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The Effect of Paclobutrazol Applications on Yield, Quality, Plant Growth and Residue in Hydroponic Tomato Cultivation

Tarık BALKAN[1], Hakan KARTAL[2]✉, Özlem YILMAZ[3]
[1,3]Tokat Gaziosmanpaşa University, Faculty of Agriculture, Department of Plant Protection, Tokat, [2]Tokat Gaziosmanpaşa University, Faculty of Agriculture, Department of Horticulture, Tokat
[1]https://orcid.org/0000-0003-4756-4842, [2]https://orcid.org/0000-0002-3870-1588, [3]https://orcid.org/0000-0001-8564-120X
✉: kartalhakan09@gmail.com

ABSTRACT

The study was conducted in 2022 in a fully automated, soilless agriculture greenhouse at the Research Centre Directorate of Tokat Gaziosmanpaşa University. The study investigated the effects of different doses of paclobutrazol (PBZ) on yield, quality, plant growth, and PBZ residue levels in tomato plants. The plant material employed in this study was the Belford F1 (Syngenta-Türkiye) pole tomato variety. The experiment was conducted in three replicates according to a random plots factorial experiment design. The results of this study indicate that foliar applications of 50 ppm, and 100 ppm PBZ produced the most optimal outcomes. The highest marketable yield was observed in the treatment with a foliar application of 50 ppm PBZ, resulting in an average yield of 385.33 kg/ha. Subsequently, a foliar application of PBZ at a rate of 100 ppm (374.24 kg/ha) was conducted, along with a control treatment (268.55 kg/ha). The study revealed no statistically significant differences between treatments in terms of fruit wet weight, dry weight, pH, and titratable acidity. Furthermore, as the PBZ doses increased, the internode length, and plant height showed a corresponding reduction. The findings of this study indicate that, in soilless tomato cultivation, foliar applications of PBZ produce superior results compared to soil applications. Additionally, no PBZ residue was detected in the fruit.

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ÖZET

Bu çalışma 2022 yılında Tokat Gaziosmanpaşa Üniversitesi Araştırma Merkez Müdürlüğü bünyesindeki tam otomasyonlu topraksız tarım serasında yürütülmüştür. Araştırmada farklı dozlarda paclobutrazol uygulamalarının domates bitkisinin verim, kalite, bitki gelişimi ve paclobutrazol (PBZ) kalıntıları incelenmiştir. Bitkisel materyal olarak Belford F1 (Syngenta-Türkiye) sırık domates çeşidi kullanılmıştır. Tesadüf parselleri faktöriyel deneme desenine göre 3 tekerrürlü olarak yürütülmüştür. Bu çalışmada domates bitkisinde verim özellikleri açısından yapılan gözlemlerde en iyi sonuç 50 ppm yapraktan PBZ ve 100 ppm yapraktan PBZ uygulamasından elde edilmiştir. En yüksek pazarlanabilir verim 50 ppm yapraktan PBZ uygulamasında 385.33 kg/da olmuştur. Bunu sırasıyla 100 ppm yapraktan PBZ uygulaması (374.24 kg/da) ve kontrol uygulaması (268.55 kg/da) takip etmiştir. Çalışmada meyve yaş-kuru ağırlık, pH ve titreedilebilir asit miktarı bakımından uygulamalar arasında istatistiksel olarak önemli bir fark gözlenmemiştir. Ayrıca, uygulamalar arasında PBZ dozları arttıkça ve buna paralel olarak boğum arası uzunluk ve bitki boyunda kısalmalar meydana gelmiştir. Bu çalışmanın sonucunda farklı PBZ uygulamaları arasında topraksız domates yetiştiriciliğinde yapraktan PBZ uygulamalarının topraktan PBZ uygulamalarına göre daha iyi sonuç verdiği; ayrıca meyvede PBZ kalıntısı oluşturmadığı tespit edilmiştir.

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INTRODUCTION

Vegetables are an essential component of the human diet, providing specific nutrients that are vital for maintaining optimal health (Keikotlhaile & Spanoghe, 2011). One of the most significant vegetables cultivated globally is the tomato (*Lycopersicon esculentum*). The tomato, a member of the Solanaceae family, contains a variety of nutrients, including carotenoids, lipids, organic acids, alcohol-insoluble solids (Minoia et al., 2010). The tomato is employed in a multitude of culinary applications, including soup, juice, ketchup, purée, and the preparation of tomato paste, pickles, and preserves from green tomatoes (Jayaramaiah et al., 2018). The tomato is cultivated extensively in both open (field), and soilless farming areas (Kartal & Geboloğlu, 2024). The collective impact of a decline in the extent of arable land, an increase in global population, a reduction in water resources, and climate change is placing significant strain on those engaged in agricultural production. One of the most promising strategies to address this challenge is the practice of soilless agriculture (Gruda et al., 2017).

Soilless agriculture refers to the cultivation of plants without the utilisation of soil as a rooting area (Yalçın & Çimrin, 2019). The system essentially comprises a cultivation method through which absorbed root nutrients are supplied by the irrigation water (Savvas et al., 2013). Soilless agriculture comprises two distinct methodologies: water culture, and solid media culture. The solid media culture method is more prevalent, although the water culture approach has also gained prominence in recent years. The preference for solid media culture over water culture is largely attributed to the lower operating costs, and ease of application associated with the former (Talaz & Engin, 2019). In soilless agriculture, a variety of media are employed, including organic (coconut fibre, peat, sawdust, bark), inorganic (perlite, vermiculite, zeolite, sand, tuff, gravel), and synthetic-organic (polyurethane foam) (Demirsoy & Uzun, 2019). The most commonly utilised soilless cultivation substrates in Türkiye are perlite, coconut fibre, and rock wool. Of these media, only perlite is a domestic material, while coconut fibre, and rock wool are imported (Toprak & Gül, 2013). Furthermore, these media are employed as a cultivation medium for plants or plant roots, rather than as a source of nutrients (Raffar, 1990).

The term "growth regulator" is used to describe any chemical that inhibits cell division, and elongation in shoot tissues, while simultaneously regulating plant height without affecting the plant's morphology (PGRSA, 2007). The misuse of plant growth regulators (PGRs), which affect physiological events, has the potential to induce health complications. Consequently, the utilisation of these substances has undergone a process of restriction, and licensing (Kumlay & Eryiğit, 2011). The utilisation of PGRs is multifaceted, encompassing applications such as the promotion of germination, the augmentation of fruit production, the acceleration of fruit maturation, the enhancement of seedling rooting, and the management of weeds (Budak, Çalışkan, & Çaylak, 1994; Kaynak & Ersoy, 1997; Aydoğdu & Boyraz, 2005). However, it is imperative to administer these substances at the appropriate dosage and timing; otherwise, a plant growth regulator that promotes growth at low concentrations may impede growth at high doses. Misuse of these substances can lead to adverse effects on both human health, and the environment. While there is a paucity of research in this area, the available evidence suggests that plant growth regulators pose a lower risk to human health than pesticides. When administered in accordance with dosage guidelines, and at optimal timing, they are essentially innocuous. However, oversupplementation or untimely application can result in residues on fruit, which have the potential to induce health complications. Furthermore, inadequate caution during application can result in acute effects arising from eye and skin contact (Halloran & Kasım, 2002; Kumlay & Eryiğit, 2011). The most commonly utilised growth regulators in hydroponics, vegetable, fruit, and other plant cultivation are daminozide, unicazol, clormequat chloride, and paclobutrazol (PBZ). Among growth regulators, paclobutrazol is presently the most widely employed in aquaculture (Wang & Gregg, 1990; Whipker & Dasoju, 1998; Pasian & Bennett, 2001; Di Benedetto & Klasman, 2007). PBZ is typically employed as an efficacious plant growth regulator in a plethora of crops, including all vegetables, apple, and cherry (Quinlan, 1981), carrot (Thomas, Barnes, & Hole, 1982), english ryegrass (Hebhlethwaite, Hampton, & McLaren, 1982), tulip (Menhenett & Hanks, 1982), and chrysanthemum (McDaniel, 1983). Paclobutrazol is a compound belonging to the triazole class of plant growth regulators. It has been observed to provide protection to a range of plants against diverse environmental stresses, including drought, cold, heat, and ultraviolet radiation (Orabi, Salman, & Shalaby, 2010).

The PBZ application has been shown to positively impact several plant traits, such as plant height, stem diameter, leaf count, root structure, and yield, while also decreasing the occurrence of lodging (Syahputra et al., 2016). The effects of PBZ on the isoprenoid pathway result in the inhibition of gibberellin synthesis, and alterations in the levels of plant hormones, characterised by an increase in the levels of cytokinin. Inhibition of gibberellin synthesis results in the accumulation of precursors in the terpenoid pathway, leading to the production of abscisic acid (Khan et al., 2009; Soumya Preman, 2017). This compound exerts a considerable impact on plant growth, and development, influencing factors such as photosynthetic rate, and phytohormone levels (Kim et al., 2012).

In studies examining the impact of PBZ application on yield, quality, and plant growth in tomato cultivation, it has been reported that PBZ application can enhance yield by augmenting fruit carrying capacity, thereby facilitating the development of a more compact, and robust structure in tomato plants (Chakrabarty, Chakraborti, & Basu, 2009; Srivastava, Dwivedi, & Srivastava, 2012). Furthermore, it has been proposed that PBZ may enhance fruit size, and improve certain quality characteristics (Hassan et al., 2017). In their research on the impact of PBZ applied to soil in apricot orchards on vegetative growth, and quality of apricot, Mir et al. (2015) reported that, in terms of fruit/plant number, and yield, a 10 g PBZ application significantly reduced vegetative growth of plants, improved fruit quality, and increased yield in both years of the study when compared to other treatments.

In a pot study on the growth, yield, and quality of white aubergine, Khandaker et al. (2020) reported that a PBZ concentration of 200 mg led to increased growth, yield, and quality. The authors thus recommended the use of PBZ for the purpose of achieving better yield, and quality in aubergine. Despite an extensive literature search, there were not many published studies on plant growth, yield, quality, and fruit residues of PBZ in tomato under soilless conditions. Given the conditions outlined above, it is crucial to evaluate the effect of PBZ on controlling plant growth, as well as its role in improving fruit yield, and quality.

The purpose of this study was two-fold: first, to investigate the effect of PBZ applications on yield, quality, and plant growth in soilless tomato cultivation; second, to ascertain whether PBZ, the active ingredient in the treatment, forms residues in tomato plants.

MATERIAL and METHOD

Place and Year of Trial

The research was conducted at the Tokat Gaziosmanpaşa University Research and Application Centre in 2022. The experimental setup was a 2000 m² heated soilless greenhouse with a fully automated system. In the course of the experiment, peat of the type known as Kekkila (brown sphagnum peat) was employed as a peat substrate. The nutrient content, and certain properties of the peat are presented in Table 1. The perlite employed is chemically inert, and has a pH of approximately 7. These characteristics render it suitable for a broad range of applications. The constituents of perlite are present in an oxide form, with a water content of 3%, and an SiO_2 content of approximately 74%. The properties of the perlite employed in the study are presented in Table 2.

Table 1. The properties of Kekkila peat
Çizelge 1. Kekkila torfunun özellikleri

Org. M. (%)	**pH**	**EC (dS/m)**	**N (mg/l)**	**P_2O_5**	**K_2O**	**MgO**
95	5.5	2.5	140	160	180	10
SO_3	**Fe**	**Mn**	**B**	**Zn**	**Cu**	**Mo**
187	0.9	1.6	0.3	0.4	1.5	0.5

Table 2. Chemical structure of perlite (Yıldız, 2014).
Çizelge 2. Perlitin kimyasal yapısı (Yıldız, 2014).

Si %	**Al**	**K**	**Na**	**Fe**
33.8	7.2	3.5	3.4	0.6
Ca	**Mg**	**O**	**H_2O**	**Other**
0.6	0.2	47.5	3.0	0.2

Method

The objective of this study was to determine whether varying doses of PBZ have a residual impact on plant yield, quality, and fruit in soilless tomato cultivation when applied via foliar or soil application. The study included five distinct PBZ treatments, including a control group (Table 3).

The study employed the Belfort F_1 tomato variety, developed by Syngenta Türkiye. The seedlings were planted on 1 May 2022. The plants were cultivated in 6-foot balcony pots with a width of 25 cm, a length of 75 cm, a height of 21 cm, and a volume of 24 litres of growing medium (Figure 1).

Table 3. Different paclobutrazol (PBZ) doses applied in the study
Çizelge 3. Çalışmada uygulanan farklı paclobutrazol (PBZ) dozları

1.	*Pure water application (Control)*
2.	*50 ppm paclobutrazol foliar application*
3.	*100 ppm paclobutrazol foliar application*
4.	*100 ppm paclobutrazol soil application*
5.	*200 ppm paclobutrazol soil application*

Figure 1. Trial setup, and post-planting view
Şekil 1. Deneme kurulumu ve ekim sonrası görünüm

The process of fertilisation, and irrigation was conducted using a fully automated system. The requisite quantities for fertilisation were prepared by modifying the methodology set forth by Hoagland & Arnon (1950), with adjustments made according to the growth status of the plants in question. Following a ten-day period, the ratio of N:P:K:Ca: Mg was prepared as 2:1:1:3:1.5:1, and fertilisation was applied at 2.0 mmhos/cm EC until the onset of flowering, and 2.2 mmhos/cm EC thereafter. The fertilisation was applied in conjunction with the irrigation, and at each instance of irrigation. Ongoing measurements were made of the drainage outputs, and measures were taken to prevent the accumulation of salinity. Irrigation was conducted six times a day at equal intervals, with each irrigation occurring automatically for a duration of two minutes. To ascertain the impact of the treatments on tomato plants, the experiment was concluded in November. This was followed by a series of observations, including marketable yield, total yield, number of fruits, number of rejects, plant height, internode distance, pH, water-soluble dry matter content, titratable acid (TA), chlorophyll index (SPAD), fruit wet-dry weight, and leaf wet-dry weight.

Observations made in the study, marketable yield (kg/da): Non-marketable fruits were separated from the fruits collected during the harvest period, and then the remaining fruits were weighed, and recorded in kg/da. Total yield (kg/da): Tomato fruits collected from each plot were weighed, and recorded in kg/ha. Number of fruits (pcs/plant): The fruits collected at each harvest were counted according to the plots, and at the end of the harvest period, the number of fruits was divided by the number of plants in the plot, and the number of fruits was calculated in units/plant. Number of rejects (pcs/plant): The fruits that reached harvest maturity were harvested, and the number of fruits that had no marketable value after harvest was recorded. Plant height (m): The length of the plant was determined by measuring the distance from the root collar to the growing tip with a tape measure. Distance between internodes (cm): The distance between the two plant exit points on the main stem of the plant was measured with the help of a ruler. Determination of pH in fruit juice: Fruit samples were passed through a juicer, and the obtained juice was measured with a pH meter (Hanna HI-9812-5N, USA). Determination of water soluble dry matter content (%): After the beginning of the harvest, the juices of the fruits taken at the 4th and 5th harvests were squeezed with a juicer, and measured with a digital refractometer without delay after filtration. Titratable acid determination (TA) (%): The juices of the harvested fruit samples were extracted using a juicer. The juices were filtered, and then titration measurements were made using the pH metric method. Then, 10 mL of juice was taken, and titrated with 0.1 N NaOH solution until the pH reached 8.1. Titration results were calculated as % according to the methodology proposed by Cemeroğlu, (2010). Chlorophyll index (Spad): Chlorophyll index (Spad) was measured using a chlorophyll meter (Minolta SPAD-502, Osaka, Japan) on the third, and fourth leaves from the bottom of the growing tip of the plants (developed leaves) during the period of the experiment. Leaf, and fruit wet-dry weights (g): Healthy leaves, and fruits were taken from the plants at the beginning, and the middle of the harvesting period, and the wet weights of the leaves, and fruits were weighed on a digital balance with a precision of 0.001 g. The wet weights of the samples were placed in paper bags, placed in an oven, and allowed to dry at 80 °C. Then, the wet, and dry weights of the dried leaves, and fruit samples were determined with a precision balance (0.01 g).

The experiment was conducted in three replicates according to a random plots factorial experiment design. Each pot contained 3 plants, and 3 pots were used in each replicate. A one-way analysis of variance (ANOVA) was conducted on the data using the SPSS 20.0 package software. The Duncan multiple comparison test was employed to ascertain whether the means differed at the 1-5% level.

Sample collection, preparation, extraction, and clean-up

Tomato samples were collected on the 1st, 3rd, 5th, 7th, and 10th day post-spraying (EC, 2002). The extraction, and clean-up procedures based on QuEChERS AOAC Method 2007.01 were executed following the guidelines provided by (Lehotay, 2007). The process steps for QuEChERS are illustrated in Figure 2. LC-MS/MS analysis of table tomatoes was conducted in triplicate.

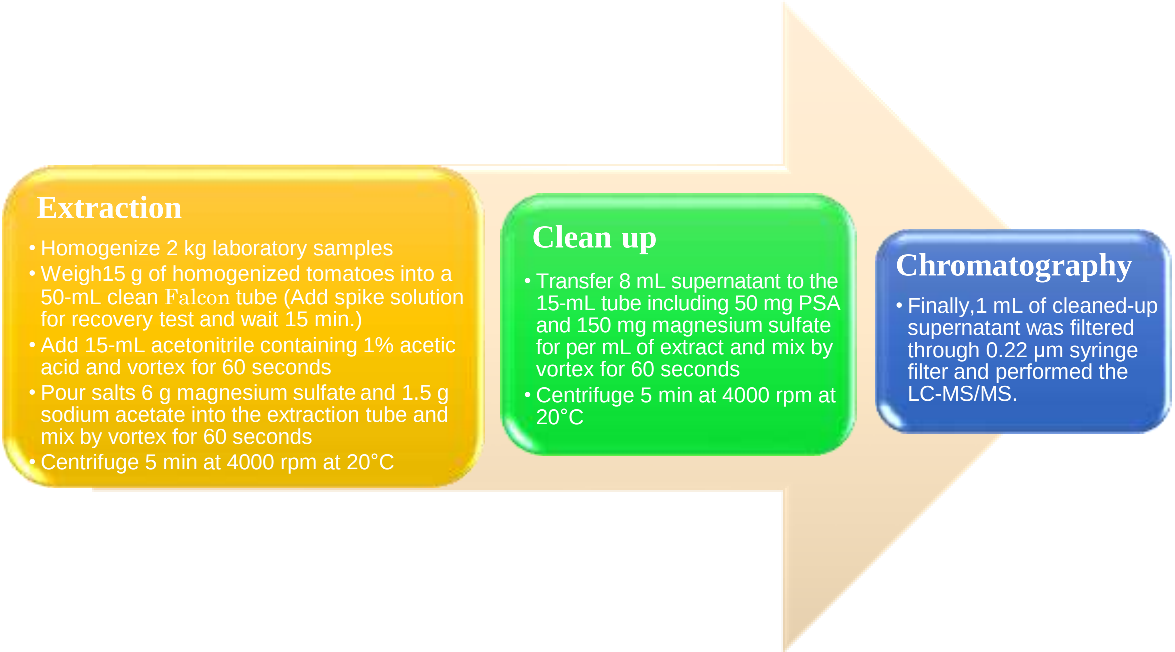

Figure 2. The analytical procedure of the QuEChERS-AOAC Official Method 2007.01.
Şekil 2. QuEChERS-AOAC Resmi Yöntemi 2007.01'in analitik prosedürü.

LC-MS/MS analyses and method verification

Analyses of PBZ were performed using a Shimadzu® LC–MS 8050 system, which is equipped with advanced UPLC, and MS/MS capabilities. The system components included a pumping device (LC-30AD), SIL-20A autosampler, degasser (DGU-20A3R), column oven (CTO-20ACV), and a tandem mass spectrometer. Chromatographic separation was achieved using a high liquid pressure chromatography column (Inertsil ODS IV C18 column, 2.1 mm x 150 mm, 3 µm particle size). A gradient elution programme was employed for the chromatographic separation, utilising eluent A, which consisted of distilled water, and 10 mM ammonium formate, and eluent B, which consisted of methanol. Gradient elution commenced with 10% of B (held for 0.5 minutes), before increasing linearly to reach 90% of B in 1 minute (held for 3 minutes), and subsequently decreasing to the initial stage (10% of B) at 4.5 minutes, where it was maintained until 5 minutes. The volume of injection for each sample was 10 µL. The flow velocity of the mobile phase was maintained at 0.4 mL/min, and the column oven was set to 40°C. Instrument parameters were precisely managed with LabSolution® software (version 5.118). Method verification was performed according to the SANTE document (SANTE, 2021; Balkan & Yılmaz, 2022).

The method validation parameters of PBZ are given in Table 4. The correlation coefficient (R2) of the PBZ calibration is 0.9993. The LOD value was calculated as 1.20, and LOQ value as 3.99. The retrieval values within the scope of the method were 97.10-104.17%, and RSD values were found in the range of 0.25-2.20% (Table 4). According to the SANTE document, the PBZ must meet 70-120% recovery, and ≤20% RSD values in order to meet the method performance criteria (SANTE, 2021). It is seen that PBZ fulfils these criteria (Table 4).

Table 4. Method optimization, and verification parameters
Çizelge 4. Metod optimizasyon ve doğrulama parametreleri

Analyte	Precursorion (m/z)	Productions (m/z, CE, eV)	RT (min)	Linear regression equation	Correlation coefficient (R^2)	LOD (µg/kg)	LOQ (µg/kg)	Fortification (µg/kg)	Reatibility Recovery % (RSD, %)	Reproducibility Recovery % (RSD, %)	U %
Paclobutrazol (PBZ)	294.4	70.1 (-21)	3.007	Y = (65059.8)X + (42256.1)	0.9993	1.20	3.99	10	104.17 (2.20)	97.10 (1.92)	7.32
		125.1 (-25)						50	97.50 (0.25)	99.68 (1.75)	
								100	100.56 (1.12)	103.72 (1.86)	

RESULTS and DISCUSSION

The impact of PBZ application on yield, quality, plant growth, and residue in tomato cultivation is presented in Tables 5, 6, 7, 8, and 9.

Table 5. Effect of PBZ applications on yield, and yield parameters of tomato
Çizelge 5. PBZ uygulamalarının domatesin verimi ve verim parametreleri üzerine etkisi

Applications	Number of fruits (pcs/plant)		Number of Discards (pcs/plant)		Marketable Yield (kg/da)		Total Yield (kg/da)	
Control	89.0±7.21	c	60.0±14.00	a	268.55±23.51	b	436.35±27.37	b
50 ppm leaf	131.0±6.24	a	62.3±07.37	a	385.33±26.76	a	516.06±18.74	a
100 ppm leaf	108.0±6.92	b	40.0±05.29	b	374.24±17.19	a	489.97±25.89	a
100 ppm soil	63.0±2.00	d	21.7±02.89	c	233.63±25.71	bc	269.78±09.01	c
200 ppm soil	49.7±5.51	e	13.7±02.52	c	192.80±17.39	c	226.12±12.99	d
p-value	0.000		0.000		0.000		0.000	
Level of importance	***		***		***		***	

***: significant at the P≤ 0.001 level.

Table 6. Effect of PBZ treatments on fruit-leaf fresh, and dry weight of tomato
Çizlege 6. PBZ uygulamalarının domatesin meyve-yaprak taze ve kuru ağırlığına etkisi

Applications	Fruit Fresh Weight (g)		Fruit Dry Weight (g)		Leaf Wet Weight (g)		Leaf Dry Weight (g)	
Control	322.00±33.65		13.40±2.19		25.33±7.02	b	3.63±0.87	b
50 ppm leaf	322.67±14.74		11.12±8.64		28.67±5.03	b	4.13±0.35	b
100 ppm leaf	313.33±23.86		15.03±2.21		39.33±5.03	a	5.47±0.67	a
100 ppm soil	324.00±41.57		14.11±4.02		41.33±1.16	a	5.30±0.17	a
200 ppm soil	326.67±14.74		12.39±3.18		44.67±7.02	a	5.30±0.56	a
p-value	0.981		0.863		0.006		0.009	
Level of importance	**ns**		**ns**		**		**	

**: Significant at the P≤0.01 level; ns: not significant.

Table 7. The impact of PBZ treatments on plant height, internode length, and chlorophyll content in tomato.
Çizelge 7. Domateste PBZ uygulamalarının bitki boyu, boğum arası uzunluğu ve klorofil içeriğine etkisi.

Applications	Plant Height (m)		İnternode length (cm)		Chlorophyll index (Spad)	
Control	2.93±0.15	a	10.00±1.00	a	51.33±3.51	c
50 ppm leaf	2.67±0.12	b	9.33±0.58	a	58.67±1.52	b
100 ppm leaf	2.47±0.10	b	8.00±0.00	b	62.00±1.00	b
100 ppm soil	1.69±0.14	c	4.33±0.58	c	66.67±1.16	a
200 ppm soil	1.60±0.11	c	3.67±0.58	c	68.67±0.58	a
p-value	0.000		0.000		0.000	
Level of importance	***		***		***	

***: Significant at the P≤0.001 level.

The administration of PBZ led to a statistically significant enhancement in the yield, and yield components of soilless tomato cultivation, with this effect being observed at the value of 0.001 according to the doses administered. The lowest number of fruits per plant was observed in the treatment group receiving 200 ppm soil-applied PBZ, while the other treatment groups exhibited a higher number of fruits than the control. Furthermore, the highest number of rejects was observed in the control group, and in the 50 ppm foliar PBZ applications. Conversely, the lowest figure was observed in the soil PBZ applications at 100, and 200 ppm.

Table 8. Effect of PBZ treatments on fruit quality characteristics of tomato
Çizelge 8. PBZ uygulamalarının domates meyvesinin kalite özelliklerine etkisi

Applications	pH		Water-soluble dry matter		Titratable Acid (TA)
Control	4.81±0.06		6.00±0.88	a	3.83±0.06
50 ppm leaf	4.89±0.03		5.97±0.37	a	3.87±0.61
100 ppm leaf	4.89±0.04		6.03±0.31	a	3.87±0.25
100 ppm soil	4.91±0.05		4.84±0.29	b	3.50±0.10
200 ppm soil	4.84±0.05		4.38±0.33	b	3.63±0.15
p-value	0.141		0.004		0.515
Level of importance	**ns**		*******		**ns**

*** : Significant at the P≤0.001 level; ns: not significant.

Table 9. Paclobutrazol residue on different days
Çizelge 9. Farklı günlerdeki paclobutrazol kalıntısı

Analysis	Treatment	Residue at 1st (µg/kg)	Residue at 3rd (µg/kg)	Residue at 5th (µg/kg)	Residue at 7th (µg/kg)	Residue at the 10th (µg/kg)
Paclobutrazol (PBZ)	Control	Nd				
	50 ppb leaf	Nd				
	100 ppb leaf	0.96 (<LOD)	2.20 (<LOQ)	0.76 (<LOD)	0.32 (<LOD	0.10 (<LOD)
	200 ppb soil	2.54 (<LOQ)	4.43	2.88 (<LOQ)	2.77 (<LOQ)	1.04 (<LOD)

LOD: Limit of detection, LOQ: Limit of quantification Nd: Not detected

The control application yielded a marketable yield of 268.55 kg/da, while the 50, and 100 ppm foliar PBZ applications yielded 385.33 kg/da, and 374.24 kg/da, respectively. Similarly, the highest total yield was obtained from applications of 50 ppm, and 100 ppm foliar PBZ, with yields of 516.06 kg/da, and 489.97 kg/da, respectively. In general, a statistically significant difference at 0.001 level was observed between treatments in terms of number of fruits, number of rejects, marketable, and total yield (Table 5). Sudrajat et al. (2021) used PBZ (p1: 0 ml/l, p2: 0.375 ml/l, p2: 0.375 ml/1, p3: 0.750 ml/1) to increase the yield, and quality of cucumber grown in hydroponic system, the lowest number of fruits was obtained from P1 (6.50 pieces), and the highest number was obtained from P3 (12.0 pieces) among PBZ treatments. Wijayanti & Dewi, (2024) applied four different PBZ doses (0 ppm (control), 25-50-75-100 ppm) on the growth, and development of beans, the lowest number of fruits in beans was obtained from 100 ppm (2.33 plants/piece), and the highest number was obtained from control (15 plants/piece). Aydınlı et al. (2021) conducted a study to ascertain the impact of foliar PBZ application on yield, and fruit quality in the apple cultivar. Although PBZ applications did not affect yield, the highest yield was observed in 10 ppm (63.26 kg), and the lowest yield was observed in 20 ppm (42.83 kg) PBZ application. Mohan et al. (2015) reported that PBZ application had positive effects on yield, and improved fruit number, and fruit quality in chilli plants. Similarly, PBZ applications have been reported to improve yield, and fruit quality in potato cultivation (Ali et al., 2018). It has been reported that PBZ application in conventional cucumber cultivation can increase yield by 36% to 58.5% more compared to cultivation without PBZ application (Budiyanto, Hajoeningtijas, & Nugroho, 2010; Harpitaningrum, Sungkawa, & Wahyuni, 2014). Khandaker et al. (2020), in a pot study on growth, yield, and quality of white aubergine, found that 200 mg PBZ concentration increased the growth, yield, and quality of aubergine under pot conditions. The application of PBZ has been demonstrated to inhibit gibberellin synthesis, and the proliferation of meristem cells, consequently inducing a decline in both flowering, and leaf area (Kim et al., 2012; Du et al., 2018). The inhibition of giberalin synthesis has been shown to result in an increase in ABA synthesis (Soumya et al., 2017), which, in turn, has been demonstrated to cause ion loss of stomatal guard cells, leading to stomatal closure, and loss of turgor, and water (Hopkins and Hüner, 2009). The closure of stomata, and the subsequent decrease in stomatal conductance, have been shown to result in a decline in photosynthesis rates (Chaves, Flexas, & Pinheiro, 2009; Wardani et al., 2022). This, in turn, leads to a reduction in the transportation of assimilates (carbohydrates), which consequently decreases the fruit weight of the plant, and by extension, the overall yield. The effects of PBZ on yield were found to vary across different plant species in the course of studies conducted for this purpose (Giovinazzo & Souza-Machado, 2000; Singh, 2000; Samaan & Nasser, 2020). Indeed, Christov et al. (1995) observed that the time of PBZ application may cause variability in yield. According to the results obtained, it is thought that the differences between the literatures are due to differences in PBZ application technique, application time, application dose, and plant species.

In soilless tomato cultivation, a statistically significant distinction at the 0.01 level was identified between the treatments in regard to leaf wet weight, and leaf dry weight. The highest leaf wet weight was observed in treatments receiving 200 ppm soil PBZ (44.67 g), 100 ppm soil PBZ (41.33 g), and 100 ppm foliar PBZ (39.33 g), respectively. The lowest recorded leaf wet weight was 25.33 g in the control treatment, and 28.67 g in the 50 ppm foliar PBZ application. Similarly, with regard to leaf dry weight, the most favourable outcome was noted in the case of 5.47 g in the 100 ppm foliar PBZ application, and 5.30 g in the 100 ppm, and 200 ppm soil PBZ applications. The least leaf dry weight was observed in the control treatment, and in the 50 ppm foliar PBZ application. There was no statistically significant difference between the treatments in terms of fruit wet, and dry weights (Table 6). Wijayanti & Dewi, (2024) applied four different PBZ doses (0 ppm (control), 25, 50, 75, and 100 ppm) on the growth, and development of beans, the lowest fruit wet weight were obtained from 100 ppm (9.26 g), and the highest was obtained from control (21.46 g). Aydınlı et al. (2021), to assess the impact of foliar PBZ application on yield, and fruit quality in apple cultivar, when the effect of treatments on fruit weight was examined; control (230.35 g), 10 ppm (233.80 g), and 20 ppm (224.19 g) doses were in the same group in terms of fruit weight, while fruit weight at 40 ppm (210.83 g) dose decreased statistically significantly compared to other treatments. Greene, (1986, 1991), and Khurshid et al. (1997a) reported that PBZ application decreased fruit weight in their studies. Similarly, another study in tomato plants reported that PBZ treatments resulted in a reduction in fruit, and leaf wet weight (Srivastava et al., 2012).

Such reductions may be attributed to the fact that PBZ controls plant growth, thereby making the plant more compact, and limiting leaf formation. However, the same study also indicated that the application of PBZ resulted in an increase in fruit, and leaf dry weight. This increase may be attributed to the fact that PBZ regulates plant growth, promotes fruit formation, and helps the plant to utilise its resources more efficiently for fruit formation. Furthermore, it can be postulated that the impact of PBZ applications on fruit, leaf wet, and dry weights may be contingent upon factors such as the dosage employed, the timing of application, and the prevailing growth conditions.

Among the PBZ treatments, the tallest plant height was achieved with the control treatment, while the shortest plant height was recorded in the 100 ppm, and 200 ppm soil PBZ treatments. In the tomato plant, the highest internode distance was obtained from the control, and 50 ppm foliar PBZ application, and the lowest was obtained from 100 ppm, and 200 ppm soil PBZ application. The highest chlorophyll content was obtained from 100 ppm, and 200 ppm soil PBZ application, and the lowest was obtained from the control application. The application of PBZ resulted in a statistically significant difference at the 0.001 level in plant height, internode length, and chlorophyll content (Table 7). Wijayanti & Dewi, (2024) applied four different PBZ doses (0 ppm (control), 25, 50, 75, and 100 ppm) on the growth, and development of beans, the lowest plant height was obtained from 100 ppm (8.60 cm) PBZ treatment, and the highest was obtained from control (251.17 cm) treatment. In our study, and other studies, plant height decreased in direct proportion as PBZ doses increased.

In PBZ-treated plants, cells can continue to divide even if gibberellin synthesis decreases. Nevertheless, cell growth was impeded as a consequence of the inhibition of gibberellin biosynthesis in the subapical meristem. In different plant species, PBZ treated plants had shorter internodes, and reduced plant height (Meena, 2014; Muneeba, 2020).

According to the PBZ application doses, a significant distinction was identified at the level of 0.001 between the water-soluble dry matter ratios in soilless tomato plants. Among the applications, better results were obtained in control, 50 ppm, and 100 ppm foliar PBZ applications than in soil PBZ applications. In addition, the impact of PBZ treatments on pH, and titratable acidity (TA) in tomato fruits was found insignificant (Table 8). Aydınlı et al. (2021) reported in their study to determine the effects of foliar PBZ application on yield, and fruit quality in apple variety that the best result in terms of water-soluble solids ratio of the fruit was obtained at 40 ppm dose (15.20%) compared to the control application, and in terms of titratable acidity ratio, the best result was obtained from 20 ppm (0.42%) PBZ application compared to the control application. Suja & Anusuya, (2018) reported in their study on the growth, and quality of tomato PKM-1 with PBZ, and sridiamine, the titratable acidity ratio (TA) was found to be 19.6% to 37.2% higher compared to the control application, and the water-soluble solids content in the fruit was found to be between 4.03-5.48.

In studies on different species, it has been reported by different researchers that PBZ application causes an increase in the water-soluble dry matter content (Jain, Sing, & Misra, 2002; Yeshitela, Robbertse, & Stassen, 2004; Burondkar et al., 2013; Samaan & Nassar, 2020), that the amount of water-soluble dry matter in apples is not affected or decreases as a result of PBZ applications from soil (Johnson & Legge, 1985; Khurshid et al., 1997b), and that it increases when applied from the leaves (Naira et al., 2017; Sha et al., 2021). One of the positive effects of PBZ on fruit quality is that it reduces the acidity rate in the fruit (Webster, Quinlan, & Richardson, 1986; Khurshid et al., 1997a; Jain et al., 2002; Burondkar et al., 2013; Samaan & Nasser, 2020; Sha et al., 2021). Nevertheless, in our study, there was no difference in pH, and TA amounts, which may be due to plant species, application time, and application doses. Paclobutrazol has been demonstrated to induce substantial metabolic alterations in plant species, culminating in a decline in TA, and pH levels. This effect is manifested by a reduction in the growth rate of plants, and the production of acidic metabolites, resulting in decreases in TA and pH (Desta & Amare, 2021; Christov, Tsvetkov, & Kovachev, 1995). The present findings suggest that plant growth regulators have significant effects on pH, and the production of acidic compounds through changes in plant metabolism. Notably, growth regulators such as Paclobutrazol have been observed to exert influence not only on pH, and acidic compound production, but also on stress responses, and plant productivity. In the context of external application, the judicious selection of the most suitable chemical, the determination of the optimal concentration, and the temporal considerations of application are of paramount importance to ensure the achievement of the desired outcome (Palavan-Ünsal, 1993; Buban, 2000). From the consumer's point of view, fruit quality characteristics of vegetables are generally assessed by criteria such as colour, size, shape, firmness, dry matter, taste and nutritional value, but the concept of quality also includes characteristics such as pH, SÇKM, and TA (Dorais, Papadopoulos, & Gosselin, 2001; Tüzel et al., 2001). Paclobutrazol has significant effects on fruit quality, particularly in fruit-eating vegetables such as tomatoes. Erman et al. (2016) reported that the application of paclobutrazol resulted in an increase in the pH level of tomato, leading to a reduction in acidity, and an enhancement in flavour. Yıldırım & Küçük, (2008) observed that the application of paclobutrazol increased the acidic components of the fruit by increasing the TA ratio, thereby improving the flavour profile. Furthermore, Kumar et al. (2015) and Şahin et al. (2010) observed that paclobutrazol increased fruit water content, and increased SÇKM, resulting in fuller, and juicier fruit tissues. These findings suggest that paclobutrazol provides multifaceted effects that improve the fruit quality of tomato. In particular, parameters such as pH, TA, and SÇKM improve the flavour, and marketability value of tomato.

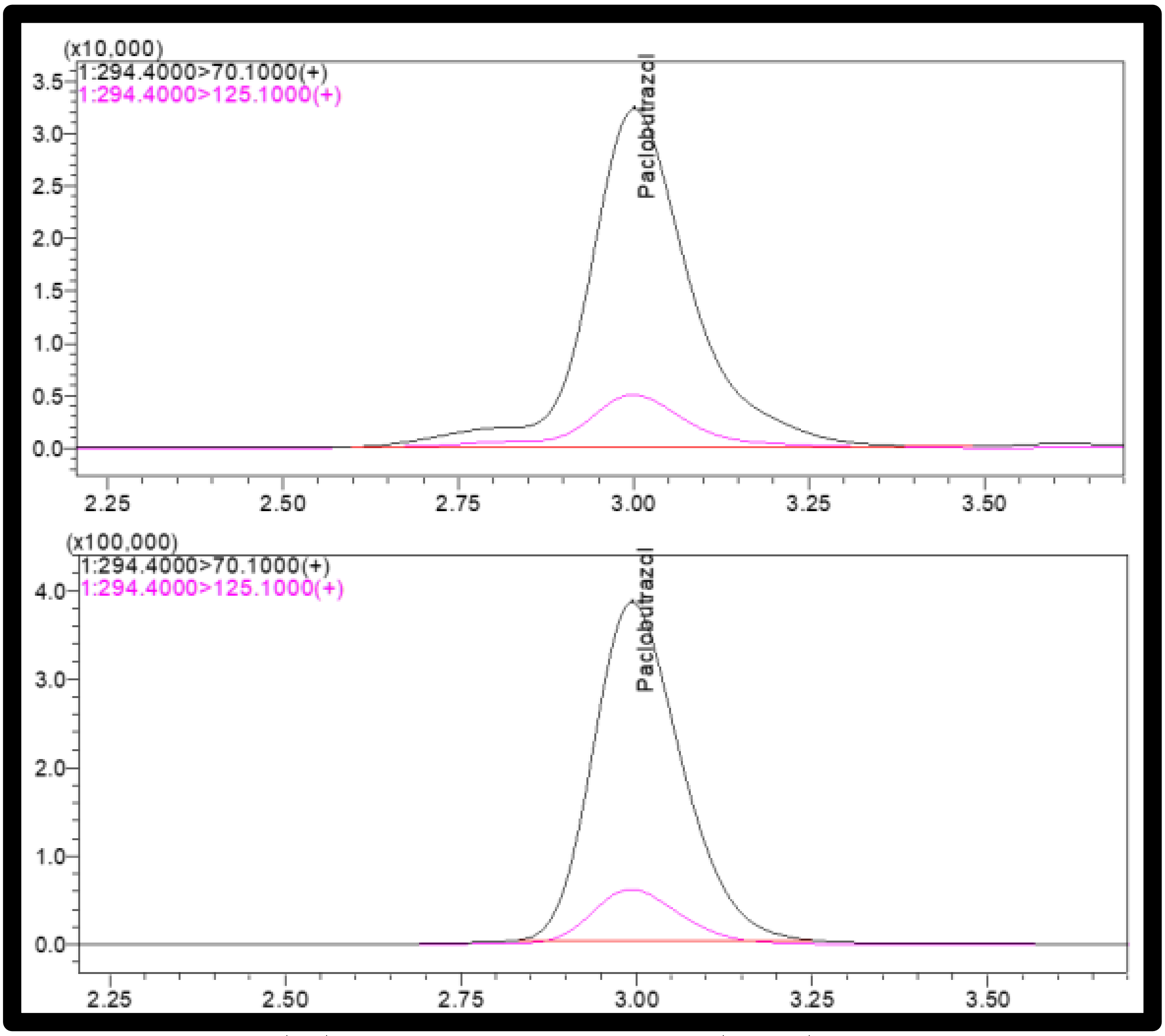

Figure 3. Paclobutrazol sample (top), and standard chromatograms (bottom)
Şekil 3. Paclobutrazol örneği (üstte) ve standart kromatogramlar (altta)

The results of paclobutrazol residue analysis are shown in Table 9. No PBZ residues were detected in the control, and 50 ppb foliar applications. PBZ residues in samples from the 100 ppb foliar application on day 3 were below the LOQ, while on the other days they were below the LOD. As a result of the 200 ppb soil application, PBZ residues in the third day samples were found to be 4.43 µg/kg, and below the LOQ on the other days (Table 9). The chromatograms of the third day sample above the LOQ, and the calibration point at a concentration of 100 µg/kg are shown in Figure 3. Çimen et al. (1999) reported that no paclobutrazol residue was found in seventh lemon in their study where they applied different doses of paclobutrazol in seventh lemon.

CONCLUSIONS

In this study on soilless tomato cultivation, it was found that foliar applications of PBZ at 50 ppm, and 100 ppm resulted in better yields compared to the control, and soil applications of PBZ. Foliar application in soilless tomato production appears advantageous for improving yield, and quality. Nevertheless, as the PBZ dosage increased, a notable decrease in plant height was observed.

Considering the study results as a whole, it would be accurate to state that PBZ applications positively affect yield, quality, and plant growth in soilless tomato production. Foliar applications of PBZ produced better results than soil applications, and no residues were detected in tomato fruits treated with PBZ according to the analytical results.

Research is required at varying ecological conditions, dosage levels, and phenological stages in order to clarify the effects of PBZ, and to contribute to the development of strategies for increasing yield, and management. Monitoring of PBZ residues is critical for ensuring food safety, and health risks can be minimised through regular residue analyses. Regulations for the use of PBZ should be established with due consideration for health, and environmental safety, while also fostering support for sustainable agricultural practices. The present study has determined that doses of 50 ppm, and 100 ppm are optimal for soilless greenhouse tomato cultivation, exhibiting favourable outcomes during the flowering, and fruit setting periods. In open field cultivation, it was determined that paclobutrazol application was more effective during active growth stages such as the spring period, considering factors such as plant species, application dose and time.

In conclusion, it is imperative for farmers to pay close attention to the precise dosage, and application timing of PBZs in order to optimise plant growth, and yield. Farmers are advised to employ the correct application techniques at the appropriate phenological stages for each plant species, and to undertake regular residue analyses to prevent any detrimental effects on environmental health. The implementation of these practices will ensure the enhancement of productivity, and facilitate the establishment of sustainable, and healthy production methodologies.

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Authorship Contributions

The authors declare that they have contributed equally to the article.

Conflict of Interest

No conflict of interest was declared by the authors.

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