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Effects of Foliar Paclobutrazol Applications on Plant Growth, Yield, Quality, and Residue Levels in Greenhouse Cucumber Cultivation

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ABSTRACT

This study evaluated the effects of foliar paclobutrazol (PBZ) applications at different doses and intervals on plant growth, yield, fruit quality, and residue levels in cucumber (Cucumis sativus L. cv. Olay F_1) cultivated under greenhouse conditions. The experiment was conducted using a randomized complete block design with three replications. PBZ was applied to shoot tips at concentrations of 10, 20, and 40 mg L^{-1}, at 7- and 14-day intervals, while distilled water was used for the control group. PBZ treatments significantly reduced plant height and internode length. The most notable reduction in plant height (20.3%) was observed with the 20 mg L^{-1} dose applied weekly. The highest marketable yield (184.03 t/ha) was achieved with the 40 mg L^{-1} PBZ treatment applied every 14 days, which was 1.08% higher than the control (182.07 t ha^{-1}). In contrast, the 20 mg L^{-1} weekly application resulted in an 11.7% decrease in yield. The average marketable fruit weight increased by 13.5% (reaching 98.44 g) under the 40 mg L^{-1} weekly treatment. However, this increase was accompanied by a 13.6% reduction in fruit number per plant. PBZ applications significantly affected the chlorophyll index (SPAD), with the highest value (55.47) recorded in the 40 mg L^{-1} treatment applied at 7-day intervals. In contrast, fruit and leaf dry matter contents were not significantly influenced by the treatments. The PBZ doses and application methods used in the study did not result in detectable residues in cucumber fruits under the experimental conditions. This finding suggests that, within the scope of this study, the application does not pose a residue-related concern for food safety and represents one of the key outcomes of the research. In conclusion, foliar PBZ applications effectively suppressed vegetative growth. The 40 mg L^{-1} treatment applied biweekly offered an optimal balance between compact growth, fruit weight, and total yield, without compromising fruit quality. or leaving harmful residues.

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Yapraktan Paklobutrazol Uygulamalarının Serada Hıyar Yetiştiriciliğinde Bitki Gelişimi, Verim, Kalite ve Kalıntı Düzeyine Etkisi

ÖZET

Bu çalışmada, serada yetiştirilen hıyar (*Cucumis sativus* L. cv. Olay F_1) bitkilerinde farklı doz ve aralıklarda yapraktan uygulanan paklobutrazolun (PBZ) bitki gelişimi, verim, meyve kalitesi ve kalıntı miktarına etkisi araştırılmıştır. Araştırma, yarı kontrollü serada tesadüf parselleri deneme desenine göre üç tekerrürlü yürütülmüştür. PBZ, sürgün uçlarına yapraktan 10, 20 ve 40 mg L^{-1} konsantrasyonlarında, 7 ve 14 günlük aralıklarla uygulanmıştır. Kontrol grubu için saf su kullanılmıştır. Sonuçta, PBZ uygulamaları bitki boyu ve boğum arası mesafeyi önemli düzeyde azaltmış, 20 mg L^{-1} 7-gün PBZ uygulaması en etkili uygulama olmuş ve bitki boyunda %20.3'lük bir azalma sağlamıştır. En yüksek pazarlanabilir verim (184.03 t ha^{-1}), 40 mg L^{-1} 14-gün PBZ uygulamasından elde edilmiş ve kontrole göre (182.07 t ha^{-1}) göre %1.08 oranında daha yüksek bulunmuştur. Öte yandan, 20 mg/L

Bahçe Bitkileri

Araştırma Makalesi

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Anahtar Kelimeler
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Paklobutrazol kalıntısı
Gıda güvenliği

dozunun 7 günlük uygulaması, verimde %11,7 oranında azalma ile sonuçlanmıştır. Pazarlanabilir meyve ağırlığı, 40 mg L^{-1} 7-gün PBZ uygulamasında %13.5 artış göstererek 98,44 g olarak belirlenmiş, ancak bu artış, bitki başına meyve sayısında %13.6'lık bir azalmaya neden olmuştur. Klorofil indeksi (SPAD) ile PBZ uygulamaları arasında anlamlı bir ilişki bulunamamış, en yüksek SPAD (55.47), 40 mg L^{-1} 7-gün PBZ uygulamasında ölçülmüştür. Çalışmada kullanılan doz ve uygulama şekilleri hıyar meyvelerinde tespit edilebilir PBZ kalıntısı bırakmamış olup, bu bulgu uygulamanın gıda güvenliği açısından tamamen güvenli olduğunu göstermekte ve çalışmanın en kritik sonuçlarından biri olarak öne çıkmaktadır. Sonuç olarak, yapraktan uygulanan PBZ, vejetatif büyümeyi etkin şekilde baskılamış, 14 günde bir uygulanan 40 mg L^{-1} PBZ dozu, kompakt bitki gelişimi, meyve ağırlığı ve toplam verim arasında optimal dengeyi sağlamış; meyve kalitesini olumsuz etkilemeden ve kalıntı oluşturmadan etkili sonuçlar vermiştir. Bu sonuçlar, PBZ'nin, sera koşullarında yüksek yoğunluklu hıyar yetiştiriciliği için potansiyel bir büyüme düzenleyici olarak kullanımını desteklemektedir.

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INTRODUCTION

Cucumber (*Cucumis sativus*) is one of the most important vegetable crops cultivated globally, with a production area of 2.19 million hectares and a total output of 97.81 million tons. China ranks first in global production with 80.17 million tons, followed by Türkiye in second place with 1.74 million tons cultivated over 32.93 thousand hectares. The Russian Federation occupies third place with a production volume of 1.68 million tons (Food and Agriculture Organization [FAO], 2023). In Türkiye, cucumber cultivation is widely practiced under both open-field and protected conditions. Particularly under greenhouse conditions, cucumber production holds a substantial share and ranks second after tomato. In 2024, cucumber cultivation under protected conditions reached 1.028 million tons on an area of 7.40 thousand hectares (Turkish Statistical Institute (TURKSTAT, 2024).

In greenhouse cucumber production, various factors contribute to overall production costs (Bayramoğlu et al., 2021). Among these, plant trellising represents a significant component. In protected cultivation systems, cucumbers are typically grown using a vertical trellising system. Cucumber plants cultivated in greenhouses exhibit continuous vegetative growth. These cultivars are usually planted at a density of 2-3 plants per square meter and can attain heights ranging from 7 to 10 meters. Excessive vegetative growth can hinder the efficiency of support structures, increase labor requirements, and consequently raise production costs. For this reason, growers seek alternative methods to regulate plant height. Various strategies have been explored to control plant elongation, and under current agronomic conditions, PBZ is recognized as one of the most effective growth regulators for this purpose. Although PBZ is employed in different species for various objectives, its application for height control in vertically growing greenhouse crops remains limited. This limitation largely stems from concerns regarding the chemical's potential risks to human and environmental health, as well as the lack of sufficient data on residue accumulation when used for this purpose.

PBZ is classified among the most potent plant growth regulators. It is transported acropetally via the xylem tissue (Desta & Amera, 2021) and exhibits anti-gibberellin activity by inhibiting gibberellic acid (GA) biosynthesis (Rademacher, 2016). Through this mechanism, it shortens internodal length, leading to significant reductions in plant height. Furthermore, PBZ has been reported to alter endogenous hormonal balance by affecting levels of abscisic acid (ABA) and cytokinins in addition to gibberellins (Fletcher & Hofstra, 1990). It plays a key role in shaping plant architecture (Cline, 2017; Diwan et al., 2022), fostering compact plant structures by reducing plant height (Lee et al., 2015), thereby enhancing efficiency in cultivation systems with limited space and resources (Ito et al., 2016). Kumar (2021) emphasized that PBZ exerts antagonistic effects on gibberellins and auxins, restricting cell elongation by inhibiting GA_3 synthesis, ultimately resulting in shorter and more compact plants. The continuation of cell division despite inhibited elongation has also been supported by Davis and Curry (1991). Similarly, Fletcher et al. (2000) reported that PBZ suppresses growth by limiting internodal length and leaf area, a phenomenon attributed to the inhibition of gibberellin biosynthesis. Comparable effects have been observed in various fruit crops (Webster & Quinlan, 1984), though depending on the application dose and plant species, PBZ may either accelerate or delay flowering (Desta & Amare, 2021).

In many plant species, PBZ is utilized in seedling production to regulate seedling height. In crops such as tomato (Brigard et al., 2006; Kum & Geboloğlu, 2024), lettuce (Geboloğlu et al., 2016), pepper (Silva et al., 2021), eggplant (Geboloğlu et al., 2015), and cucumber (Aktaş et al., 2024), PBZ effectively restricts seedling elongation and contributes to the production of compact, healthy, and high-quality transplants. Beyond seedling production, PBZ has demonstrated efficacy in reducing stem elongation in a wide range of crops, particularly ornamentals. The potential of PBZ to regulate plant height in vertically trellised crops has also been demonstrated. Ramos Fernández et al. (2020) reported that the application of 50 mg/L PBZ in tomato significantly reduced plant height and internodal length. Similarly, Novita (2022) found that a dose of 250 mg/L PBZ applied after transplanting effectively limited height growth in tomato plants. Cázarez Flores et al. (2018) reported that an application of 150 mg/L PBZ to the cotyledon leaves of cucumber reduced plant height by 23.93%. In addition to height regulation, PBZ has been reported to affect several morphological and physiological characteristics in tomato, including fruit shape, pericarp cell structure, flowering time, and yield (Chen et al., 2020; Li et al., 2022). These diverse effects underscore the utility of PBZ as a versatile tool for growers and researchers seeking to manage plant growth in a controlled manner.

From an application standpoint, PBZ is generally administered via foliar spraying or soil drenching, with both methods yielding effective outcomes (Rademacher, 2015). Because PBZ is transported upward via the xylem, it tends to accumulate in the leaves and exhibits limited mobility in the phloem (Witchard, 1997; Singh & Ram, 2000; Rademacher, 2000). This characteristic contributes to lower residue levels in fruits and seeds (Davis et al., 1988). Therefore, the appropriate selection of application method and dosage is crucial.

The objective of this study is to investigate the effects of foliar-applied PBZ on plant height, yield, quality parameters, and potential residue accumulation in cucumber fruits grown under greenhouse conditions. Additionally, the study aims to assess whether internode shortening can be utilized as an effective strategy to control plant height and to elucidate the potential implications of this practice on greenhouse production systems.

MATERIAL and METHOD

This study was conducted between May 1 and October 30, 2021, in the greenhouse of Tokat Gaziosmanpaşa University Research and Application Center, in Tokat, Türkiye. The research site is situated between 39°51'-40°55' North latitude and 35°27'–37°39' East longitude.

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 vine-like cucumber cultivar "Olay F_1" (AG Seed Company). 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.

Irrigation and Fertilisation Practices

Irrigation was carried out 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), adjusted to the developmental stage of the plants. Starting from the fifth day after transplanting, the nutrient solution was formulated with an elemental ratio of N:P:K:Ca: Mg = 2:1:3:1:1. 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. The pH of the nutrient solution was maintained at 6.5 throughout the experiment. 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 terminated six times daily at equal intervals, with each cycle lasting two minutes. The experiment was concluded on October 30, following the completion of all observations and recordings of treatment effects on cucumber plants.

Paclobutrazol (PBZ) Applications

In determining the PBZ doses and application intervals in the study, previous literature was also taken into account. However, in the literature, the effects of PBZ have mostly been tested at the seedling stage, and therefore, there are very few studies on the effects of PBZ application throughout the vegetation period. Moreover, there is insufficient research on the application of PBZ to vegetables via soil or foliar routes, as well as on single versus multiple applications. Based on these data, relevant literature that could shed light on the research topic was utilized when determining PBZ doses and application intervals in the experiment (Berova & Zlatev, 2000; Patel, 2007; Juarez-Rodriguez et al., 2022). Furthermore, based on observations from our prior trials, doses of 50 mg/L and especially 100 mg/L caused temporary suppression of growth at the shoot apical meristem in cucumber plants. Therefore, all subsequent treatments were carefully limited to a maximum concentration of 40 mg/L during dose optimization.

PBZ applications were performed using Cultar 25SC (Active Ingredient: 250 g/L paclobutrazol; Formulation: suspension concentrate; Syngenta). Before application, PBZ solutions were prepared at concentrations of 10, 20, and 40 mg/L. Plants that did not receive PBZ treatment were evaluated as the control. 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 20, 2021. In the experiment, a total of 22 PBZ applications were performed at 7-day intervals, whereas 11 applications were carried out at 14-day intervals. Control plants were sprayed similarly with 5 mL of distilled water per plant onto the shoot apex to ensure uniform handling across treatments.

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 (kg·ha^{-1}): 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 (kg·ha^{-1}): 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.

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.

Physiological and Physical 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 was used for non-destructive assessment of chlorophyll content (Dadhich et al., 2023).

Leaf Dry Matter Content (%): For leaf dry matter measurements, samples were collected twice, at 45 and 60 days after transplanting. From each plot, the fourth and fifth fully expanded leaves were sampled from the top of the plant downward. 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 matters were subsequently measured, and leaf dry matter content was calculated as the ratio of dry matter 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 matters were measured, and fruit dry matter content was calculated as the ratio of dry matter to fresh weight, expressed as a percentage.

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 an HPLC column (Inertsil ODS IV).

For PBZ residue analysis, cucumber fruit samples were collected after the 1st, 3rd, 5th, 7th, and 10th applications of PBZ performed at 14-day intervals. Accordingly, samples from both the 7-day interval and 14-day interval treatments were collected on the day following the corresponding 14-day interval PBZ application. The sample preparation procedures followed the QuEChERS AOAC Method 2007.01, by Lehotay (2011). The verification of the method adhered to SANTE guidelines (SANTE, 2021; Balkan & Yılmaz, 2022). According to SANTE guidelines, the method meets the required validation criteria of 70-120% recovery and ≤20% RSD values (SANTE, 2021).

Experimental Design and Statistical Analysis

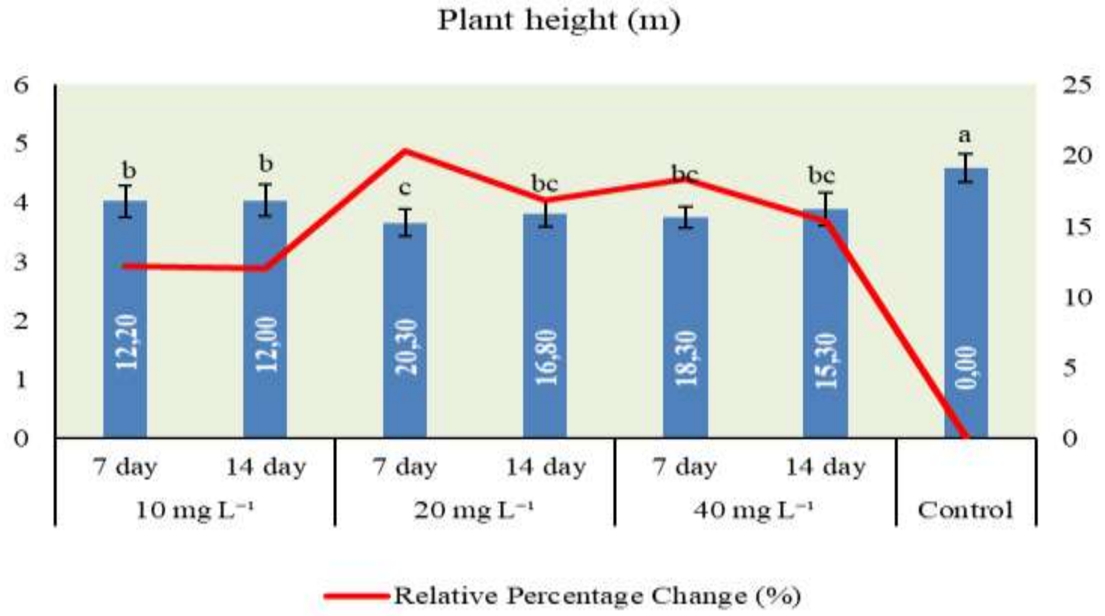
The trial was conducted in a randomized complete block design with three replications. Each replication consisted of five pots, with two plants per pot. Data were statistically analyzed using one-way analysis of variance (ANOVA) in SPSS 20.0. Mean separations were performed using Tukey's HSD test at a 5% significance level. Effect sizes were calculated using Cohen's d and partial eta squared (η^2).

RESULTS and DISCUSSION

Plant Height and Internode Length

The effects of PBZ applications on plant height are illustrated in Figure 1. Control treatment exhibited an average plant height of 4.59 m, whereas all PBZ treatments resulted in significant and pronounced reductions in plant height. The most notable decrease was observed in the 20 mg/L PBZ treatment applied at a 7-day interval, with an average height of 3.66 m, representing an approximately 20% reduction compared to the control. Similar significant decreases in plant height were also recorded at other PBZ concentrations, all significantly lower than the control values. ANOVA results revealed that PBZ treatments exerted a highly significant effect on plant height ($p<0.001$; $\eta^2=0.905$). Post hoc Tukey HSD tests confirmed statistically significant differences between the control and all PBZ treatments, with the greatest reductions observed in the 20 mg/L PBZ 7-day interval (mean difference = 0.92 m), 40 mg/L PBZ 7-day interval (mean difference = 0.84 m), and 20 mg/L PBZ 14-day interval (mean difference = 0.77 m) treatments ($p<0.05$). These findings indicate a clear dose-dependent suppression of plant height by PBZ.

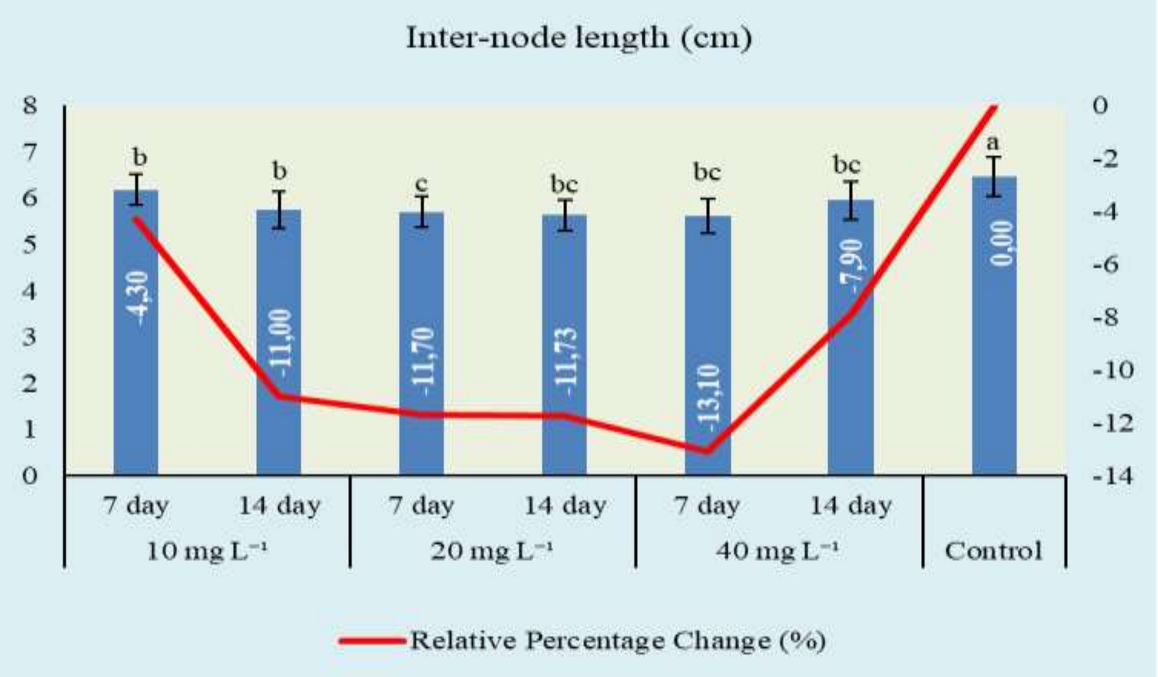
Figure 2 illustrates the effects of PBZ treatments on internode length. The control group displayed an average internode length of 6.46 cm, whereas all PBZ treatments decreased this parameter. The most substantial reductions were recorded in the 40 mg/L PBZ 7-day interval treatment (5.61 cm; 13.2% decrease) and the 20 mg/L PBZ 14-day interval treatment (5.63 cm; 12.9% decrease). Lower doses of 10 mg/L PBZ applied at 7- and 14-day intervals induced more moderate reductions of 4.3% and 11.0%, respectively. ANOVA analyses demonstrated that PBZ doses exerted a strong and significant influence on internode length ($p=0.002$; $\eta^2=0.731$). Post hoc Tukey HSD tests further verified significant differences in internode length between the control and the 20–40 mg/L PBZ treatments at the 7-day interval, as well as the 10–20 mg/L PBZ treatments at the 14-day interval ($p<0.05$). The largest mean differences were observed between the control and 40 mg/L PBZ 7-day interval (mean difference = 0.8467 cm), and control and 20 mg/L PBZ 14-day interval (mean difference = 0.8267 cm) treatments. These results collectively indicate that PBZ application significantly and dose-dependently reduces internode length. The shortening of internodes contributes to increased plant compactness and has potential implications for yield improvement, underscoring PBZ's role as a crucial regulator of plant morphology



Error bars represent the mean ± standard deviation (SD). Different letters indicate significant differences between treatments according to Tukey's multiple comparison test ($p < 0.05$). The red curve illustrates the relative percentage change in response to the treatments, with reference to the control.

Figure 1. Effect of PBZ treatments on plant height of cucumber

Şekil 1. PBZ uygulamalarının hıyarda bitki boyuna etkisi



Error bars represent the mean ± standard deviation (SD). Different letters indicate significant differences between treatments according to Tukey's multiple comparison test ($p < 0.05$). The red curve illustrates the relative percentage change in response to the treatments, with reference to the control.

Figure 2. Effect of PBZ treatments on inter-node length of cucumber

Şekil 2. PBZ uygulamalarının hıyarda boğum arası uzunluğa etkisi

The results of this study clearly demonstrate that PBZ significantly suppresses vegetative growth in cucumber, with both plant height and internode length reduced in a dose and frequency-dependent manner. The untreated control group exhibited the greatest plant height and internode length, while the 20 mg/L PBZ treatment applied weekly resulted in the most compact growth. This finding aligns with previous reports (Patel, 2007; Kazemi, 2013) that higher concentrations of PBZ effectively reduce vine elongation. Internode length reduction followed a similar pattern, and a strong positive correlation between plant height and internode length reinforces that PBZ's primary mechanism involves inhibition of internodal elongation, likely through suppression of gibberellin biosynthesis (Desta & Amare, 2021). Flores et al. (2018) also reported decreased shoot elongation after PBZ application, suggesting improved seedling quality and transplant success. Interestingly, lower PBZ concentrations (e.g., 10 mg/L) applied less frequently showed milder effects, indicating that growth suppression can be modulated based on cultivation goals. This supports findings by Ozgur (2011) and Barcenas Jr et al. (2023), who noted that PBZ is most effective when appropriately dosed and timed to balance vegetative control. Overall, the findings suggest that PBZ offers a practical tool for producing compact cucumber plants suitable for high-density cultivation and greenhouse management.

Yield and Fruit Characteristics

Table 1 presents the outcomes of PBZ applications on cucumber yield and fruit characteristics. In the study, it was determined that different PBZ doses and application intervals had a statistically significant impact on marketable yield ($p<0.001$; $\eta^2=0.898$). Marketable yields ranged from 160.77 t/ha (20 mg/L PBZ, 7-day interval) to 184.03 t/ha (40 mg/L PBZ, 14-day interval). Notably, the 40 mg/L PBZ treatment applied every 14 days resulted in a yield that was 1.1% higher than the control treatment. Conversely, the 20 mg/L PBZ treatment applied at a 7-day interval reduced marketable yield by 11.7% relative to the control. Marketable yield difference between control and 20 mg/L PBZ 7-day interval treatment was calculated as 21.3 t/ha (Cohen's d=4.41), indicating a substantial practical effect size. Post hoc multiple comparisons (Tukey HSD test) confirmed that the yield differences between the control and the 10 and 20 mg/L PBZ doses at both 7- and 14-day intervals were statistically significant ($p<0.05$). These findings demonstrate that PBZ dose and application frequency exert a large and meaningful effect on marketable yield, with lower doses and more frequent applications leading to substantial reductions. The inclusion of effect size indices (partial η^2 and Cohen's d) underscores that these differences are not only statistically significant but also practically relevant.

Total yield was also significantly influenced by PBZ treatments ($p=0.001$; $\eta^2=0.763$). Total yield varied from 180.66 t/ha (10 mg/L PBZ applied every 14 days) to 201.82 t/ha (40 mg/L PBZ applied every 14 days). The control treatment yielded 201.62 t/ha, while the 10 mg/L PBZ 14-day interval treatment resulted in a 10.4% decrease in total yield compared to the control. By contrast, the 40 mg/L PBZ 14-day interval treatment showed a slight yield increase of 0.1% relative to the control. Post hoc multiple comparisons (Tukey HSD test) indicated that the differences in total yield between the control and the 10 and 20 mg/L PBZ treatments (both applied every 14 days) were statistically significant ($p<0.05$). Specifically, the 10 mg/L PBZ treatment led to a significant yield reduction of 20.96 t/ha (Cohen's d=4.20) compared to the control, while the 20 mg/L PBZ treatment caused a yield reduction of 17.43 t/ha (Cohen's d=3.72). These findings not only demonstrate statistical significance but also reveal large practical effect sizes.

Mean marketable fruit weight was highly responsive to PBZ treatments ($p=0.000$; $\eta^2=0.897$). The greatest fruit weight (98.44 g) was recorded under the 40 mg/L PBZ 7-day interval treatment—a 13.5% increase relative to the control (86.69 g). The 40 mg/L PBZ treatment applied every 14 days (90.85 g) resulted in a 4.8% increase compared to the control; however, this difference was not statistically significant. In contrast, all other treatments, including the 10 and 20 mg/L PBZ applications at 7- and 14-day intervals, exhibited similar and lower fruit weights, ranging from 86.99 to 88.65 g. Post hoc multiple comparisons using the Tukey HSD test revealed that the difference in marketable fruit weight between the control and the 40 mg/L PBZ 7-day interval treatment was statistically significant ($p<0.05$). This treatment resulted in a substantial and statistically significant increase of 11.75 g (Cohen's d =4.65) compared to the control. Although the 10 and 20 mg/L PBZ treatments showed numerically higher marketable fruit weights than the control, these differences were not statistically significant ($p>0.05$). These findings highlight the pronounced positive effect of the 40 mg/L PBZ 7-day interval treatment on marketable fruit weight, while suggesting that other tested PBZ concentrations had negligible impacts on this parameter.

PBZ applications significantly reduced the number of marketable fruits per plant ($p=0.000$; $\eta^2=0.895$). The highest number of fruits was recorded in the control group (78.60 fruits/plant). The most notable reduction occurred with the 40 mg/L PBZ treatment applied at 7-day intervals, yielding 67.90 fruits/plant (a 13.6% decrease). The same dose applied at 14-day intervals resulted in a more moderate reduction (75.79 fruits/plant; a 3.6% decrease). Additionally, 10 and 20 mg/L PBZ treatments consistently lowered the marketable fruit number. Post hoc Tukey HSD tests revealed that the control group had significantly higher fruit numbers compared to the 10-20 mg/L PBZ

7-day interval, 10 mg/L PBZ 14-day interval, and 40 mg/L PBZ 7-day interval treatments ($p<0.05$). The 40 mg/L PBZ 14-day interval PBZ treatment did not differ significantly from the control group ($p=0.353$). Further analysis confirmed that this treatment resulted in significantly higher fruit numbers compared to the 10 mg/L PBZ 7-day interval and 20 mg/L PBZ 14-day interval treatments, while no significant differences were observed among those intermediate concentrations ($p>0.05$). In conclusion, PBZ application at intermediate concentrations significantly reduced marketable fruit numbers, whereas 40 mg/L PBZ 14-day interval treatment mitigated this effect and maintained fruit production similar to the control group.

The present study demonstrates that PBZ has a distinct and dose-dependent influence on cucumber yield components, with the highest total and marketable yields obtained from the 40 mg/L biweekly treatment, while lower doses or more frequent applications resulted in yield reductions. These findings are consistent with Globerson et al. (1989), who reported that PBZ reduced cucumber plant size without significantly affecting fruit number when applied early, though our results suggest that repeated foliar applications at high frequency may suppress reproductive output, as seen in the 40 mg/L weekly group. This is further supported by Perera and Kumarasinghe (2025), who observed that PBZ reduced fruit number in salad cucumber under weekly application, likely due to excessive suppression of vegetative and reproductive growth. Similarly, Rai et al. (2003) found that while PBZ improved certain quality parameters in bottle gourd, it also significantly decreased fruit length and vine growth, aligning with our observation that lower PBZ doses did not translate into yield benefits. Kore et al. (2003) also highlighted the growth-regulating potential of PBZ in cucurbits, though they emphasized the need for optimal concentration to prevent yield suppression. The reduction in fruit number and yield at lower or overly frequent doses in our study reflects these concerns and suggests that the timing and concentration of PBZ are critical for maintaining productivity. Furthermore, while Magnitskiy et al. (2006) reported that PBZ seed soaking reduced fruit weight in cucumber, our foliar applications—particularly the 40 mg/L treatments-significantly increased average fruit weight, indicating that method and site of application greatly influence yield responses. Supporting this, Davis et al. (1988) explained that PBZ's inhibition of gibberellin biosynthesis can either enhance or suppress yield depending on how it alters assimilate distribution and reproductive development. This dual effect was also noted by Knurshid et al. (1999) in apples and Nishizawa (1993) in strawberries, where PBZ improved yield in some contexts but reduced it in others. PBZ is a known inhibitor of gibberellin (GA) biosynthesis, which plays a crucial role in cell division and elongation processes (Rademacher, 2000). The reduction in GA levels leads to a slowdown in cell division, particularly affecting the early stages of floral development (Davies, 2010). Consequently, this hormonal limitation adversely impacts flower initiation and formation, resulting in a decreased number of flowers and therefore fewer fruits (Olszewski al., 2002). The reduction in fruit number can be directly linked to impaired floral organogenesis due to suppressed GA synthesis. However, the resources that would have been allocated to a higher fruit load are redirected to fewer developing fruits, promoting enhanced cell expansion and consequently greater fruit weight (Nayak, 2022).

Under PBZ treatments, the inverse relationship observed between fruit number and fruit size underscores the critical role of GA in balancing reproductive organ development and fruit growth. Overall, these findings highlight the necessity for carefully planned PBZ application strategies. Excessive or poorly timed PBZ applications can restrict fruit set and reduce yield, whereas optimized high-dose, low-frequency applications have the potential to increase individual fruit weight while maintaining or slightly enhancing marketable yield by mitigating negative impacts on total fruit production. In the present study, PBZ applications significantly reduced plant height (up to 20% reduction), thereby achieving the desired compact plant architecture. However, variations in marketable yield were determined not by plant height reduction alone, but by the contrasting effects on fruit number and weight. Notably, the 40 mg/L PBZ treatment applied at 14-day intervals reduced plant height by 16%, increased fruit weight by 4.8%, and improved marketable yield by 1.1%, thereby offering an economically advantageous approach. In contrast, the 20 mg/L PBZ treatment applied at 7-day intervals, although achieving a 20% reduction in plant height, resulted in an 11.7% decrease in fruit number, leading to a 21.3 t/ha yield loss and consequent economic disadvantage. These results demonstrate that reduced plant height alone does not guarantee economic success; rather, the balance between fruit number and weight must be carefully optimized based on PBZ dose and application interval. Economic analyses further revealed that the 40 mg/L PBZ treatment at 14-day intervals represents the most economically favorable strategy. This approach not only promotes a more compact plant form, extending the duration of growth within greenhouse conditions, but also achieves a slight yield enhancement, thus representing the most promising treatment for maximizing economic returns.

Although our study did not analyze endogenous hormones, previous reports show that PBZ influences hormonal balance beyond gibberellin inhibition. PBZ has been reported to increase ABA and auxin while reducing GA and cytokinin activity, partly by modulating biosynthetic and transporter genes (Opio et al., 2020). These hormonal shifts are linked with improved stomatal regulation, chlorophyll stability, and enhanced tolerance to abiotic stresses (Rademacher, 2000; Desta and Amare, 2021). Such mechanisms may partly explain the higher chlorophyll content and stress resilience observed in PBZ-treated plants. In addition, PBZ modifies assimilate allocation by limiting vegetative growth and redirecting carbohydrates toward reproductive sinks. In our study, this adjustment did not increase fruit number but led to higher average fruit weight, indicating that assimilates were preferentially invested in fruit enlargement rather than the initiation of new flowers. This pattern suggests a trade-off in the source–sink relationship, where enhanced resource supply to existing fruits may have reduced the potential for continued flowering. Consequently, the positive impact of PBZ on yield performance appears to be driven more by fruit biomass accumulation than by fruit set, reflecting a coordinated effect of hormonal adjustments and assimilate redistribution.

Table 1. Effect of PBZ doses and application intervals on yield and fruit characteristics of cucumber

Çizelge 1. PBZ dozları ve uygulama aralıklarının hıyarda verim ve meyve özelliklerine etkisi

PBZ Doses	Application Interval	Marketable Yield (t/ha)	Total Yield (t/ha)	Marketable Fruit Weight (g)	Marketable Fruit Number (fruits/plant
10 mg L^{-1}	7 day	165.99 (SD=5.23)^{b}	197.40 (SD=7.91)^{ab}	88.65 (SD=2.28)^{b}	70.09 (SD=1.97)^{b}
10 mg L^{-1}	14 day	164.39 (SD=5.51)^{b}	180.66 (SD=7.09)^{c}	86.99 (SD=2.26)^{b}	70.70 (SD=1.85)^{b}
20 mg L^{-1}	7 day	160.77 (SD=5.94)^{b}	188.84 (SD=7.18)^{abc}	88.38 (SD=2.60)^{b}	68.07 (SD=2.53)^{b}
20 mg L^{-1}	14 day	164.44 (SD=5.32)^{b}	184.19 (SD=7.92)^{bc}	87.27 (SD=1.49)^{b}	70.53 (SD=1.99)^{b}
40 mg L^{-1}	7 day	178.65 (SD=6.91)^{a}	197.42 (SD=8.89)^{ab}	98.44 (SD=2.05)^{a}	67.90 (SD=1.95)^{b}
40 mg L^{-1}	14 day	184.03 (SD=6.87)^{a}	201.82 (SD=8.77)^{a}	90.85 (SD=2.35)^{b}	75.79 (SD=1.70)^{a}
Control		182.07 (SD=6.39)^{a}	201.62 (SD=9.95)^{a}	86.69 (SD=2.33)^{b}	78.60 (SD=1.85)^{a}
Significance					
p		0.000	0.001	0.000	0.000
Sig.		***	**	***	***
η^2		0.898	0.763	0.897	0,895

Means in the same column followed by the same letter are not significantly different ($p < 0.05$) according to Tukey's HSD test. ** and *** represents statistically significant difference at $p < 0.01$ and $p<0,001$, respectively. (SD) represents the standard deviation.

Chlorophyll Index, Fruit Dry Matter, and Leaf Dry Matter

The effects of PBZ treatments on chlorophyll index, fruit dry matter, and leaf dry matter in cucumber are summarized in Table 2. PBZ treatments significantly influenced the chlorophyll index (SPAD) ($p = 0.019$, $\eta^2 = 0.617$), with SPAD values ranging from 47.92 to 55.47 units. The highest chlorophyll index was recorded at the 40 mg/L PBZ dose applied biweekly, representing a 3.4% increase compared to the control (53.65 units). Conversely, the lowest SPAD value was observed at the 20 mg/L PBZ dose applied every 7 days, corresponding to a 10.7% decrease relative to the control. Multiple comparison analyses indicated that both the 20 mg/L PBZ 7-day intervals and the 10 mg/L PBZ 14-day intervals treatments significantly reduced the chlorophyll index, whereas the 40 mg/L PBZ treatment applied weekly maintained chlorophyll levels comparable to the control. Cohen's d effect size analysis revealed a very large effect for the 20 mg/L PBZ applied weekly ($d > 1.2$), a large effect for the 40 mg/L PBZ applied weekly ($d = 0.85$), and a negligible effect for the 40 mg/L PBZ applied biweekly ($d = 0.10$). These results suggest that lower PBZ doses or more frequent applications tend to decrease chlorophyll content, while higher doses administered every two weeks can preserve or slightly enhance chlorophyll index values.

Regarding fruit dry matter, PBZ applications did not yield statistically significant effects ($p = 0.155$; $\eta^2 = 0.446$). Fruit dry matter varied between 3.85% and 4.15%, with the highest value recorded under the 20 mg/L PBZ treatment applied biweekly, which corresponded to an approximate 7.7% increase compared to the control (3.85%). The lowest fruit dry matter was observed in the control group. According to Tukey's HSD multiple comparisons, no statistically significant differences were identified among PBZ treatments ($p > 0.05$), indicating that neither the PBZ dose nor the application frequency markedly influenced fruit dry matter. Cohen's d calculations demonstrated a moderate effect size ($d \approx 0.75$) for the 20 mg/L biweekly application, a small effect ($d \approx 0.45$) for the 10 mg/L biweekly treatment, and a very small effect ($d \approx 0.25$) for the 40 mg/L weekly treatment. Other treatments exhibited negligible effect sizes without statistical relevance. Collectively, these findings imply that PBZ treatments do not significantly affect fruit dry matter, although the 20 mg/L dose applied every 14 days may slightly enhance it.

PBZ treatments had no significant impact on leaf dry matter ($p = 0.391$, $\eta^2 = 0.328$). Leaf dry matter ranged from 10.45% to 11.68%, with the highest value observed under the 10 mg/L PBZ treatment applied biweekly and the lowest under the 40 mg/L weekly application. Tukey's HSD tests revealed no statistically significant differences in leaf dry matter among the different PBZ treatments ($p > 0.05$). Homogeneous subset analysis indicated that the lowest leaf dry matters occurred with the 20 and 40 mg/L PBZ applications at 7-day intervals, whereas the highest values were linked to the 10 and 20 mg/L doses applied every two weeks. Overall, these results suggest that varying PBZ doses do not exert a pronounced effect on leaf dry matter, with all treatments maintaining leaf dry matter close to control levels.

The application of PBZ significantly influenced leaf chlorophyll concentration in cucumber, with the highest index observed at 40 mg/L applied weekly, supporting earlier findings that PBZ enhances chlorophyll accumulation. Studies by Wang (1985) and Steffens and Wang (1986) demonstrated similar effects in cucumber and apple, attributing the increase to PBZ's inhibition of gibberellin biosynthesis, which suppresses cell elongation and promotes chlorophyll retention. Lolaei et al. (2013) also reported a dose-dependent rise in chlorophyll content with PBZ, while Cázarez Flores et al. (2018) observed a 26% increase in cucumber seedlings, reinforcing the compound's consistent positive effect on chlorophyll levels. However, this enhancement appears dose-sensitive; in the current study, the 20 mg/L weekly treatment resulted in the lowest chlorophyll index, indicating that suboptimal doses may lead to stress or metabolic imbalance. In contrast, PBZ had no significant effect on fruit or leaf dry matter content. This contrasts with Cázarez Flores et al. (2018), who reported increased aerial dry matter in seedlings, likely due to developmental stage differences. Taken together, while earlier studies have emphasized PBZ's potential to enhance chlorophyll content, the current findings suggest that such effects may not always be statistically significant and can vary depending on dose and application frequency, underlining the need for further research to determine optimal treatment conditions.

Table 2. Effect of PBZ doses and application intervals on chlorophyll index, fruit dry matter and leaf dry matter of cucumber

Çizelge 2. PBZ dozları ve uygulama aralıklarının hıyarda klorofil indeksi, meyve ve yaprak kuru madde içeriğine etkisi

PBZ Doses	Application Interval	Chlorophyll index (SPAD)	Fruit Dry Matter (%)	Leaf Dry Matter (%)
10 mg L^{-1}	7 day	51.81 (SD=1.64)^{ab}	3.95 (SD=0.10)	10.95 (SD=0.56)
10 mg L^{-1}	14 day	48.56 (SD=2.08)^{b}	4.13 (SD=0.16)	11.68 (SD=0.67)
20 mg L^{-1}	7 day	47.92 (SD=4.05)^{b}	4.06 (SD=0.20)	10.58 (SD=0.74)
20 mg L^{-1}	14 day	50.37 (SD=3.29)^{ab}	4.15 (SD=0.10)	11.16 (SD=0.58)
40 mg L^{-1}	7 day	55.47 (SD=1.32)^{a}	4.06 (SD=0.16)	10.45 (SD=0.73)
40 mg L^{-1}	14 day	51.23 (SD=1.04)^{ab}	4.00 (SD=0.06)	11.14 (SD=0.34)
Control		53.65 (SD=1.72)^{ab}	3.85 (SD=0.08)	10.97 (SD=0.88)
Significance				
P		0.019	0.155	0.391
Sig.		*	ns	ns
η^2		0.617	0.446	0.328

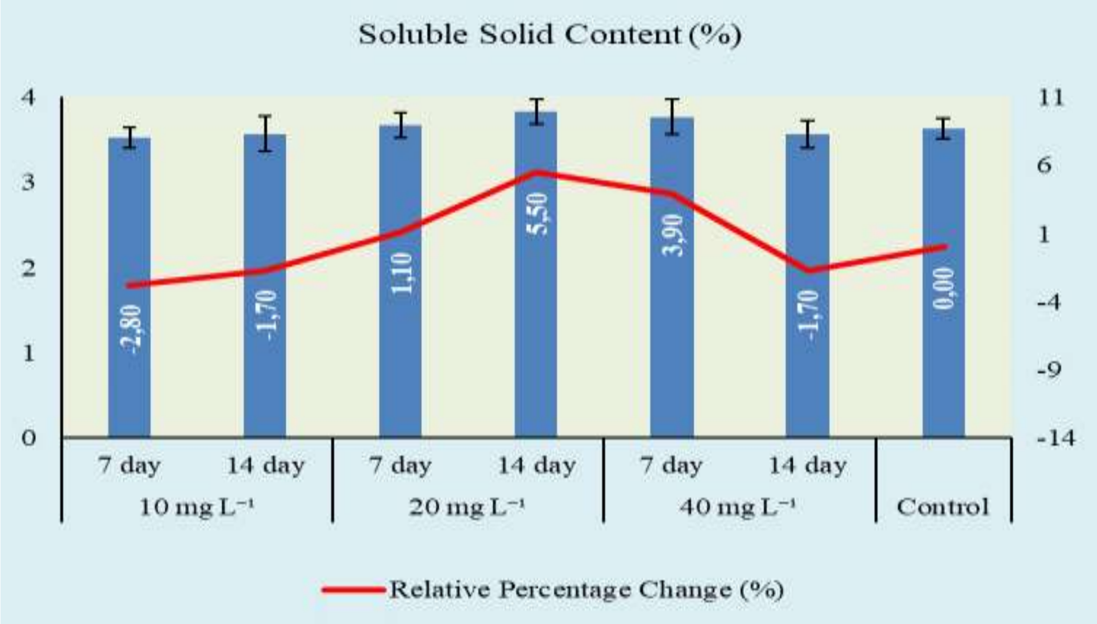
Means in the same column followed by the same letter are not significantly different ($p < 0.05$) according to Tukey's HSD test. * represents statistically significant difference at $p < 0.05$. ns represents differences are not statistically significant ($p > 0.05$). (SD) represents the standard deviation.

Soluble Solid Content (SSC), Titratable Acidity (TA), and pH

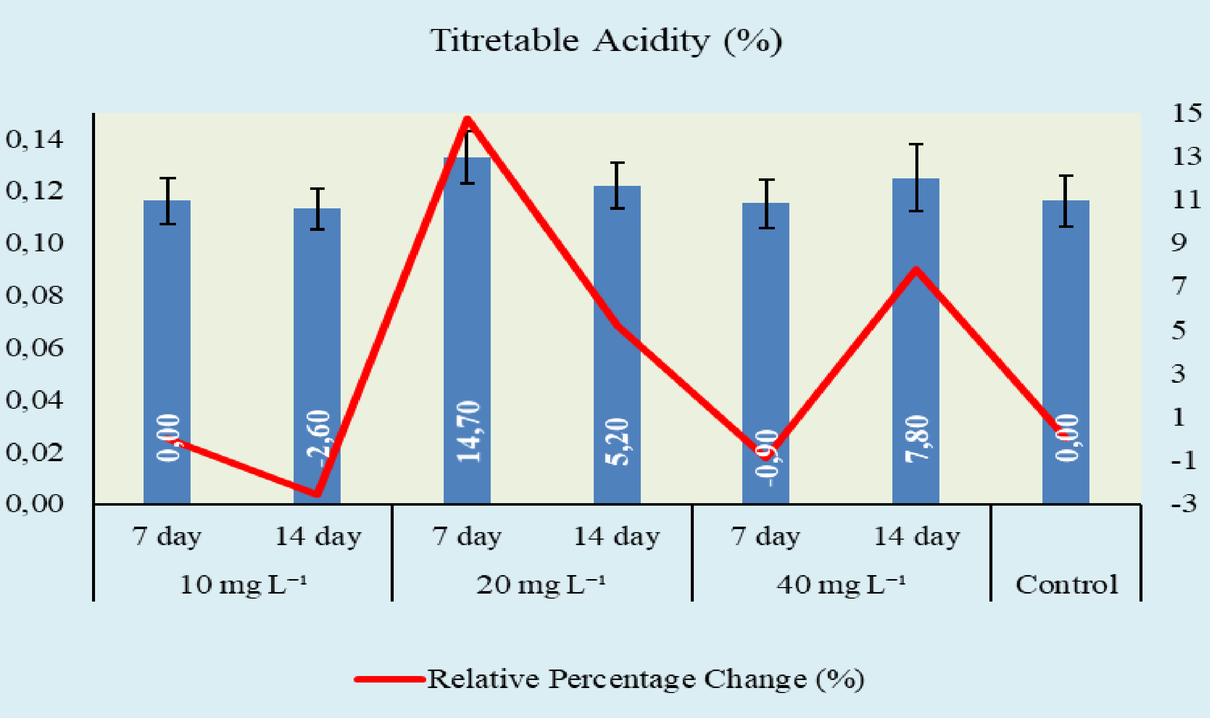
The effects of PBZ applications on the SSC of cucumber are summarized in Figure 3. PBZ treatments did not lead to statistically significant differences in soluble solid content ($p = 0.216$; $\eta^2 = 0.409$). SSC values ranged from 3.53% to 3.83%. The highest SSC was recorded in the 20 mg/L PBZ treatment with a 14-day interval, while the lowest value was observed in the 10 mg/L PBZ treatment with a 7-day interval. Multiple comparison analyses (Tukey HSD) confirmed the absence of statistically significant differences among the PBZ treatments ($p > 0.05$). Homogeneous subset analysis showed that the 10 mg/L PBZ treatments (7 and 14-day intervals) and the 40 mg/L PBZ 14-day interval treatment formed a group with similar, lower SSC values. In contrast, the 20 and 40 mg/L PBZ treatments with a 7-day interval and the 20 mg/L PBZ 14-day interval treatment exhibited slightly higher SSC values, although these differences were not statistically significant. These results indicate that PBZ applications, regardless of dose or application interval, did not significantly affect fruit dry matter content. The effect size was moderate, suggesting that while some PBZ doses tended to slightly increase SSC, the overall impact of PBZ applications on SSC was not statistically significant. Overall, all treatments maintained SSC values within a narrow range.

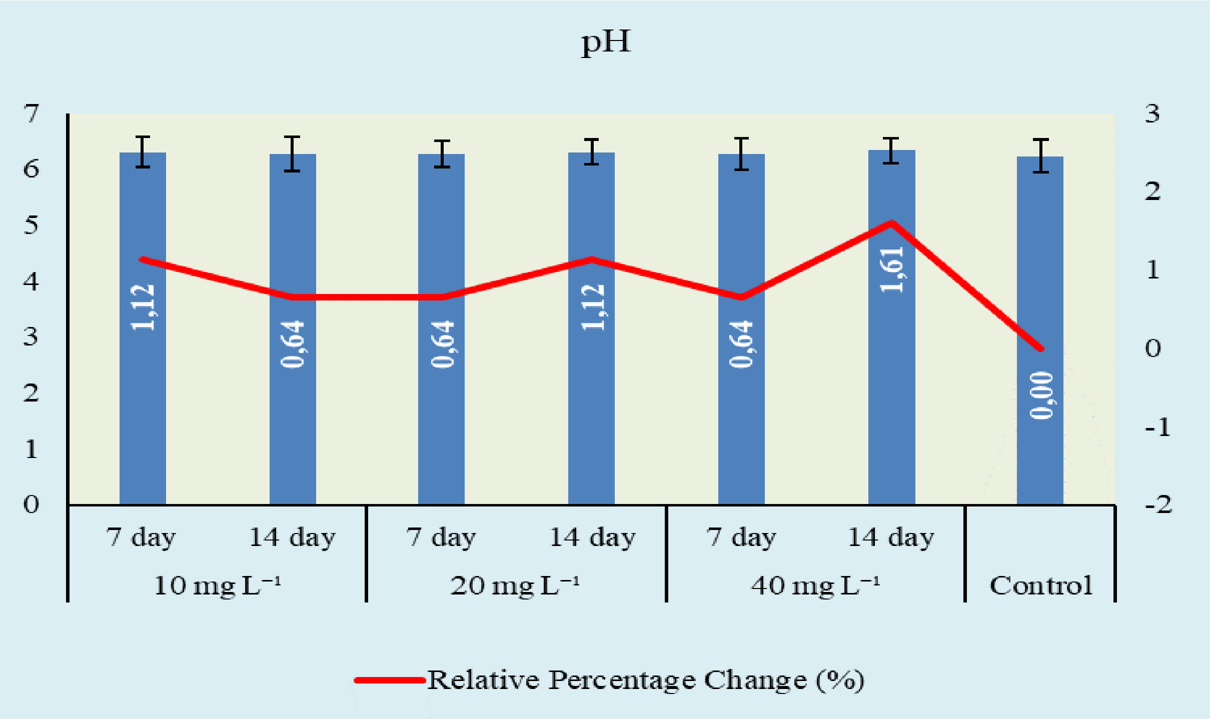
The effects of PBZ applications on total acidity (TA) in cucumber are summarized in Figure 4. PBZ treatments did not result in statistically significant differences in TA content ($p = 0.376$; $\eta^2 = 0.334$). TA values ranged from 0.113% to 0.133%. The highest TA was observed in the 20 mg/L PBZ treatment with a 7-day interval, while the lowest value was found in the 10 mg/L PBZ 14-day interval treatment. Multiple comparison analyses (Tukey HSD) confirmed the absence of statistically significant differences among PBZ treatments ($p > 0.05$). Homogeneous subset analysis indicated that the 10 mg/L PBZ 7-day interval and 40 mg/L PBZ 14-day interval treatments formed a group with similar, lower TA values. The 20 mg/L PBZ 7-day interval treatment exhibited the highest TA value, although the difference was not statistically significant. These results suggest that PBZ applications did not significantly affect TA content in cucumber fruits. The moderate effect size indicates that although some numerical differences were noted, they were not statistically meaningful. In summary, while certain PBZ doses and application intervals showed a tendency to slightly alter TA content, the overall impact of PBZ on total acidity was not statistically significant, and all treatments maintained TA values within a narrow range.

The effects of PBZ applications on fruit pH are summarized in Figure 5. PBZ treatments did not lead to statistically significant differences in fruit pH ($p = 0.932$; $\eta^2 = 0.110$). pH values ranged from 6.23 to 6.33 across treatments. The highest pH was recorded under the 40 mg/L PBZ 14-day interval treatment, while the lowest was observed in the control group. Multiple comparison analyses (Tukey HSD) confirmed the absence of statistically significant differences among PBZ treatments ($p > 0.05$). Homogeneous subset analysis indicated that all treatments formed a single group, showing no significant differences in pH values. These findings suggest that PBZ applications did not significantly influence fruit pH. The small effect size implies that any observed differences were minor and not statistically relevant. Overall, PBZ had no significant impact on fruit pH, and pH values remained within a narrow range across all treatments. Collectively, these findings indicate that PBZ, when applied at concentrations between 10 and 40 mg/L at either 7- or 14-day intervals, does not significantly alter key fruit quality parameters such as SSC, TA, or pH. Although minor numerical differences were observed—such as a 5.5% increase in SSC at 20 mg/L, 14-day-the lack of statistical significance ($P > 0.05$) underscores PBZ's limited and inconsistent impact on sugar accumulation. This aligns with results reported by Benjawan et al. (2007), who found no significant effect of PBZ on SSC or acidity in okra pods. Similarly, in cucumber, Kazemi (2013) observed an initial increase in SSC at low PBZ doses (2.5–5.0 mg/L), but higher concentrations led to a decline, suggesting a narrow optimal range for quality enhancement. In watermelon, Mutmain et al. (2023) reported notable increases in SSC across multiple PBZ treatments, though this species-dependent response may not translate to cucumber. Conversely, Huang et al. (1989) observed a slight reduction in SSC in watermelon under higher PBZ concentrations, supporting the current study's finding that high or frequent PBZ applications may not enhance, and could even slightly suppress, sugar levels in cucurbits. Regarding acidity and pH, the negligible differences across treatments observed here are consistent with the literature, indicating PBZ's minimal effect on acid–base balance. Overall, these findings confirm that PBZ, within the tested dose and interval range, does not compromise organoleptic fruit quality in cucumber, reinforcing its viability as a growth regulator when fruit marketability is a priority.



Error bars represent the mean ± standard deviation (SD). The red curve illustrates the relative percentage change in response to the treatments, with reference to the control.
Figure 3. Effect of PBZ treatments on SSC of cucumber
Şekil 3. PBZ uygulamalarının hıyarda suda çözünebilir kuru madde miktarına etkisi





Error bars represent the mean ± standard deviation (SD). The red curve illustrates the relative percentage change in response to the treatments, with reference to the control.
Figure 5. Effect of PBZ treatments on pH of cucumber
Şekil 5. PBZ uygulamalarının hıyar meyve suyunda pH içeriğine etkisi

Effect of Paclobutrazol Applications on Residue Levels in Cucumber Fruits

In the present study, PBZ residues were not detected at levels above the method's detection limit in cucumber fruit samples. The validated LC-MS/MS method employed exhibited a limit of detection (LOD) of 1.09 µg/kg and a limit of quantification (LOQ) of 3.64 µg/kg, demonstrating that any residues present below these thresholds could not be analytically determined. Consequently, the absence of measurable PBZ may be attributed not only to its limited phloem mobility, which restricts translocation to fruit tissues, but also to the possibility of trace-level residues falling below the detection capabilities of the analytical method.

PBZ is a triazole-based plant growth regulator known to be absorbed primarily through the roots when applied to the soil and subsequently translocated via the xylem to apical meristems, leaves, and, to a lesser extent, reproductive organs such as fruits (Early & Martin, 1988; Rademacher, 2000; Maheshwari et al., 2022). In contrast to soil application, the present study employed low-dose foliar applications specifically targeting the shoot apex, which likely restricted the systemic movement of PBZ, particularly toward fruit tissues. This aligns with previous findings indicating that PBZ exhibits limited phloem mobility (Fletcher et al., 2000), although partial translocation via the phloem has been suggested under certain conditions (Witchard, 1997; Singh & Ram, 2000). Given that fruit tissues are predominantly supplied through the phloem, the absence of detectable PBZ residues in the harvested fruit is consistent with its limited phloem mobility and preferential accumulation in vegetative tissues (Davis et al., 1988; Kishore et al., 2022). Furthermore, evidence from Magnitskiy et al. (2006) supports this conclusion; no PBZ residues were detected in cucumber or tomato fruits, even when seeds were soaked in PBZ concentrations as high as 1000 mg/L. Furthermore, Balkan et al. (2025) reported that in foliar PBZ applications in tomato, residue levels vary depending on the applied dose, and that residue accumulation may occur in tomato fruits when higher concentrations are used or when the application is performed via soil. While foliar application may result in reduced systemic efficacy compared to soil application, the primary objective of growth suppression was achieved without compromising fruit safety. These findings underscore the potential of foliar PBZ application as a viable strategy for canopy management in horticultural crops, especially when residue minimization is a critical concern. Future research should systematically investigate the comparative pharmacokinetics and residue profiles of PBZ under different application routes and environmental conditions to optimize its use for sustainable crop production.

CONCLUSION

This study demonstrated that foliar-applied PBZ effectively regulates vegetative growth in cucumber by significantly reducing plant height and internode length in a dose- and frequency-dependent manner. Higher PBZ concentrations applied at shorter intervals resulted in the most pronounced growth suppression, supporting its utility for producing compact plants suitable for high-density cultivation and greenhouse management. Yield responses varied with treatment strategy. While frequent, lower-dose applications reduced total and marketable yield, biweekly high-dose treatments maintained or slightly enhanced productivity by increasing individual fruit weight. These findings suggest that appropriate calibration of PBZ concentration and application timing is critical to avoid excessive vegetative restriction that may limit reproductive development. PBZ also improved leaf chlorophyll content, particularly at higher doses, indicating enhanced photosynthetic potential or delayed senescence. However, the compound had no statistically significant effect on fruit or leaf dry matter, soluble solids content, titratable acidity, or pH, implying that fruit quality remained stable across treatments. Importantly, no PBZ residues were detected in fruit following foliar application to shoot apices. This absence aligns with the compound's limited phloem mobility and suggests that foliar application represents a safe method for vegetative control without compromising food safety. Although economic analysis was not within the scope of this study, the observed reduction in vegetative growth suggests that PBZ application may reduce labor requirements for pruning and tying; future studies could evaluate its effects on unit area costs, labor savings, and potential economic returns.

In summary, PBZ offers an effective and residue-free tool for controlling vegetative growth in cucumber when applied foliarly at optimized doses and intervals. Its ability to regulate canopy size while preserving yield and quality underscores its potential in sustainable greenhouse production systems. In future studies, it would be valuable to investigate the effects of PBZ on key genes in the GA biosynthesis pathway in cucumber (e.g., GA20ox, GA3ox), to compare different application methods such as foliar spray, soil drench, or drip irrigation, and to evaluate the effects of varying PBZ doses and intervals on efficacy and residue profiles. Additionally, assessing PBZ performance under biotic and abiotic stress conditions, as well as monitoring GA3 and ABA accumulation in roots and shoots during such applications, would provide further insights into its physiological and practical impacts.

Contribution Rate Statement Summary of Researchers

The authors declare their contributions of the authors is equal.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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