the total phenolic content, total flavonoid levels, antioxidant activity, or antioxidant capacity of the tomato fruit (Table 12). Tomatoes are known for their high content of phenolic and flavonoid compounds, which contribute to their potency as a natural source of antioxidants. Previous research has demonstrated the significant levels of total phenolics and flavonoids in tomatoes, which provide health benefits to consumers (Cahyanti et al., 2021; Silva-Beltrán et al., 2015). Additionally, tomatoes exhibit strong antioxidant activity, helping to protect cells from damage caused by free radicals. The high phenolic and flavonoid content is also associated with anti-inflammatory and anti-cancer properties. Antioxidant capacity plays a critical role in maintaining oxidative balance and preventing degenerative diseases, as well as premature aging.

Furthermore, ANOVA results revealed that vitamin C content was significantly affected by the treatments. Duncan's Multiple Range Test (DMRT) at a 5% significance level (Table 13) highlighted clear differences among the treatments. The application of 100 ppm GA_3 resulted in a vitamin C content of 3.55 mg 100 g^{-1}, significantly higher than that of the other treatments, including 50 ppm GA_3 (1.58 mg 100 g^{-1}) and the control (2.35 mg 100 g^{-1}). These findings align with those of Kapłan et al. (2018) and Verma et al. (2021), who also reported an increase in vitamin C content following GA_3 application. Vitamin C is essential for collagen production, skin health, and iron absorption, and it serves as an antioxidant that protects cells from free radical damage. Tomatoes can therefore make a significant contribution to meeting daily vitamin C requirements. Consuming tomatoes with elevated vitamin C levels not only supports overall health but also provides a natural, flavorful way to boost antioxidant intake, promoting greater well-being.

Conclusions

The GA_3 treatment with a concentration of 100 ppm and PBZ at 150 ppm had a positive effect on several growth parameters, yield, and quality parameters of *Tymoti* F_1 tomato fruits. The GA_3 treatment at 100 ppm influenced the increase in plant height, number of flowers, number of fruits, fruit weight, h° value, and vitamin C. The concentration of 150 ppm enhanced parameters such as lycopene, β-carotene, and total carotenoids. PBZ treatment suppressed growth but increased parameters such as L* and b* peel color at a concentration of 50 ppm. The concentration of 100 ppm increased fruit diameter, while the 150 ppm treatment improved leaf chlorophyll index, flowering age, fruit set, total soluble solids, fructose, glucose, and total sweetness index. All treatments did not influence parameters such as stem diameter, a*, C*, fruit firmness, fruit water content, sucrose, total phenolic content, total flavonoids, IC_{50}, and AEAC.

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Conflict of Interest

The authors indicate no conflict of interest in this work.

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