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EVALUATION OF FOLIAR PACLOBUTRAZOL APPLICATION ON GROWTH SUPPRESSION, YIELD, RESIDUE LEVELS AND FRUIT QUALITY IN GREENHOUSE TOMATO CULTIVATION

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Abstract: This study investigated the effects of foliar paclobutrazol (PBZ) applications at varying doses and intervals on the vegetative growth, yield, fruit quality, and residue accumulation in greenhouse-grown tomatoes. The experiment was conducted from April to November 2021 in a controlled greenhouse environment at Tokat Gaziosmanpaşa University, Türkiye. Indeterminate beef tomato cultivar Bellfort F_1 (Enza Zaden) was used in the study. PBZ was applied foliarly at concentrations of 10, 20, and 40 mg/L at 7-day and 14-day intervals. Results indicated that PBZ significantly reduced plant height and internode length, with the most compact plants observed under the 40 mg/L 14-day treatment. However, yield-related parameters responded more favorably to lower PBZ doses. The highest marketable yield (175.59 t/ha) and total yield (178.27 t/ha) were obtained under the 10 mg/L 14-day treatment, which also supported greater fruit number and higher dry matter content. Moderate PBZ doses improved fruit weight and chlorophyll index, whereas higher doses tended to suppress yield and quality. While fruit soluble solids and titratable acidity were not significantly affected, slight improvements were noted under moderate PBZ treatments. Importantly, no PBZ residues were detected in fruit samples. These findings demonstrate that foliar PBZ application at low doses is effective for controlling vegetative growth without compromising fruit quality or leaving detectable residues. The results support the use of foliar PBZ as a safe and practical growth regulation strategy for high-density tomato production under greenhouse conditions.

Keywords: Plant height control, Internod length, Solanum lycopersicum, PBZ residue, Yield, Growth retardan

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1. Introduction

Tomato (*Solanum lycopersicum*) is one of the most important vegetable crops worldwide and in Türkiye in terms of both production and consumption. According to 2023 data, World tomato production reached approximately 192.32 million tonnes across an area of about 5.12 million hectares. China (70.21 million tonnes) and India (20.43 million tonnes) lead in production, followed by Türkiye in third place, with 13.30 million tonnes cultivated over 166.32 thousand hectares (Food and Agriculture Organization (FAO, 2023). In Türkiye, tomato cultivation is widely practiced in both open-field and greenhouse conditions. Notably, greenhouse tomato production accounts for a significant share, with approximately 4.16 million tonnes produced under protected cultivation as of 2024 (TSI, 2025).

Indeterminate tomato cultivars, commonly grown in greenhouses, exhibit continuous and prolonged vegetative growth. These cultivars are typically planted at a density of 2–3 plants per square meter, and individual plants can reach heights of 7 to 10 meters. The excessive vegetative growth complicates the use of support systems and increases labor demands, which in turn raises production costs. Consequently, there is a growing interest among producers in developing alternative methods to control plant height. Both physical and chemical strategies are employed for this purpose, with plant growth regulators (PGRs) playing a central role.

Paclobutrazol (PBZ), a member of the triazole chemical group, is a widely used PGR known for its efficacy in restricting plant height, particularly under greenhouse conditions. As an antagonist of gibberellins (GAs) and auxins, PBZ inhibits GA_3 biosynthesis, thereby limiting cell elongation and division and ultimately suppressing shoot elongation (Kumar, 2021). Gibberellins are known to promote internode elongation; however, the inhibition of their biosynthesis by PBZ results in plants with compact growth due to continued cell division but reduced cell elongation (Dayan et al., 2012; Kalra and Bhatla, 2018; Chen et al., 2020). This feature has made PBZ widely applicable in vegetable and ornamental seedling production. Numerous studies have demonstrated the beneficial effects of PBZ on seedling height control and quality. Research on various crops such as lettuce (Geboloğlu et al., 2016), cucumber (Aktaş et al., 2024), tomato (Kum and Geboloğlu, 2024; Brigard et al., 2006), pepper (Silva et al., 2021), and eggplant (Geboloğlu et al., 2015) has shown that PBZ effectively restricts seedling height and contributes to the development of more compact and healthier seedlings.

PBZ is typically applied via two main methods: foliar spraying and drenching the growing medium. Both application techniques have been reported to yield effective results (Rademacher, 2015). Due to its limited mobility in the phloem and upward (acropetal) movement through the xylem, PBZ tends to accumulate in leaves (Witchard, 1997; Rademacher, 2000; Singh and Ram, 2000; Kumar, 2023). As a result, PBZ residue levels in fruit and seeds remain low (Davis et al., 1988, Kumar, 2023).

In tomato cultivation, PBZ application shortens internode length, resulting in compact plant architecture. This allows the production of sturdier plants without negatively affecting flowering quality (Mansuroglu et al., 2009; Currey and Lopez, 2010). Similar growth-regulating effects of PBZ have also been reported in various fruit species (Ghosh et al., 2022). Depending on the application dose and crop species, PBZ may delay or accelerate flowering (Desta and Amare, 2021). Previous studies have shown that PBZ can significantly influence several morphological and physiological traits in tomatoes, including plant height, fruit shape, pericarp cell structure, flowering time, and fruit yield (Chen et al., 2020; Li et al., 2022).

The aim of this study is to determine the effects of foliar-applied paclobutrazol on plant height, yield, quality parameters, and residue levels in fruits of tomato plants grown under greenhouse conditions. The study also aims to evaluate the feasibility of controlling plant height by reducing internode length and to assess the potential implications of this application on the greenhouse production process.

2. Materials and Methods

This study was conducted between April 20 and November 10, 2021, in the greenhouse of Tokat Gaziosmanpaşa University Research and Application Center, located in Tokat province, which lies between the Central Black Sea and Central Anatolia Regions of Türkiye. The research site is situated between 39°51'–40°55' North latitude and 35°27'–37°39' East longitude.

2.1. Experimental Conditions and Plant Material

In the experiment, plants were grown in six-legged pots measuring 75×25×21 cm with a volume of 24 liters. The pots were placed on a ground surface covered with white plastic mulch. The study was carried out in a 2000 m^2 greenhouse equipped with heating and semi-automated environmental controls, with a height of 5 meters. A sterilized mixture of peat moss and perlite in a 2:1 ratio was used as the growing medium.

The plant material used was the indeterminate tomato cultivar "Bellfort F_1" (Enza Zaden). The seedlings were transplanted approximately 40 days after sowing, at the 4–5 true leaf stage. Plants were spaced at 1.20 m between rows and 0.40 m within rows, with two plants placed per pot.

2.2. Irrigation and Fertilisation Practices

Irrigation was carried out four times per day using Hoagland nutrient solution, with a daily total of 500 ml of solution applied per plant. The nutrient solutions were prepared in 1000-liter tanks. Fertilisation and irrigation were conducted simultaneously using a fully automated fertigation system.

Fertiliser concentrations were determined based on the method developed by Hoagland and Arnon (1950), with modifications made according to the developmental stages of the plants. Accordingly, the nutrient solution was prepared with an elemental ratio of N:P:K:Ca:Mg = 2:1:2:1.5:1 until the flowering stage, and N:P:K:Ca:Mg = 2:1:3:1.5:1 from flowering until the end of the harvest. While preparing the nutrient solution, fertilisers from Peters Professional containing N:P:K+trace elements (TE) were used, which include a full range of micronutrients. Calcium was supplied through calcium nitrate, and magnesium through magnesium nitrate. Fertigation began on the fourth day after transplanting, following an initial period of four days during which the seedlings were irrigated with plain water only. The electrical conductivity (EC) of the solution was maintained at 2.0 dS/m before flowering and increased to 2.2 dS/m after the onset of flowering. Fertilisation was applied during each irrigation cycle. Regular measurements were taken from drainage water to monitor and prevent salt accumulation in the growing medium. Irrigation was performed six times daily at equal intervals, with each cycle lasting two minutes. The experiment was concluded on November 20, following the completion of all observations and recordings of treatment effects on tomato plants.

2.3. Paclobutrazol (PBZ) Applications

Paclobutrazol applications were performed using Cultar 25SC (Active Ingredient: 250 g/L paclobutrazol; Formulation: suspension concentrate; Syngenta). Prior to application, PBZ solutions were prepared at concentrations of 10, 20, and 40 mg/L. Applications were conducted in two different intervals: every 7 days and every 14 days. PBZ was applied as a foliar spray, specifically targeting the shoot apex, using a hand-held sprayer. In each application, 5 mL of the prepared PBZ solution was sprayed per plant. The first PBZ application was initiated either 7 or 14 days after transplanting, depending on the treatment schedule. Plants receiving the first application 7 days after transplanting were treated at 7-day intervals thereafter, while those treated at 14 days after transplanting were subsequently treated at 14-day intervals. The final PBZ application was conducted on October 30, 2021. Control plants were sprayed similarly with 5 mL of distilled water per plant onto the shoot apex to ensure uniform handling across treatments.

2.4. Observations and Measurements

Plant Height (m): After the completion of all harvests, the plant height, defined as the distance from the root collar to the apical meristem, was measured using a measuring tape. The average plant height for each plot was subsequently calculated and expressed in meters.

Internode Length (cm): Following the completion of the harvests, the internode length for each plant within the plot was measured using a measuring tape. The mean internode length per plant was then calculated to determine the average internode length in centimeters.

Marketable Yield (t/ha): During each harvest, the collected fruits were categorized as either marketable or non-marketable. Marketable fruits were weighed using a precision scale with an accuracy of 0.01 g, and the corresponding fruit weights for each plot were recorded. Upon completion of all harvests, the total marketable fruit weight per plot was converted to yield values, which were then expressed in tons per hectare.

Total Yield (t/ha): For each harvest, both marketable and non-marketable fruits were weighed together using a precision balance with an accuracy of 0.01 g, and the weights were recorded. After all harvests were completed, the total fruit weight per plot was calculated and subsequently converted to yield values, expressed in tons per hectare.

Marketable Fruit Number (fruits/plant): The marketable fruits collected during each harvest were divided by the number of plants in the plot to calculate the number of fruits per plant. Following the completion of all harvests, the total number of fruits harvested per plant was calculated.

Marketable Fruit Weight (g): The weight of the fruits harvested during each collection was divided by the number of fruits, and the average marketable fruit weight for each harvest was calculated. After all harvests were completed, the average weight of the total harvest was calculated, and the marketable fruit weights were determined.

2.5. Physicochemical Fruit Quality Analysis

Fruit samples were collected during the fourth and sixth harvests. The samples were homogenized using a blender, and the resulting pulp was filtered through Whatman No. 42 filter paper. The filtrate was used for the determination of pH, soluble solids content (SSC, %), and titratable acidity (TA, %).

The pH was measured using a digital pH meter (Hanna HI-9812-5N, USA). Soluble solids content was determined with a digital refractometer and expressed as a percentage (% Brix). Titratable acidity was calculated as citric acid equivalent. For TA measurement, 20 mL of fruit juice was titrated with 0.1 N NaOH solution until reaching a pH of 8.1. TA was determined following the pH-metric method described by Cemeroğlu (2010) and expressed as a percentage.

2.6. Physiological Measurements

Chlorophyll Index (SPAD): The chlorophyll index of the leaves was measured eight weeks after transplanting. Measurements were conducted on all plants within each plot, targeting the fourth and fifth fully expanded leaves from the apical meristem downward. A portable SPAD chlorophyll meter (Minolta SPAD-502, Osaka, Japan) was used for non-destructive assessment of chlorophyll content.

Leaf Dry Matter Content (%): For each plot, the fourth and fifth fully expanded leaves were collected from each plant. Fresh weights were immediately recorded using a precision analytical balance (±0.001 g accuracy). The leaf samples were then dried in a forced-air oven at 65°C until reaching a constant weight. Dry weights were subsequently measured, and leaf dry matter content was calculated as the ratio of dry weight to fresh weight, expressed as a percentage.

Fruit Dry Matter Content (%): At the fourth and sixth harvests, two representative fruits were randomly selected from each plot. Fresh weights were determined using a precision analytical balance (±0.001 g accuracy). The fruits were quartered and oven-dried at 65°C until a constant weight was achieved. After drying, dry weights were measured, and fruit dry matter content was calculated as the ratio of dry weight to fresh weight, expressed as a percentage.

2.7. Residue Analysis

The analysis of PBZ was conducted using a Shimadzu® LC-MS 8050 system, which possesses advanced UPLC, and MS/MS capabilities. The chromatographic separation was achieved using a HPLC column (Inertsil ODS IV). The multiple reaction monitoring (MRM) transitions employed for the detection, and quantification of PBZ in LC-MS/MS analysis are enumerated below: The precursor ion at m/z 294.10 was monitored with product ions at m/z 125.10, 130.10, and 134.80. The collision energies applied for these transitions were -15.0 eV, -15.0 eV, and -28.0 eV, respectively. The declustering potential were set at -38.0 V, -33.0 V, and -35.0 V, while the entrance potentials were maintained at -21.0 V, -22.0 V, and -27.0 V, respectively.

A gradient elution method was employed, using eluent A (distilled water with 5 mM ammonium formate), and eluent B (methanol with 5 mM ammonium formate). The gradient elution program was structured as follows: Initially, the mobile phase consisted of 10% eluent B. The concentration of eluent B was then increased to 99% over a period of 7 minutes (from 1.00 min to 8.00 min), and maintained at this level until 12.00 min. At 13.00 min, the concentration of eluent B was reduced back to 10%, and held at this level until 13.01 min. The total runtime was 15.00 min, at which point the system was programmed to stop. Instrument parameters were controlled using LabSolution® software (version 5.118). The retention time (RT) for PBZ was determined to be 9.983 minutes, as shown in the chromatogram (Figure 1). This confirms the accurate identification of PBZ under the specified chromatographic conditions.

Tomato fruit samples were collected after on 1st, 3rd, 5th, 7th, and 10th treatments after spraying PBZ. The sample preparation procedures followed the QuEChERS AOAC Method 2007.01, by Lehotay (2007). The verification of the method adhered to SANTE guidelines (SANTE, 2021; Balkan and Yılmaz, 2022). According to SANTE guidelines, the method meets the required validation criteria of 70-120% recovery, and ≤20% RSD values. The method verification parameters in Table 1 demonstrate high sensitivity, accuracy, and precision, aligning with SANTE guidelines, and previous literature (Balkan and Kara, 2021).

2.8. Experimental Design and Statistical Analysis

The trial was conducted in a randomized plot design with three replications. Each replication consisted of five pots, with two plants per pot. Data were statistically analyzed using one-way analysis of variance (ANOVA) in SPSS 20.0. Mean separations were performed using Duncan's Multiple Range Test at significance levels of 5%.

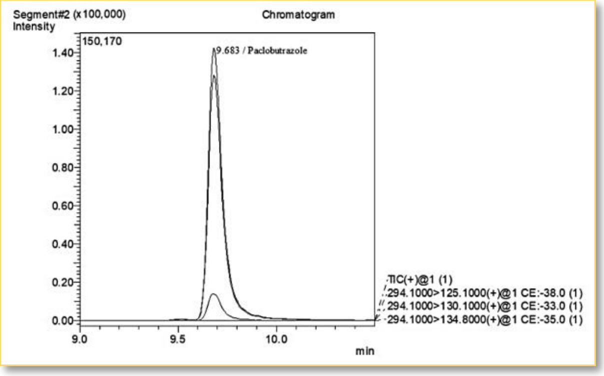

Figure 1. Chromatogram of paclobutrazole obtained from LC-MS/MS analysis after injection of a 25 µg/kg standard solution.

Table 1. Method optimization, and verification parameters

Analyte	RT (min)	Linear regression equation	Correlation coefficient (R^2)	LOD (µg/kg)	LOQ (µg/kg)	Fortification (µg/kg)	Repeatability Recovery % (RSD, %)	Reproducibility Recovery % (RSD, %)	U %
Paclobutrazol (PBZ)	9.683	Y= (24402.8)X + (44949.2)	0.99947	1.09	3.64	10	90.62 (4.10)	91.46 (7.24)	20.62
						50	103.1 (3.91)	102.08 (5.82)	
						100	104.39 (1.45)	100.88 (4.32)	

3. Results and Discussion

3.1. Plant Height and Internode Length

In this study, the findings clearly demonstrated that PBZ treatments significantly reduced both plant height and internode length. Plant height was significantly influenced by PBZ doses and application frequency (P ≤0.001). The shortest plants were recorded in the 40 mg/L 14-day PBZ treatment (3.37 m), closely followed by 20 mg/L 14-day (3.38 m) and 40 mg/L 7-day (3.44 m) treatments. All PBZ-treated plants were significantly shorter than the control plants (3.93 m). Particularly, the 40 mg/L 14-day application emerged as highly effective in achieving a compact plant architecture, which is crucial for optimizing space and improving plant management in greenhouse tomato production. Internode length was also significantly reduced by PBZ treatments (P ≤ 0.001). The shortest internodes were observed in plants treated with 40 mg/L 14-day PBZ treatment (19.77 cm). Similarly, 20 mg/L 7-day and 40 mg/L 7-day treatments also resulted in compact internode lengths (19.79 cm and 20.73 cm, respectively). In contrast, control plants exhibited the longest internodes (23.14 cm). The effects of PBZ applications on plant height and internode length in tomato are presented in Table 2.

A strong positive relationship was observed between plant height and internode length. Applications that reduced plant height simultaneously shortened internode length. Notably, the 40 mg/L 14-day treatment consistently resulted in both the shortest plant height and the most condensed internode structure, making it the most effective strategy for promoting a compact growth habit. This parallel reduction suggests that PBZ regulates vertical growth primarily by shortening internodal segments rather than reducing the number of internodes. Such coordinated growth control is ideal for intensive cultivation systems aiming for high planting densities, better canopy management, and improved operational efficiency. The literature supports these findings. Carr and Jaffe (1995) reported that PBZ applications decreased internode length in tomato plants. Flores et al. (2018) observed significant reductions in plant height in cucumber (24%), zucchini (34.7%), melon (16.3%), and watermelon (23.4%) following PBZ treatments. Studies across different species such as tomato (Banoo et al., 2020), canola (Hua et al., 2014) and bean (Bekheta and Talaal, 2009) have consistently reported similar trends. The underlying mechanism involves the inhibition of gibberellin biosynthesis. PBZ inhibits the enzyme ent-kaurene oxidase, a key enzyme in the gibberellin biosynthetic pathway, thereby restricting cell elongation while cell division continues (Kondhare et al., 2014; Banoo et al., 2020). As a result, plant height is significantly reduced due to the inhibition of gibberellin biosynthesis in the subapical meristem (Meena, 2014). Tesfahun and Menzir (2018) further emphasized that plant height reduction was mainly associated with reduced elongation of internodes rather than a decrease in the number of internodes. Similarly, Novita (2022) demonstrated that PBZ significantly reduced plant height in tomato plants. The results of this study clearly show that PBZ application at 40 mg/L with a 14-day interval is the most effective strategy for achieving compact plant growth in greenhouse tomato production. Through growth regulation, PBZ-treated plants became shorter, more compact, and easier to manage, enhancing spatial efficiency and operational practicality in intensive greenhouse systems.

3.2. Yield and Fruit Characteristics

The effects of PBZ treatments on yield and fruit-related characteristics are presented in Table 3. Marketable yield was significantly influenced by both the dose of paclobutrazol and the application interval (P≤0.01). The highest marketable yields were recorded under the 10 mg/L PBZ treatments, particularly at the 14-day (175.59 t/ha) and 7-day (174.51 t/ha) intervals, both of which were significantly superior to most other treatments (Table 3). In contrast, the 20 mg/L 14-day application resulted in the lowest marketable yield (151.22 t/ha). Notably, the 10 mg/L treatments outperformed the control treatment (159.66 t/ha), indicating that lower PBZ doses can enhance marketable yield under greenhouse conditions. Total yield followed a similar pattern (P≤0.01), with the highest values observed in the 10 mg/L 7-day (177.13 t/ha) and 10 mg/L 14-day (178.27 t/ha) PBZ treatments. Conversely, the 20 mg/L 14-day application produced the lowest total yield (154.86 t/ha), suggesting that higher PBZ concentrations, particularly when applied less frequently, may exert an inhibitory effect on yield formation. The control group (163.20 t/ha) yielded moderately but was consistently surpassed by all 10 mg/L treatments. Marketable fruit weight was also significantly affected by PBZ application (P≤0.01). The heaviest fruits were obtained with the 20 mg/L 7-day (174.49 g) and 10 mg/L 7-day (172.86 g) treatments, demonstrating that moderate PBZ doses can positively influence fruit weight. In contrast, the control group produced the lightest fruits (152.72 g). Moreover, the 40 mg/L 14-day treatment yielded relatively smaller fruits (157.32 g), suggesting that excessive PBZ application may restrict individual fruit growth despite controlling vegetative development. Regarding the number of marketable fruits per plant, significant differences among treatments were evident (P≤0.01). The highest fruit number was recorded under the 10 mg/L 14-day treatment (55.13 fruits/plant), closely followed by the control (53.34 fruits/plant) and the 40 mg/L 7-day treatment (52.57 fruits/plant). The 20 mg/L 14-day treatment resulted in the lowest fruit number (46.15 fruits/plant), reinforcing the notion that higher doses combined with extended application intervals may negatively impact reproductive performance.

Collectively, these findings suggest that PBZ applications at moderate doses (10 mg/L) effectively optimize both canopy structure and yield outcomes. Higher doses (40 mg/L) successfully enhanced plant compactness but led to reductions in yield parameters. In contrast, the 10 mg/L treatments, particularly when applied at a 14-day interval, achieved a favorable balance between vegetative growth regulation and high productivity, supporting their use as an efficient management strategy in greenhouse tomato production. These results are consistent with previous studies emphasizing the benefits of PBZ on crop yield and morphology. Rai et al. (2002) reported improved yield and quality parameters in various vegetable crops following PBZ application, while Jyothsna et al. (2022) observed enhanced yield in okra due to improved physiological traits and plant compactness. Similarly, Berova and Zlatev (2000) demonstrated that PBZ improved early fruit yield and water-use efficiency in tomatoes, aligning with the findings of this study that moderate PBZ doses enhance yield without compromising plant vigor. Conversely, Souza-Machado et al. (1999) observed no significant differences in total tomato yield despite accelerated maturity, suggesting that environmental conditions and cultivar characteristics may modulate PBZ efficacy. Meanwhile, studies by Giovinazzo et al. (2001) and Mohamed et al. (2011) corroborated the yield-enhancing potential of PBZ under specific production systems. Furthermore, Baloch et al. (2019) demonstrated that higher PBZ concentrations increased both fruit number and size in ornamental pepper, paralleling the present findings where moderate PBZ doses enhanced fruit size and number in tomatoes. Villavicencio et al. (2015) also indicated that while growth retardants significantly reduced plant height, they did not necessarily diminish fruit yield, highlighting the complex, species-specific responses to plant growth regulators.

3.3. Chlorophyll Index, Fruit Dry Matter and Leaf Dry Matter

In the study, leaf chlorophyll index among treatments ranged from 55.41 ± 5.65 to 60.13 ± 6.43 SPAD units. Although statistical analysis revealed no significant differences among treatments (p=0.528), numerical trends were evident. The highest chlorophyll index was recorded in the 20 mg/L 7-day PBZ treatment, while the lowest was observed in the 40 mg/L 14-day PBZ group. The control plants exhibited an intermediate value of 57.50 ± 6.31 SPAD units (Fig. 2). Notably, moderate PBZ doses (10–20 mg/L) tended to slightly enhance chlorophyll content relative to both the control and high-dose (40 mg/L) treatments, albeit without statistical significance. These findings align with prior research demonstrating that PBZ can promote higher chlorophyll concentrations. Berova and Zlatev (2000) reported increased photosynthetic activity following PBZ application in tomatoes, and similar enhancements of chlorophyll content in triazole-treated plants were documented by Xia et al. (2018) and Amooaghaie and Shariat (2014). Increased chlorophyll content is often attributed to PBZ's role in reducing gibberellin synthesis, leading to denser and darker green leaves. Although no significant enhancement was detected statistically in the present study, the numerical increases in SPAD values at moderate doses suggest a potential physiological benefit of PBZ in improving chlorophyll retention and leaf greenness.

Fruit dry weight percentages were significantly influenced by PBZ treatments (p ≤ 0.01). The highest fruit dry weights were recorded in the 10 mg/L 7-day (6.32% ± 0.39) and 10 mg/L 14-day (6.24% ± 0.31) treatments, closely followed by the 20 mg/L 14-day treatment (6.23% ± 0.39). In contrast, the 40 mg/L treatments produced notably lower fruit dry weights: 5.35% ± 0.32 (7 days) and 5.45% ± 0.29 (14 days). Control plants exhibited the lowest fruit dry weight at 5.12% ± 0.29 (Fig. 2). These results clearly demonstrate that lower PBZ doses, particularly at 10 mg/L, and shorter application intervals are more effective in enhancing fruit dry matter accumulation. Similar effects of PBZ in promoting dry matter partitioning towards reproductive organs have been reported in other crops. For instance, Huang et al. (1995) observed enhanced dry matter allocation to fruits in PBZ-treated apple trees, while Setia et al. (1996) and Tekalign and Hammes (2005) noted improved assimilate partitioning towards economic yield organs in Brassica and potato, respectively. The observed suppression of vegetative growth by PBZ likely redirects assimilates towards reproductive sinks, thus improving fruit dry weight percentage. Conversely, high PBZ doses (40 mg/L) negatively affected fruit dry weight, indicating potential over-suppression of physiological processes necessary for optimal fruit development. This outcome aligns with previous findings where excessive PBZ concentrations led to decreased biomass and compromised growth (Khalil and Rahman, 1995; Rigsby et al., 2025).

Leaf dry weight percentages varied between 14.31% ± 0.81 and 15.49% ± 0.89 across treatments, but these differences were not statistically significant (p=0.243). The highest leaf dry weight was recorded in the 10 mg/L 7-day treatment, followed by 10 mg/L 14-day and 20 mg/L 7-day applications. The lowest value was found in the 40 mg/L 14-day treatment (Fig. 2). Although not statistically meaningful, the numerical trend suggests that lower PBZ doses may slightly enhance leaf dry matter content. This is consistent with Senoo and Isoda (2003), who found no significant changes in leaf dry matter in PBZ-treated peanut plants. However, minor increases in leaf dry matter could be attributed to a thicker, more compact leaf structure induced by PBZ, resulting in heavier leaves per unit area. These structural changes are consistent with PBZ's known effects on plant morphology, including reduced leaf expansion and thicker mesophyll tissue (Berova and Zlatev, 2000; Xia et al., 2018).

Table 2. Effect of PBZ treatments on plant height and internode length of tomato

PBZ Doses	Application Interval	Plant Height (m)	Inter-node Length (cm)
10 mg/L	7 day	3.56 ± 0.22^{b}	21.48 ± 1.86^{ab}
10 mg/L	14 day	3.41 ± 0.20^{b}	20.32 ± 1.83^{b}
20 mg/L	7 day	3.46 ± 0.21^{b}	19.79 ± 1.78^{b}
20 mg/L	14 day	3.38 ± 0.21^{b}	20.56 ± 1.67^{b}
40 mg/L	7 day	3.44 ± 0.23^{b}	20.73 ± 2.08^{b}
40 mg/L	14 day	3.37 ± 0.24^{b}	19.77 ± 2.08^{b}
Control		3.93 ± 0.26^{a}	23.14 ± 2.22^{a}
Significance			
P-value		0.003	0.009
Sig.		**	**

Means in the same column followed by the same letter are not significantly different (P<0.05) according to Duncan's multiple range test.
** Represents statistically significant difference at P≤0.01.

Table 3. Effect of PBZ treatments on yield and fruit characteristics in Tomato

PBZ Doses	Application Interval	Marketable Yield (t/ha)	Total Yield (t/ha)	Marketable Fruit Weight (g)	Marketable Fruit Number (fruits/plant)
10 mg/L	7 day	174.51 ± 9.42^{a}	177.13 ± 9.67^{a}	172.86 ± 14.86^{a}	51.54 ± 3.31^{ab}
10 mg/L	14 day	175.59 ± 9.41^{a}	178.27 ± 10.43^{a}	162.65 ± 13.42^{bc}	55.13 ± 3.22^{a}
20 mg/L	7 day	166.37 ± 9.78^{ab}	173.14 ± 9.19^{ab}	174.49 ± 12.46^{a}	48.72 ± 3.22^{bc}
20 mg/L	14 day	151.22 ± 8.31^{c}	154.86 ± 8.96^{d}	167.22 ± 11.87^{ab}	46.15 ± 3.00^{c}
40 mg/L	7 day	168.03 ± 8.58^{ab}	172.12 ± 9.63^{abc}	163.23 ± 10.25^{bc}	52.57 ± 4.94^{a}
40 mg/L	14 day	158.69 ± 8.09^{bc}	162.77 ± 8.92^{cd}	157.32 ± 9.54^{cd}	51.54 ± 4.78^{ab}
Control		159.66 ± 8.53^{bc}	163.20 ± 8.82^{bcd}	152.72 ± 9.78^{d}	53.34 ± 5.18^{a}
Significance					
P		0.008	0.001	0.002	0.002
Sig.		**	**	**	**

Means in the same column followed by the same letter are not significantly different (P<0.05) according to Duncan's multiple range test.
** Represents statistically significant difference at P≤0.01.

3.4. Soluble Solid Content , Titratable Acidity and pH

In the study, soluble solids content in tomato fruits exhibited numerical variations among treatments, although these differences were not statistically significant (p=0.056). SSC values ranged from 5.83% ± 0.35 in the 10 mg/L 7-day PBZ treatment to 6.13% ± 0.55 in the control group. The highest SSC values were recorded in the control and 20 mg/L 7-day PBZ treatment groups (6.13% ± 0.44), suggesting that moderate doses of PBZ might support higher soluble solids accumulation. In contrast, the lowest SSC values were associated with the 40 mg/L PBZ treatments, particularly at the 14-day interval (5.93% ± 0.55) (Fig. 3). These findings align partially with previous research. For instance, Sarker and Rahim (2018) reported that PBZ application increased TSS in mango fruits, suggesting an enhancement in fruit quality at moderate PBZ doses. However, in other studies, such as those by Sansavini et al. (1986) and Deigado et al. (1986), PBZ application did not significantly affect SSC in apple and citrus fruits, respectively. This discrepancy could be attributed to species-specific responses, application methods, or environmental conditions during fruit development. The slight numerical increase in SSC observed at moderate PBZ doses in this study may indicate a potential, although limited, role of PBZ in improving fruit sweetness.

Titratable acidity (TA) values ranged narrowly from 0.181% ± 0.010 (40 mg/L 7-day PBZ) to 0.193% ± 0.011 (20 mg/L 7-day PBZ), and no significant differences were detected among treatments (p = 0.661) (Fig. 3). The control group exhibited a TA value of 0.185% ± 0.012, which was comparable to the PBZ-treated groups. Previous studies offer mixed results regarding PBZ's effects on fruit acidity. For example, Suja and Anusuya (2018) observed varying acid ratios following PBZ treatments in tomato, while Jain et al. (2002) and Burondkar et al. (2013) reported increased TA content in mango and lemon. Conversely, Samaan and Nasser (2020) and Sha et al. (2021) highlighted PBZ's role in reducing fruit acidity. In the current study, the negligible impact of PBZ on TA is consistent with findings in other crops such as grape (Christov et al., 1995) and strawberry (Lolaei et al., 2012), suggesting that the effect of PBZ on acidity might be minor in tomato or strongly influenced by cultivar-specific and environmental factors.

The pH values across all treatments ranged from 4.53 ± 0.40 (control) to 4.73 ± 0.36 (40 mg/L 14-day PBZ). Although no statistically significant differences were found (p = 0.184), a slight trend towards higher pH values with increasing PBZ doses, particularly at 40 mg/L, was observed (Fig. 3). These findings are in line with the results of Sansavini et al. (1986), who reported no significant effect of PBZ on pH in apple fruit quality studies. Similarly, Banoo et al. (2020) found that PBZ treatment did not substantially alter the internal quality parameters in tomatoes, including acidity and sweetness, despite improving yield attributes. The small pH increases observed at higher PBZ concentrations in this study might reflect subtle shifts in fruit chemical composition, possibly linked to altered metabolic processes under PBZ-induced growth regulation.

3.5. Effect of Paclobutrazol Applications on Residue Levels in Tomato Fruit

No paclobutrazol residues were detected in fruit samples collected at various time points, including one day after application. According to previous studies, PBZ applied to the soil is absorbed by the roots and transported via the xylem to apical meristems, leaves, and fruits (Early and Martin, 1988; Rademacher, 2000; Mahesvari et al., 2022). In the present study, however, lower doses were used, and applications were conducted foliarly, which may have limited the translocation of PBZ to the fruits and prevented residue accumulation. Fletcher et al. (2000) have reported that PBZ is not phloem-mobile, although some evidence suggests that it may exhibit limited movement in the phloem (Witchard, 1997; Singh and Ram, 2000). Given that PBZ is predominantly transported through the xylem and tends to accumulate in the leaves, with minimal phloem mobility, its low residue levels in fruits—supplied mainly via the phloem—are consistent with expectations (Davis et al., 1988.

These findings suggest that foliar application may reduce PBZ efficacy compared to soil application due to limited systemic movement. However, one of the primary objectives of this study—plant height reduction—was successfully achieved, and no residue was detected in the fruits. Therefore, foliar application of PBZ may be considered an effective strategy for growth regulation when residue management is a priority. Future research should explore the systemic behavior and residue dynamics of PBZ by comparing different application methods (foliar vs. soil) and dose levels in tomatoes and other vegetable crops.

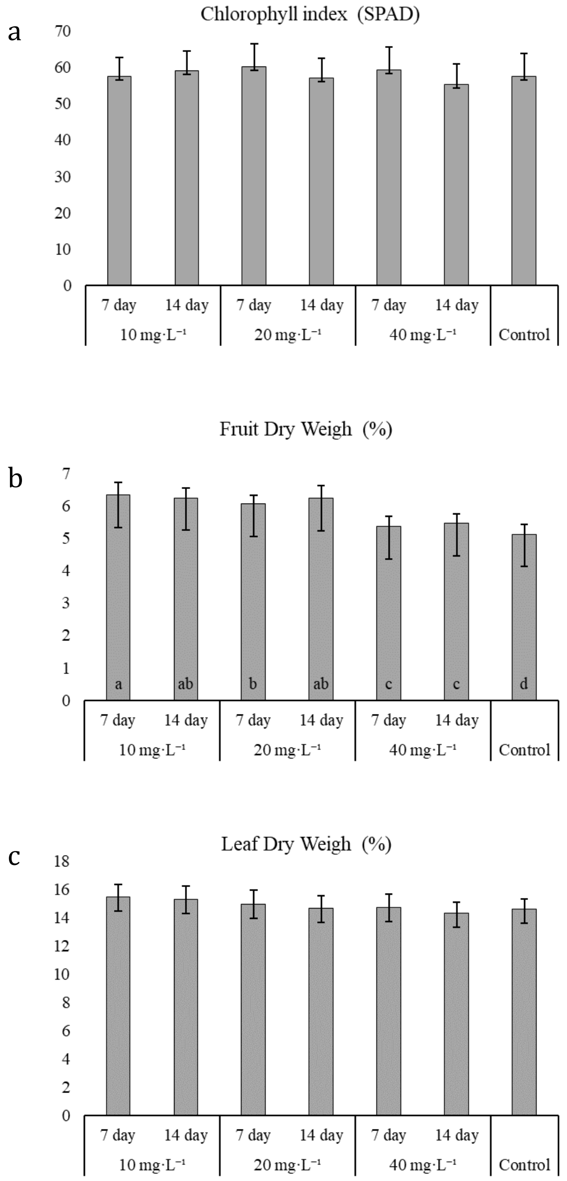

Figure. 2. Effect of PBZ treatments on chlorophylle index (a), fruit (b) and leaf dry weight (c) of tomato.

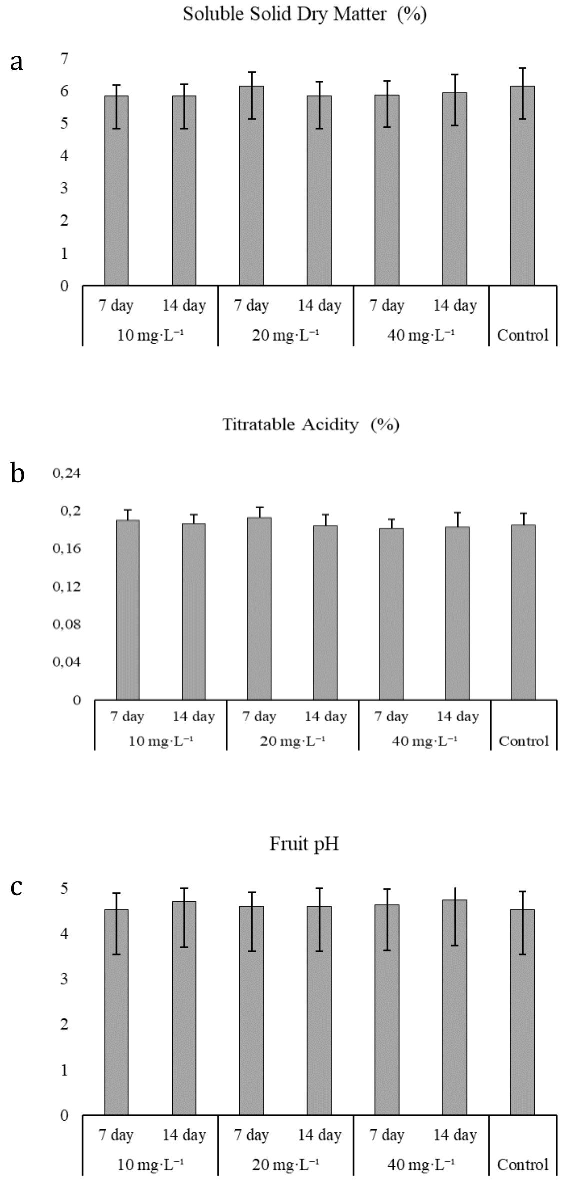

Figure. 3. Effect of PBZ treatments on soluble solid dry matter (a), titretable acidty (b) and fruit pH (c) of tomato.

4. Conclusion

This study comprehensively evaluated the effects of foliar paclobutrazol applications at different doses and intervals on plant growth, yield, fruit quality, physiological characteristics, and residue levels in greenhouse-grown tomatoes with a long production cycle. The results clearly demonstrated that PBZ significantly reduced plant height and internode length, with the most compact plant architecture achieved under the 40 mg/L dose applied every 14 days. This application was particularly effective for managing vertical growth, which is crucial for optimizing plant spacing and improving operational efficiency in high-density greenhouse systems.

In terms of yield, the 10 mg/L PBZ treatment, applied at both 7-day and 14-day intervals, resulted in the highest marketable and total yields, suggesting that lower PBZ doses effectively regulate vegetative growth while enhancing reproductive development. In contrast, higher doses (especially 20 and 40 mg/L) negatively impacted yield parameters, including fruit number and total yield. Regarding fruit weight, moderate doses of PBZ (10–20 mg/L) were found to positively influence fruit size, whereas excessive doses (40 mg/L) led to smaller fruits.

Physiological assessments indicated a numerical increase in chlorophyll index and dry matter content in both fruit and leaves, although these differences were not statistically significant. Quality parameters, including soluble solids content, titratable acidity, and pH, showed no significant differences across treatments. A key finding was the absence of detectable PBZ residues in fruit samples, indicating that foliar applications do not lead to residue accumulation in the harvested fruits.

In conclusion, foliar applications of PBZ at lower doses (10 mg/L), particularly at 14-day intervals, proved to be an effective strategy for regulating growth, enhancing yield, and ensuring residue-free fruit production in greenhouse tomato cultivation. These findings support the use of PBZ as a growth regulator, offering both agronomic and food safety benefits. Further studies should investigate the systemic behavior and residue dynamics of PBZ in different application methods (foliar vs. soil) and across various vegetable crops.

Author Contributions

Percentages of the authors' contributions are present below. All authors reviewed and approved final version of the manuscript.

	Ö.Y.	E. P.	T. B.	N. G.
C	30	30	20	20
D	50	40	10	
S			50	50
DCP	30	30	20	20
DAI	20	20	30	30
L	20	20	30	30
W		20	30	50
CR		20	30	50
SR		20		80
PM	20	30	20	30
FA	25	25	25	25

C= concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declare no conflict of interest.

Ethical Consideration

Since no studies involving humans or animals were conducted, ethical committee approval was not required for this study.

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