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ARTICLE

Effects of Paclobutrazol Application Methods and Dosages on the Growth, Morphological Characteristics, and Color Quality of *Silene compacta* Fisch.

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ABSTRACT: This study was conducted to determine the effects of paclobutrazol (PBZ) application methods and dosages on the growth, leaf, flower, and color characteristics of *Silene compacta* Fisch., a natural species with high potential for use as a seasonal bedding and potted ornamental plant in landscape design. The experiment was carried out under greenhouse conditions, where potted plants received a single PBZ application during the vegetative stage. The study was arranged in a completely randomized design with a 2 × 3 factorial structure. PBZ was applied either as a foliar spray or as a soil drench at doses of 0, 1.250, and 2.500 mg a.i. per plant. Measurements were taken at the 90% flowering stage. The study revealed that increasing PBZ dosages led to a significant delay (10–15 days) in flowering time. Increasing PBZ dosages significantly suppressed plant height, internode length, inflorescence and leaf traits; conversely, stem diameter and fresh stem (86%) and root (132%) weights increased markedly. While application methods exerted contrasting effects on leaf number and thickness, the suppressive effect of the soil drench method on growth was found to be more dominant than that of the foliar spray. Specifically, high-dose soil applications restricted plant height by 80% (5.0–6.0 cm) to create a compact form, whereas foliar-sprayed plants resulted in a growth trend closer to the control (17.5–18.5 cm). In terms of color quality, PBZ did not exert a negative effect on the primary color tones. Specifically, the soil drench application at a dosage of 2.500 mg a.i./plant increased leaf lightness and saturation; meanwhile, the foliar spray at a dosage of 2.500 mg a.i./plant significantly enhanced flower color saturation (chroma) compared to the control group. These results establish an important theoretical and practical foundation for the use of *S. compacta* in urban landscape design and potted interior/exterior arrangements with a compact form and high visual quality.

KEYWORDS: *Silene compacta*; growth retardants; morphological development; colorimetric analysis; ornamental quality

1 Introduction

The floriculture industry is becoming an increasingly diversified option due to its great aesthetic, social, environmental, and economic significance [1]. The domestication of native species is both necessary and important in terms of increasing species diversity across different sectors of the ornamental plants industry, as well as reducing maintenance costs for the long-term use of these species and minimizing the environmental impact of maintenance practices.

Silene compacta Fischer is one of the 147 taxa naturally distributed in Türkiye belonging to the genus *Silene* of the Caryophyllaceae family [2]. Naturally occurring across the western, southern, central, northern, eastern, and southeastern regions of Türkiye at a wide range of altitudes from sea level up to 2100 m, *S. compacta* is a completely glabrous, biennial, or short-lived perennial species with erect stems reaching up to 120 cm in height, bearing numerous pink flowers in terminal clusters [3,4]. These characteristic features present a significant potential for the use of *S. compacta* as a seasonal ornamental plant in landscape design. Especially its attractive flowers and relatively long flowering period enhance the possibility of utilizing the species as a border plant or ground cover in roof and rock gardens [4,5]. The fact that *S. compacta* is a tall species capable of reaching 120 cm in its natural state makes the attainment of dwarf individuals a commercial and aesthetic necessity, both to achieve the desired form characteristics in potted plant production and to provide compact seasonal flower alternatives suitable for narrow spaces in landscape design.

Excessive internode elongation and the consequent uncontrolled vegetative growth observed in many plant species lead to both the formation of massive architectures that complicate plant management and the loss of aesthetic value due to a loose growth habit. The negative impacts created by this situation have been defined as excessively large tree structures creating management difficulties in species such as *Mangifera indica* [6]; whereas in species such as *Paeonia lactiflora*, it has been reported that ornamental value is severely affected due to rapidly elongating internodes and a loose plant form [7]. Similarly, in natural species suitable for potted production such as *Consolida orientalis*, the 'unpleasant appearance' resulting from excessive plant elongation has been emphasized as the most significant problem restricting the use of these plants [8]. The limited number of such studies focused on the domestication of natural species and the regulation of plant morphology necessitates the investigation of new approaches that will enhance the landscape performance of ornamental plants. In this context, plant growth regulators (PGRs), which modulate plant growth and restructure plant architecture, are widely utilized.

Triazole-group growth retardants are widely utilized for controlling plant height and optimizing aesthetic form. Paclobutrazol (PBZ), one of the most effective members of this group, suppresses cell elongation by interfering with the *ent*-kaurene oxidation pathway in gibberellin biosynthesis, thereby providing the plant with a more compact structure [9,10]. PBZ not only reduces undesirable longitudinal shoot growth [11] but also increases the number of flowers per plant [12]. Furthermore, it plays significant roles in promoting reproductive growth to ensure early harvest [13] and increasing fruit set and overall yield [6]. It also functions as a versatile growth regulator [14] with the potential to strengthen tolerance against abiotic stresses such as drought and heat, as well as to increase relative water content and antioxidant enzyme activities [7,14].

When the studies in the literature are examined, the effects of PBZ especially on plant height, plant width, and stem diameter are prominent. It has been determined in many species—such as *Helianthus annuus* and *Zinnia elegans* by Ahmad et al. [15] and *Paeonia lactiflora* by Wu et al. [7]—that PBZ applications provide a more compact form by limiting plant height and width; Ghosh et al. [10] determined in *Jatropha curcas* that it restricts vegetative growth; and Mansuroğlu et al. [8] in *Consolida orientalis*, Karagüzel et al. [16] in *Lupinus varius*, and Park and Faust [17] in *Petunia hybrida* reported that it shortens plant height. It has been reported in studies by Wu et al. [7] and Mansuroğlu et al. [8] that it particularly increases mechanical resistance and minimizes the risk of lodging by increasing stem diameter.

Root and stem characteristics in ornamental plants influence their ability to exhibit maximum performance depending on the environment and conditions in which they are used. In this context, some studies have examined the effect of PBZ on biomass partitioning and determined that it varies according to the species. Taha and Sorour [18] reported that PBZ promotes root dry weight and development in *Pentas lanceolata*; conversely, Ahmad et al. [15] found it to cause a decrease in total fresh and dry weight in *Zinnia elegans* and *Helianthus annuus*.

While the flowers of some plants are more prominent in terms of ornamental value, in others, both leaf and flower characteristics enhance the ornamental value and play an important role in fulfilling various functions in the areas where they are utilized in landscape design. Upon examining the studies in the literature, the effects of PBZ on different leaf and flower characteristics have been investigated according to plant species specifications. It has been determined by Ribeiro et al. [19] in *Capsicum annuum* that changes in leaf number, length, and width depend on the genetic structure and application method; while it was identified that leaf number in *Gypsophila bicolor* by Parlakova Karagöz et al. [20], leaf area in *Pentas lanceolata* by Taha and Sorour [18] and *Paeonia lactiflora* by Wu et al. [7], and leaf thickness in *Paeonia lactiflora* by Wu et al. [7] vary according to application methods and dosages. The effects of PBZ on flowering time and certain inflorescence characteristics were determined in *Consolida orientalis* by Mansuroğlu et al. [8] and *Lupinus varius* by Karagüzel et al. [16], while its effect on flowering time was examined in *Iris nigricans* by Al-Khassawneh et al. [21]. Furthermore, the effects of PBZ on leaf and flower color characteristics have been demonstrated in *Dianthus caryophyllus* by Bañón et al. [22], *Gypsophila bicolor* by Parlakova Karagöz et al. [20], and *Consolida orientalis* by Mansuroğlu et al. [8].

Al-Khassawneh et al. [21] reports that the most common methods of application of growth regulators are foliar sprays and media drenches. In foliar spray applications, the capacity of plants to absorb the active ingredient may remain limited due to high evapotranspiration rates; conversely, it has been determined that development control yields much more successful results in soil drench applications, as roots absorb the substance more effectively and in higher quantities [23]. In contrast, the soil drench application enables the effective uptake of the active ingredient by the roots, from where it is translocated through the xylem to the apical meristems [14]; this systemic movement is a characteristic feature of paclobutrazol-based formulations [24].

Paclobutrazol application in bedding plant production is a widely utilized method for achieving a compact plant form that enhances greenhouse space utilization efficiency, shipping density, and tolerance to physical handling stresses in the post-production environment [17]. Furthermore, the use of plants dwarfed by this method in landscape design does not only offer an aesthetic compactness but also increases ecological resistance thanks to the developed strong root system, providing many functional advantages in the urban landscape. This morphological transformation allows the plant to remain more stable in urban areas with limited soil volume and to exhibit a more sustainable performance against environmental stress factors.

While the literature clearly demonstrates that Paclobutrazol has significant potential for restricting vegetative growth in various plant species, there is a need for scientific studies regarding PBZ applications on *S. compacta*, a natural bedding plant species possessing highly effective ornamental value with its leaf color, form, and flowers. In this context, the aim of the study is to determine the effects of different PBZ application methods and dosages on the growth characteristics and visual quality of *S. compacta*.

2 Materials and Methods

2.1 Plant Material and Experimental Conditions

In this study, plants obtained from the seeds of *S. compacta* were used as plant material. The seeds were collected from a naturally occurring population of *S. compacta* in the Cevizli village of the Akseki district, Antalya province. The experiment was conducted during the 2022–2023 growing season at the Ornamental Plants Research Greenhouse of the Faculty of Agriculture, Akdeniz University. Seed sowing was performed on 07 October 2022, into trays filled with a 1:1 peat-perlite mixture. When the seedlings reached the 5–6 leaf stage after germination (15 November 2022), they were transplanted into pots with a volume of 3 L. The plants were grown for approximately four months following transplantation. Hormone applications were performed once on 04 April 2023, when the plants reached the growth criteria where they had adapted to the new environment, developed lateral branches with an average length of 3 cm, and the first internode length on the main stem was approximately 1 cm. Only plants with lateral branches were included in the evaluation during the experiment. Throughout the trial, the plants were hand-watered as needed, and no fertilization was applied.

Each pot was filled with 100% local garden soil. Samples of the soil used to fill the pots were analyzed. The soil pH was determined to be 7.95, with a lime content of 23.60% and a salt content of 0.01%. The saturation percentage was 45.50%, the organic matter content was 1.05%, and the total nitrogen (N) content was 0.10%. The amount of plant-available phosphorus (P) was found to be 4.16 kg P_2O_5/da, and the amount of plant-available potassium (K) was 84.35 kg K_2O/da. The available calcium (Ca) content was determined as 1837.50 kg CaO/da, and the available magnesium (Mg) content was 172.25 kg MgO/da. The plant-available iron (Fe) content was 6.41 ppm, manganese (Mn) was 5.34 ppm, and zinc (Zn) was 0.83 ppm. The plant-available copper (Cu) content was determined to be 1.68 ppm, the bulk density was 1.07 g/cm^3 and the sand ratio was 50.00%. The clay ratio was 19.6%, the silt ratio was 30.40%, and the cation exchange capacity (CEC) was 13.05 me/100 g.

Temperature and relative humidity measurements in the greenhouse were recorded regularly for 9 months (including October-June). While the highest maximum temperature was recorded in October 2022 at 41.2°C, the lowest maximum temperature occurred in January 2023 at 20.7°C. The highest minimum temperature was measured in June 2023 at 16.60°C, and the lowest minimum temperature was recorded in February 2023 at 0.1°C. The highest average temperature was determined in June 2023 at 25.1°C, and the lowest average temperature was in February 2023 at 9.9°C. The highest average relative humidity was recorded in December 2022 at 76.7%, and the lowest average relative humidity was in October 2022 at 53.2%.

2.2 Experimental Design

The experiment was conducted based on a 2 × 3 factorial structure within a Completely Randomized Design (CRD) to examine the effects of Paclobutrazol on plant growth. The factorial structure consisted of two application methods (soil drench and foliar spray) and three Paclobutrazol dosage levels (0 mg a.i./plant; 1.250 mg a.i./plant; 2.500 mg a.i./plant). A total of six treatments were obtained through these combinations. Each treatment was organized with three replications, and each replication contained 10 plants. Thus, a total of 180 plants were used in the experiment.

2.3 Paclobutrazol Applications

In this study, Paclobutrazol was used as a growth-retarding hormone. The applications were carried out on 04 April 2023, in a 2 × 3 factorial arrangement using two different methods and three dosage levels. The hormone solutions were prepared by diluting a concentrated paclobutrazol suspension (Cultar 250 g·L^{-1} SC; Syngenta, İzmir, Türkiye). The applied dosages were standardized based on the amount of active ingredient per plant (mg a.i./plant). The PBZ dosages and application techniques utilized in this study were adapted from the methodologies of Mansuroğlu et al. [8] and Karagüzel et al. [16], established for comparable herbaceous taxa.

2.3.1 Foliar Application

A volume of 5 mL of solution (0, 250, and 500 mg· L^{-1}) was applied to each plant using a sprayer in a manner that avoided runoff. Control plants were sprayed with the same volume of tap water.

2.3.2 Drench Application

The required amount of active ingredient was dissolved in 200 mL of water (0, 6.25, and 12.5 mg· L^{-1}) and applied directly to the growing medium. The control group received 200 mL of tap water.

2.4 Data Collection

The changes in flowering percentages and plant heights over time were determined every 7 days from the hormone application date (04 April 2023) until the 90% flowering period (26 June 2023). The 90% flowering period was defined as the stage when 90% of the plants had formed at least one inflorescence and 90% of these inflorescences had fully bloomed. The following measurements were carried out during this period, and the data and evaluations in the findings section are presented under these headings. All of these measurements were performed on every plant.

2.4.1 Some Growth Characteristics

Under this heading, the determination of plant height, plant width, number of lateral branches, and lateral branch length were addressed, and these are presented under the same heading in the results section. Plant height (cm) was measured from the soil surface of the pot to the apex, and plant width (cm) was measured across the two widest perpendicular points of the canopy using a ruler. For lateral branch characteristics, the number of lateral branches per plant was counted, and the lengths of these branches were measured with a ruler to record the average lateral branch length (cm).

2.4.2 Leaf Characteristics

The number of leaves on the main stem and the total number of leaves on the entire plant were counted. Leaf width (cm) and leaf length (cm) were measured with a ruler on 5 leaves from the main stem of each plant. Leaf area (cm^2) was determined using a leaf area meter, and leaf thickness (mm) was measured with a digital caliper on 5 leaf samples from the main stem of each plant.

2.4.3 Floral Characteristics

The flowering period (days) was defined as the number of days from transplanting into pots to the appearance of the first flower. The total number of inflorescences and the maximum number of inflorescences on the main stem were counted. For each plant, the width (cm) and length (cm) of all inflorescences on the main stem with 90% of flowers open were measured using a ruler, and the number of flowers per inflorescence was determined by counting the flowers on these inflorescences. On the same inflorescences, flower diameter (cm) and flower length (cm) were measured, and petal length (mm) and width (mm) were measured on these flowers using a ruler. Peduncle length (cm) was determined by measuring the distance between the attachment point of the inflorescences to the main stem and the inflorescence using a ruler, while peduncle thickness (mm) was measured at the midpoint of the peduncle using a digital caliper. The maximum number of inflorescences on the main stem was calculated for each PBZ application method and dose by determining the highest inflorescence number observed on the main stem of plants in each replicate, and then averaging across replicates.

2.4.4 Stem and Root Characteristics

Stem thickness (mm) on the main stems was measured 3 cm above the soil level using a digital caliper, and the main stem internode length (cm) was determined using a ruler. The fresh and dry weights (g) of the stem and root parts were measured with a scale sensitive to 0.001 g. To determine the dry weights, the separated root and stem parts were dried in an incubator adjusted to 70°C for 3 days.

2.4.5 Leaf and Flower Color Characteristics

Color values (L*, a*, b*), in leaves and flowers were determined according to the CIELAB system using a digital colorimeter (Minolta CR-400, Osaka, Japan). Chroma (C^*) and Hue angle ($\boldsymbol{h}^\circ$) values were calculated using the following formulas: $C^* = (a^{*2} + b^{*2})^{1/2}$ and $\boldsymbol{h}^\circ = \arctan(b^*/a^*)$. For color measurements, leaf samples were taken from the middle sections of the main stems, and flower samples were taken from the inflorescences on the main stem.

2.5 Statistical Analysis

The effects of application method (M) and dose (D) factors were evaluated using a two-way analysis of variance (Two-Way ANOVA). In the ANOVA results, significance levels were indicated as *, **, and *** (representing $p \leq 0.05$; $p \leq 0.01$; $p \leq 0.001$ respectively), while non-significant results were denoted as N. S. Duncan's multiple range test ($p > 0.05$) was used for mean comparisons. All analyses were performed using IBM SPSS Statistics (Version 20) software.

3 Results

3.1 Effects of Paclobutrazol Applications on Time-Dependent Changes in Plant Height and Flowering Percentage

The data presented in Fig. 1 indicate that the dwarfing effect of paclobutrazol on plant height began to become apparent 7 days after application (in the April 10 measurements) for both foliar spray and soil drench applications. Two weeks after application, significant differences in plant height were observed between the application methods and the doses used. Although increasing doses of paclobutrazol led to a dose-dependent decrease in plant height in both application methods, plants treated with paclobutrazol via the soil drench method exhibited much more restricted growth throughout the trial period compared to the control group and foliar spray applications at the same doses (Fig. 1). Particularly in soil drench applications, doses of 1.250 and 2.500 mg a.i./plant almost completely halted plant height development shortly after application, and these plants followed a horizontal trend, remaining stable in the range of approximately 5.0–6.0 cm until the end of the experiment. In contrast, plants treated with foliar spray showed a growth trend closer to the control group, reaching a height of 17.5–18.5 cm by the end of the trial.

When the flowering percentages were analyzed, the earliest onset of flowering was observed in the control group and low-dose foliar spray applications (Fig. 2). The control plants, along with those treated with 1.250 and 2.500 mg a.i./plant foliar sprays, exhibited the most rapid development, reaching flowering rates of approximately 30%, 43%, and 50%, respectively, by May 29. By the conclusion of the experiment (June 26), while the foliar spray applications achieved high flowering percentages ranging from 70% to 90%, the control group remained at approximately 46%. Conversely, the most delayed flowering was recorded in plants where paclobutrazol was administered via the soil drench method. In the final observations conducted on June 26, the flowering percentage in plants treated with 1.250 and 2.500 mg a.i./plant soil drench doses reached only 20%–23% (Fig. 2). These findings demonstrate that soil-applied paclobutrazol treatments not only radically suppressed vegetative growth (shoot elongation) but also significantly delayed and restricted the flowering process compared to foliar applications.

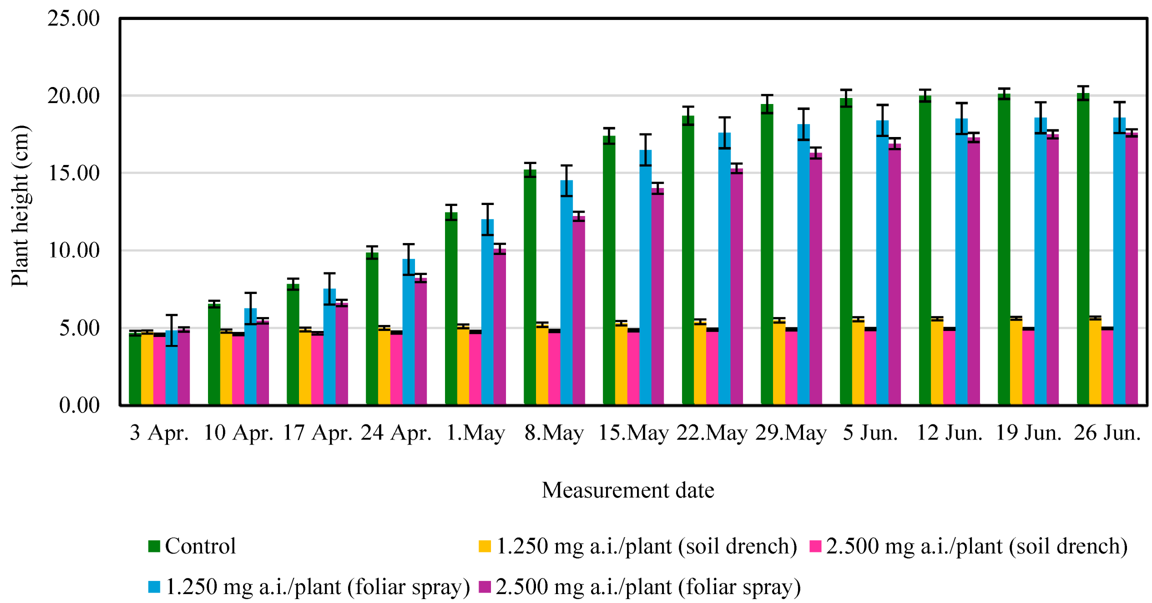

Figure 1: Effects of different paclobutrazol doses and application methods on the plant height development of *S. compacta* during the growth period. Control group represents non-treated plants. Soil drench and foliar spray refer to the two different application methods utilized at dosages of 1.250 and 2.500 mg a.i./plant. Data points and columns represent the mean plant height values calculated from three independent replicates (n = 3). Vertical error bars denote the standard error (SE) of the mean. Measurements were performed at 7-day intervals, starting from 3 April until 26 June.

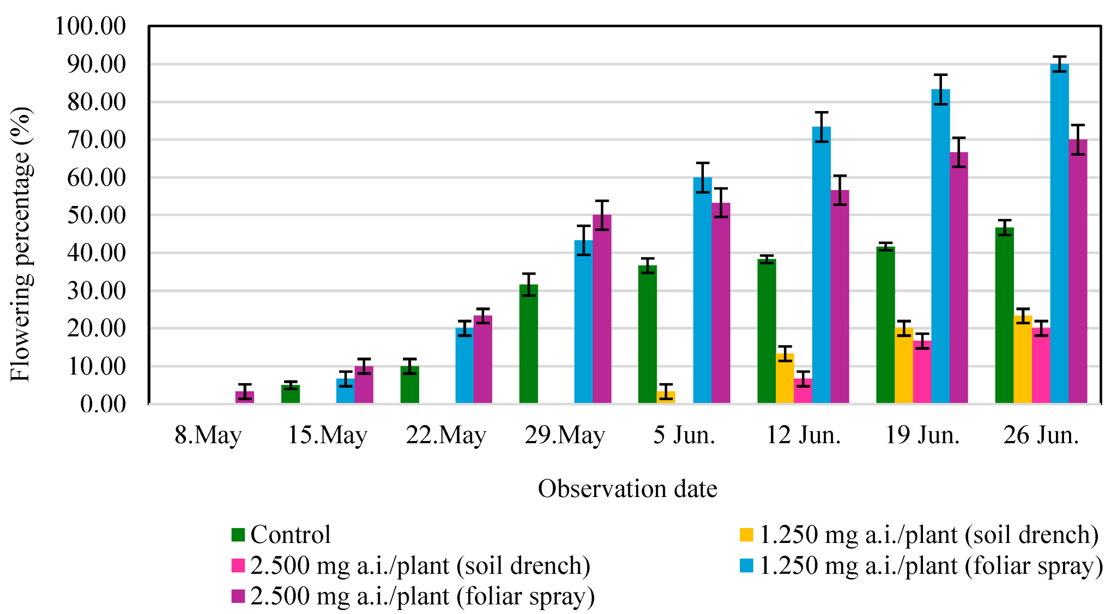

Figure 2: Effects of different paclobutrazol doses and application methods on the flowering percentage of *S. compacta* during the flowering period. Control group represents non-treated plants. Soil drench and foliar spray refer to the two different application methods utilized at dosages of 1.250 and 2.500 mg a.i./plant. Data points and columns represent the mean flowering percentages calculated from three independent replicates (n = 3). Vertical error bars denote the standard error (SE) of the mean. Measurements were performed at 7-day intervals, with the observation period extending from the initial hormone application until 26 June.

3.2 Effects of Paclobutrazol Application Methods and Doses on Some Growth Characteristics

The results of the analysis of variance demonstrated the effects of application method and dose on the growth characteristics of *S. compacta* (Table 1). According to the statistical results, the application method had a significant influence on plant height and lateral branch length. While the paclobutrazol dose exerted a significant effect on plant height, its main effect on plant width, number of lateral branches, and lateral branch length was found to be non-significant. Furthermore, the interactions between application method and dose were determined to be statistically non-significant for plant height, plant width, number of lateral branches, and lateral branch length.

Table 1: Mean squares from analysis of variance for the effect of application method and doses of paclobutrazol on plant height, plant width, number of lateral branches, and lateral branch length of *S. compacta*.

Source of Variation	df	Mean Square			
		Plant Height (cm)	**Plant Width (cm)**	**Number of Lateral Branches (count)**	**Lateral Branch Length (cm)**
Replication	2	22.180^{NS}	0.400^{NS}	0.460^{NS}	7.870^{NS}
Application method	1	527.800^{**}	1.927^{NS}	1.212^{NS}	72.040^{**}
Dose	2	144.240^{*}	0.530^{NS}	0.171^{NS}	9.195^{NS}
Application method × dose	2	17.412^{NS}	0.121^{NS}	2.268^{NS}	2.694^{NS}
Error	12	36.620	1.140	1.230	4.842
Total	19				

Note: ^{NS}, *, **: Nonsignificant or significant at $p < 0.05$ and 0.01, respectively.

Results of Duncan's multiple range test indicated that soil drench applications were more effective in restricting the vegetative growth of *S. compacta* compared to foliar spray applications (Table 2). In both application methods, increasing PBZ doses resulted in a reduction in plant height; however, while soil drench applications led to a marked decrease in plant height, foliar spray applications of the same doses exhibited a more limited dwarfing effect compared to the control. Furthermore, PBZ doses reduced the number and length of lateral branches in both application methods relative to the control (Table 2).

Table 2: Influence of paclobutrazol application method and doses on plant height, plant width, number of lateral branches, and lateral branch length of *S. compacta*.

Characteristic and Application Method	Dose (mg a.i./Plant)			Significance^{z}
	Control	**1.250**	**2.500**	
Plant height (cm)				
Soil drench	16.71a^{y}	5.63a	4.96a	**NS**
Foliar spray	23.61a	18.58a	17.60a	**NS**
Plant width (cm)				
Soil drench	12.17a	11.80a	12.01a	**NS**
Foliar spray	13.14a	12.36a	12.44a	**NS**
Number of lateral branches (count)				
Soil drench	5.13a	4.33a	3.66a	**NS**
Foliar spray	5.11a	3.67a	4.12a	**NS**
Lateral branch length (cm)				
Soil drench	4.73a	3.73a	3.58a	**NS**
Foliar spray	9.90a	8.03a	6.12a	**NS**

Note: ^{z}Linear (L) or quadratic (Q) response at $p \leq 0.05$. ^{y}Within dose (column) and each characteristic, means followed by the same letter are not significantly different at the 5% level according to Duncan's multiple range test. NS: not significant.

3.3 Effects of Paclobutrazol Application Methods and Doses on Leaf Characteristics

The results of the analysis of variance revealed that the application method, dose, and the application method × dose interaction had highly significant statistical effects on the number of leaves on the main stem and the total number of leaves per plant in *S. compacta* (Table 3). Furthermore, while a significant effect of the paclobutrazol dose was detected on the leaf area of the main stem; no significant effect of either the application method or dose was observed on leaf width, leaf length, or leaf thickness.

Table 3: Mean squares from analysis of variance for the effect of application method and doses of paclobutrazol on leaf characteristics of *S. compacta*.

Source of Variation	df	Mean Square					
		Leaf Count on the Main Stem (Count)	Total Leaf Count Per Plant (Count)	Leaf Width on the Main Stem (cm)	Leaf Length on the Main Stem (cm)	Leaf Area on the Main Stem (cm^2)	Leaf Thickness on the Main Stem (mm)
Replication	2	0.903^{NS}	0.500^{NS}	3.358^{NS}	5.611^{NS}	0.490^{NS}	0.010^{NS}
Application method	1	603.434^{***}	186.889^{***}	4.371^{NS}	0.091^{NS}	0.396^{NS}	0.001^{NS}
Dose	2	25.5230^{***}	18.167^{**}	1.152^{NS}	4.997^{NS}	10.274^{**}	0.005^{NS}
Application method × dose	2	67.164^{***}	81.722^{***}	1.880^{NS}	2.780^{NS}	0.370^{NS}	0.036^{NS}
Error	12	1.375	1.778	2.648	3.747	0.976	0.017
Total	19						

Note: ^{NS}, **, ***: Nonsignificant or significant at $p < 0.01$ and 0.001, respectively.

According to the results of Duncan's multiple range test, an increase in dose within the soil drench applications led to an increase in the number of leaves on the main stem and the total number of leaves compared to the control. Conversely, in foliar spray applications, increasing doses resulted in a decrease in both parameters (Table 4). This suggests that soil drench application promotes more dense foliage in conjunction with a more compact plant structure.

In *S. compacta*, it was determined that leaf length values decreased with increasing doses in both application methods, with the shortest leaves occurring at the highest dose of the foliar spray application. Regarding leaf width, the moderate dose in the soil drench application slightly increased leaf width, while the highest dose resulted in the narrowest leaves. In foliar spray applications, the widest leaves were identified at the moderate dose (Table 4). Consequently, soil drench application promoted the formation of a greater number of leaves, albeit of a smaller size, in *S. compacta*.

Table 4: Influence of application method and doses of paclobutrazol on leaf characteristics of *S. compacta*.

Characteristic and Application Method	Dose (mg a.i./Plant)			Significance^z
	Control	1.250	2.500	
Leaf count on the main stem (count)				
Soil drench	$28.92b^y$	37.33a	39.00a	**L, Q**
Foliar spray	25.00a	22.78a	22.73a	**L**
Total leaf count per plant (count)				
Soil drench	69.00b	77.67a	79.00a	**L, Q**
Foliar spray	71.00a	68.00b	67.33b	**L**
Leaf width on the main stem (cm)				
Soil drench	1.29a	1.33a	1.20a	**L**
Foliar spray	1.43a	1.89a	1.46a	**NS**

Table 4: *Cont.*

Characteristic and Application Method	Dose (mg a.i./Plant)			Significance^z
	Control	1.250	2.500	
Leaf length on the main stem (cm)				
Soil drench	4.66a	3.10a	2.68a	**NS**
Foliar spray	4.57a	3.71a	2.60a	**NS**
Leaf area on the main stem (cm^2)				
Soil drench	4.86a	3.49ab	2.29b	**NS**
Foliar spray	4.29a	3.77ab	2.69b	**L**
Leaf thickness on the main stem (mm)				
Soil drench	0.62a	0.54a	0.53a	**NS**
Foliar spray	0.46a	0.65a	0.63a	**NS**

Note: ^{z}Linear (L) or quadratic (Q) response at $p \leq 0.05$. ^{y}Within dose (column) and each characteristic, means followed by the same letter are not signifi cantly different at the 5% level according to Duncan's multiple range test. NS: not significant.

3.4 Effects of Paclobutrazol Application Methods and Doses on Floral Characteristics

The results of the analysis of variance demonstrated that the application method and dose had highly significant statistical effects on the number of days from planting to first flowering, the number of inflorescences, inflorescence length and diameter, the number of flowers in the main stem inflorescence, and the peduncle length in *S. compacta* (Table 5). Furthermore, the interactions between the application method and dose were found to be statistically significant for the number of inflorescences, petal length and width, peduncle length, and the number of days from planting to first flowering.

According to the data in Table 6, paclobutrazol applications delayed flowering by extending the duration from planting to the first flowering compared to the control group. This effect became more pronounced with increasing doses in the soil drench application, whereas it remained more limited in foliar spray applications. While the total number of inflorescences decreased with increasing doses in the soil drench treatment, the foliar spray application exhibited lower values at the moderate dose and higher values at the high dose relative to the control. The maximum number of flowers on the main stem decreased with increasing doses in the soil drench application, while the highest value was identified at the moderate dose (1.250 mg a.i.) of the foliar spray application. In both application methods, the number of flowers in the main stem inflorescence decreased with increasing doses (Table 6).

The means for inflorescence morphology and floral characteristics indicated that the inflorescence length and width, as well as flower length and width, were higher in the control plants for both application methods. Regarding the soil drench application, petal length and width were determined to be at their highest values in the control, whereas these values reached a maximum at the moderate dose in the foliar spray application. While peduncle length significantly decreased with increasing PBZ doses, peduncle thickness increased at the highest doses in both methods, with the maximum value recorded at the 2.500 mg a.i. dose of the soil drench application (Table 6). Consequently, paclobutrazol applications delayed flowering; however, they promoted a more compact, upright, and proportional inflorescence structure in *S. compacta.*

Table 5: Mean squares from analysis of variance for the effect of application method and doses of paclobutrazol on floral characteristics of *S. compacta*.

Source of Variation	df	Mean Square											
		TIC (Count)	MICOMS (Count)	IWOMS (cm)	ILOM (cm)	FCIOMS (Count)	Flower Diameter (cm)	Flower Length (cm)	Petal Length (mm)	Petal Width (mm)	IPLOMS (cm)	IPTOMS (mm)	Days to Flower
Replication	2	0.021^{NS}	4.222^{NS}	0.116^{NS}	0.161^{NS}	255.311^{NS}	0.009^{NS}	0.020^{NS}	0.014^{NS}	0.053^{NS}	0.124^{NS}	0.014^{NS}	1.722^{NS}
Application method	1	1.280***	4.500^{NS}	8.820***	1.306*	37,656.827***	0.201***	0.016^{NS}	4.500***	1.306**	22.422***	0.154^{NS}	1549.388***
Dose	2	0.062**	1.055^{NS}	1.720*	1.079*	3056.927**	0.000^{NS}	0.072^{NS}	0.430^{NS}	0.085^{NS}	44.781***	0.273^{NS}	217.055***
Application method × dose	2	0.206***	1.500^{NS}	1.182^{NS}	0.229^{NS}	981.993^{NS}	0.014^{NS}	0.030^{NS}	0.875*	0.326*	6.522***	0.019^{NS}	464.388***
Error	12	0.006	1.666	0.419	0.172	293.766	0.009	0.023	0.138	0.079	0.347	0.124	2.222
Total	19												

Note: TIC, Total inflorescence count per plant; MICOMS, Maximum inflorescence count on the main stem; IWOMS, Inflorescence width on the main stem; ILOM, Inflorescence length on the main stem; FCIOMS, Flower count per inflorescence on the main stem; IPLOMS, Inflorescence peduncle length on the main stem; IPTOMS, Inflorescence peduncle thickness on the main stem. ^{NS}, *, **, ***: Nonsignificant or significant at $p < 0.05$, 0.01 and 0.001, respectively.

Table 6: Influence of application method and doses of paclobutrazol on floral characteristics of *S. compacta.*

Characteristic and Application Method	Dose (mg a.i./Plant)			Significance[z]
	Control	1.250	2.500	
Total inflorescence count per plant (count)				
Soil drench	0.53a[y]	0.30b	0.23b	**L, Q**
Foliar spray	0.67b	1.17a	0.83b	**Q**
Maximum inflorescence count on the main stem (count)				
Soil drench	2.33a	1.67a	1.33a	**NS**
Foliar spray	2.33a	3.67a	2.33a	**NS**
Inflorescence width on the main stem (cm)				
Soil drench	6.03a	4.13b	4.87ab	**NS**
Foliar spray	6.60a	6.47ab	6.17b	**L**
Inflorescence length on the main stem (cm)				
Soil drench	3.72a	2.70a	3.13a	**NS**
Foliar spray	4.17a	3.67ab	3.33b	**L**
Flower count per inflorescence on the main stem (count)				
Soil drench	56.57a	37.67a	30.33a	**NS**
Foliar spray	154.33a	151.00a	93.67b	**L**
Flower diameter (cm)				
Soil drench	1.58a	1.50a	1.58a	**NS**
Foliar spray	1.33a	1.40a	1.30a	**NS**
Flower length (cm)				
Soil drench	2.50a	2.15b	2.27b	**L, Q**
Foliar spray	2.30a	2.23a	2.20a	**NS**
Petal length (mm)				
Soil drench	8.83a	7.67b	7.83b	**L**
Foliar spray	7.00a	7.33a	7.00a	**NS**
Petal width (mm)				
Soil drench	3.97a	3.33a	3.82a	**Q**
Foliar spray	3.17a	3.33a	3.00a	**NS**
Inflorescence peduncle length on the main stem (cm)				
Soil drench	7.93a	1.54b	1.60b	**L, Q**
Foliar spray	7.93a	5.67b	4.17c	**L**
Inflorescence peduncle thickness on the main stem (mm)				
Soil drench	2.36a	2.33a	2.73a	**NS**
Foliar spray	2.30b	2.07c	2.50a	**L, Q**
Days to first flower (days)				
Soil drench	181c	202b	209a	**L, Q**
Foliar spray	181a	181a	174b	**L, Q**

Note: [z]Linear (L) or quadratic (Q) response at $p \leq 0.05$. [y]Within dose (column) and each characteristic, means followed by the same letter are not signifi cantly different at the 5% level according to Duncan's multiple range test. NS: not significant.

3.5 Effects of Paclobutrazol Application Methods and Doses on Stem and Root Characteristics

The results of the analysis of variance indicated that the application method had highly significant statistical effects on the main stem diameter, internode length of the main stem, stem fresh weight, and root dry weight (Table 7). As a main effect, the paclobutrazol dose induced significant changes in stem diameter, internode length, and both stem and root fresh weights. Furthermore, the application method × dose interaction was determined to be statistically significant only for the internode length of the main stem (Table 7).

Table 7: Mean squares from analysis of variance for the effect of application method and doses of paclobutrazol on stem and root characteristics of *S. compacta.*

Source of Variation	df	Mean Square					
		Main Stem Thickness (mm)	Internode Length on the Main Stem (cm)	Stem Fresh Weight (g)	Stem Dry Weight (g)	Root Fresh Weight (g)	Root Dry Weight (g)
Replication	2	0.179^{NS}	1.029^{NS}	32.848^{NS}	1.248^{NS}	23.408^{NS}	3.510^{NS}
Application method	1	0.728**	15.493***	219.87**	1.795^{NS}	10.361^{NS}	19.821*
Dose	2	0.308*	11.287***	165.715**	2.995^{NS}	46.502*	2.794^{NS}
Application method × dose	2	0.170^{NS}	2.337*	21.008^{NS}	0.137^{NS}	1.608^{NS}	4.795^{NS}
Error	12	0.078	0.552	16.524	1.34	11.554	3.085
Total	19						

Note: ^{NS}, *, **, ***: Nonsignificant or significant at $p < 0.05$, 0.01 and 0.001, respectively.

According to the mean values in Table 8, paclobutrazol applications increased the main stem diameter compared to the control group, and this effect was more pronounced especially in the soil drench application. Internode length decreased with increasing doses in both application methods; however, the soil drench application shortened the internodes more potently than the foliar spray. While stem fresh weight increased with increasing doses in both methods, statistically significant differences between doses for stem dry weight were observed only in the soil drench application (Table 8).

Regarding root characteristics, increasing paclobutrazol doses enhanced root fresh weight compared to the control in both application methods. For root dry weight, the application method was the decisive factor, with the soil drench application maintaining a higher level of dry matter accumulation in the roots than the foliar spray. These findings indicate that while paclobutrazol limits stem elongation, it promotes stem diameter and root development. As shown in Fig. 3, the soil drench application was particularly effective in producing *S. compacta* plants with shorter stature, robust stems, and a balanced root system.

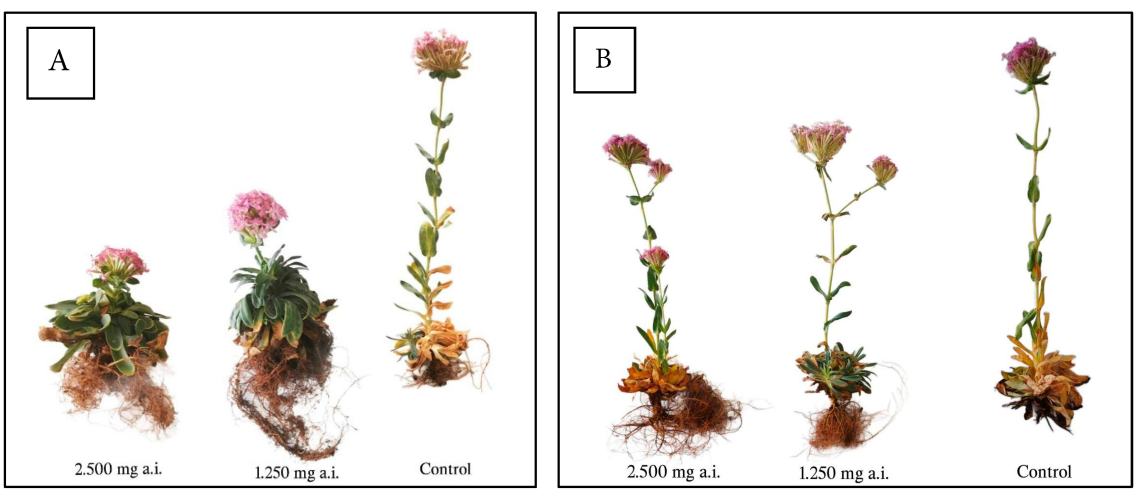

Figure 3: Visual appearances of the effects of soil-applied (**A**) and foliar-applied (**B**) paclobutrazol doses on *S. compacta.*

Table 8: Influence of application method and doses of paclobutrazol on stem and root characteristics of *S. compacta.*

Characteristic and Application Method	Dose (mg a.i./Plant)			Significance^z
	Control	1.250	2.500	
Main stem thickness (mm)				
Soil drench	3.00a^y	3.67a	3.67a	**NS**
Foliar spray	2.97a	2.99a	3.17a	**NS**
Internode length on the main stem (cm)				
Soil drench	4.17a	0.77b	0.67b	**L, Q**
Foliar spray	4.58a	3.42ab	3.17a	**L**
Stem fresh weight (g)				
Soil drench	15.04b	25.27ab	28.00a	**L**
Foliar spray	12.19b	15.14b	20.00a	**L**
Stem dry weight (g)				
Soil drench	6.79a	7.34a	8.00a	**NS**
Foliar spray	5.83a	6.96a	7.44a	**L**
Root fresh weight (g)				
Soil drench	4.26b	9.48a	9.89a	**L**
Foliar spray	3.56a	8.31a	7.21a	**NS**
Root dry weight (g)				
Soil drench	4.05a	5.79a	3.62a	**NS**
Foliar spray	1.34a	2.29a	3.53a	**NS**

Note: ^{z}Linear (L) or quadratic (Q) response at $p \leq 0.05$. ^{y}Within dose (column) and each characteristic, means followed by the same letter are not signifi cantly different at the 5% level according to Duncan's multiple range test. NS: not significant.

3.6 Effects of Paclobutrazol Application Methods and Doses on Leaf Color Characteristics

The results of the analysis of variance revealed that the application method did not exert a statistically significant main effect on the investigated leaf color parameters, including lightness (L*), red-green balance (a*), yellow-blue balance (b*), hue angle (h°), and chroma (C*) (Table 9). In contrast, the paclobutrazol dose induced statistically significant changes in the leaf a*, b*, and chroma values. Furthermore, while the application method × dose interaction was determined to be highly significant for the a*, b*, and chroma parameters, this interaction was found to be statistically non-significant for lightness and hue angle (Table 9).

Table 9: Mean squares from analysis of variance for the effect of application method and doses of paclobutrazol on leaf color characteristics of *S. compacta.*

Source of Variation	df	Mean Square				
		L*	a*	b*	Hue (Degrees)	Chroma
Replication	2	6.127^{NS}	0.794^{NS}	3.058^{NS}	22.623^{NS}	1.899^{NS}
Application method	1	2.111^{NS}	0.003^{NS}	0.178^{NS}	1.115^{NS}	0.168^{NS}
Dose	2	10.611^{NS}	5.317*	56.331**	0.572^{NS}	61.78**
Application method × dose	2	1.565^{NS}	7.143*	57.089**	10.341^{NS}	63.583**
Error	12	5.823	1.302	6.840	7.325	7.457
Total	19					

Note: ^{NS}, *, **: Nonsignificant or significant at $p < 0.05$ and 0.01, respectively.

According to the mean values in Table 10, paclobutrazol applications did not significantly alter the overall lightness (L*) and hue angle (h°), values of the plants compared to the control group. In contrast, the Chroma value, which reflects leaf color saturation, as well as the color components (a*) and (b*), were found to be sensitive to dose increases, particularly in the soil drench application. In the soil drench method, the (b*) and Chroma values reached their maximum at the highest dose (2.500 mg a.i.), whereas the highest values for these parameters in the foliar spray application were recorded in the control plants. Consequently, leaf color saturation and numerical color parameters in *S. compacta* can be manipulated through the appropriate combination of application method and dose.

Table 10: Influence of application method and doses of paclobutrazol on leaf color characteristics of *S. compacta.*

Characteristic and Application Method	Dose (mg a.i./Plant)			Significance[z]
	Control	1.250	2.500	
L*				
Soil drench	45.63a[y]	44.34a	47.28a	**NS**
Foliar spray	48.94a	46.40a	48.56a	**NS**
a*				
Soil drench	−4.71b	−3.68b	−7.60a	**L, Q**
Foliar spray	−5.30a	−5.45a	−5.14a	**NS**
b*				
Soil drench	13.32b	11.80b	22.85a	**L, Q**
Foliar spray	17.28a	14.53a	15.56a	**NS**
Hue (degrees)				
Soil drench	109.05a	107.09a	108.49a	**NS**
Foliar spray	108.12a	110.54a	108.12a	**NS**
Chroma				
Soil drench	14.14b	12.36b	24.11a	**L, Q**
Foliar spray	18.11a	15.52a	16.41a	**NS**

Note: [z]Linear (L) or quadratic (Q) response at $p \leq 0.05$. [y]Within dose (column) and each characteristic, means followed by the same letter are not signifi cantly different at the 5% level according to Duncan's multiple range test. NS: not significant.

3.7 Effects of Paclobutrazol Application Methods and Doses on Flower Color Characteristics

The results of the analysis of variance indicated that the application method had highly significant statistical effects on all flower color parameters, with the exception of lightness (L*) (Table 11). It was determined that neither the paclobutrazol dose nor the application method × dose interaction exerted a statistically significant effect on any of the investigated flower color parameters. This evidence demonstrates that the color profile of *S. compacta* flowers is shaped by the application method itself rather than the dosage level employed.

Table 11: Mean squares from analysis of variance for the effect of application method and doses of paclobutrazol on flower color characteristics of *S. compacta.*

Source of Variation	df	Mean Square				
		L*	a*	b*	Hue (Degrees)	Chroma
Replication	2	16.468^{NS}	14.257^{NS}	4.021^{NS}	6.064^{NS}	15.292^{NS}
Application method	1	0.623^{NS}	132.519**	34.500**	43.742**	144.896**
Dose	2	5.632^{NS}	2.829^{NS}	1.515^{NS}	2.767^{NS}	2.854^{NS}
Application method × dose	2	0.736^{NS}	13.717^{NS}	6.290^{NS}	9.881^{NS}	15.356^{NS}
Error	12	16.732	9.976	1.972	2.943	10.552
Total	19					

Note: ^{NS}, **: Nonsignificant or significant at $p < 0.01$, respectively.

According to the mean values in Table 12, flower lightness (L*) was found to be higher in control plants for both application methods. Regarding the red-green (a*) and yellow-blue (b*) components of flower color, the foliar spray application generally produced higher numerical values compared to the soil drench method. Similarly, Chroma values, which represent color saturation, remained higher in the foliar spray application, indicating that the flowers possessed a more vivid appearance under this treatment (Table 12).

While hue angle (h°), values showed statistically significant changes depending on the dose increase in the foliar spray application, they remained at levels similar to the control group in the soil drench application. Consequently, the paclobutrazol doses applied to restrict plant height did not exert a negative effect on the primary color characteristics and lightness of the flowers; thus, floral aesthetics were preserved.

Table 12: Influence of application method and doses of paclobutrazol on flower color characteristics of *S. compacta.*

Characteristic and Application Method	Dose (mg a.i./Plant)			Significance^z
	Control	1.250	2.500	
L*				
Soil drench	48.55a^y	50.28a	51.00a	**NS**
Foliar spray	49.48a	50.87a	50.59a	**NS**
a*				
Soil drench	40.82a	40.89a	37.29a	**NS**
Foliar spray	45.31a	43.88a	46.10a	**NS**
b*				
Soil drench	−4.50a	−3.54a	−2.05a	**NS**
Foliar spray	−6.11a	−5.11a	−7.19a	**Q**
Hue (degrees)				
Soil drench	353.72a	355.14a	357.20a	**NS**
Foliar spray	352.30a	353.27a	351.13a	**Q**
Chroma				
Soil drench	41.08a	41.06a	37.39a	**NS**
Foliar spray	45.72a	44.18a	46.66a	**NS**

Note: ^{z}Linear (L) or quadratic (Q) response at $p \leq 0.05$. ^{y}Within dose (column) and each characteristic, means followed by the same letter are not signifi cantly different at the 5% level according to Duncan's multiple range test. NS: not significant.

3.8 Relationships between Growth Characteristics

The analyses of the relationships among certain growth characteristics and Pearson correlation coefficients (r) in *S. compacta* are presented in Table 13. According to the analysis results, a highly significant positive correlation was determined between plant height and both internode length (r = 0.854, $p < 0.01$) and total number of inflorescences (r = 0.611, $p < 0.01$), while a significant positive correlation was found with lateral branch length (r = 0.582, $p < 0.05$). Conversely, strong negative correlations were identified between plant height and total leaf count (r = −0.665, $p < 0.01$), main stem thickness (r = −0.612, $p < 0.01$), stem fresh weight (r = −0.636, $p < 0.01$), and root dry weight (r = −0.592, $p < 0.01$).

Significant positive relationships were detected between lateral branch length and both internode length (r = 0.549, $p < 0.05$) and total number of inflorescences (r = 0.520, $p < 0.05$), whereas significant negative correlations were observed with stem fresh weight (r = −0.535, $p < 0.05$) and root dry weight (r = −0.553, $p < 0.05$). Total leaf count exhibited strong positive correlations with main stem thickness (r = 0.679, $p < 0.01$) and stem fresh weight (r = 0.656, $p < 0.01$). Furthermore, total leaf count was found to be in a very strong negative relationship with internode length (r = −0.740, $p < 0.01$) and total number of inflorescences (r = −0.792, $p < 0.01$).

Table 13: Relationships among growth characteristics and Pearson correlation coefficients (r) in *S. compacta*.

Growth Characteristics	Growth Characteristics									
	Lateral Branch Length (cm)	**Total Leaf Count Per Plant (Count)**	**Leaf Area on the Main Stem (cm^2)**	**Main Stem Thickness (mm)**	**Internode Length on the Main Stem (cm)**	**Stem Fresh Weight (g)**	**Stem Dry Weight (g)**	**Root Fresh Weight (g)**	**Root Dry Weight (g)**	**Total Inflorescence Count Per Plant (Count)**
Plant height (cm)	0.582*	−0.665**	0.132	−0.612**	0.854**	−0.636**	−0.429	−0.412	−0.592**	0.611**
Lateral branch length (cm)		−0.407	0.214	−0.462	0.549*	−0.535*	−0.154	−0.167	−0.553*	0.520*
Total leaf count per plant (count)			−0.073	0.679**	−0.740**	0.656**	0.274	0.261	0.345	−0.792**
Leaf area on the main stem (cm^2)				−0.341	0.407	−0.468*	−0.337	−0.432	0.048	0.108
Main stem thickness (mm)					−0.724**	0.427	0.095	0.363	0.236	−0.574*
Internode length on the main stem (cm)						−0.790**	−0.500*	−0.653**	−0.464	0.607**
Stem fresh weight (g)							0.720**	0.588*	0.495*	−0.573*
Stem dry weight (g)								0.572*	0.280	−0.244
Root fresh weight (g)									0.437	−0.229
Root dry weight (g)										−0.460

Note: *, **: Significant at $p < 0.05$ and $p < 0.01$, respectively (2-tailed).

A negative relationship was determined between leaf area and stem fresh weight (r = −0.468, $p < 0.05$). Main stem thickness exhibited negative correlations with internode length (r = −0.724, $p < 0.01$) and number of inflorescences (r = −0.574, $p < 0.05$). Significant positive correlations were observed between internode length and total number of inflorescences (r = 0.607, $p < 0.01$), while significant negative relationships were found with stem fresh weight (r = −0.790, $p < 0.01$), root fresh weight (r = −0.653, $p < 0.01$), and stem dry weight (r = −0.500, $p < 0.05$). Positive correlations were identified between stem fresh weight and stem dry weight (r = 0.720, $p < 0.01$), root fresh weight (r = 0.588, $p < 0.05$), and root dry weight (r = 0.495, $p < 0.05$), whereas a negative relationship was found with the number of inflorescences (r = −0.573, $p < 0.05$). A significant positive correlation was determined between stem dry weight and root fresh weight (r = 0.572, $p < 0.05$).

4 Discussion

Paclobutrazol (PBZ), as a triazole-class plant growth regulator, inhibits cell elongation and modulates plant architecture by suppressing the oxidation of ent-kaurene in the gibberellin (GA) biosynthetic pathway [7,9]. In this comprehensive study conducted on *S. compacta*, the data obtained regarding vegetative growth, floral development, and biomass partitioning demonstrate that PBZ holistically restructures plant physiology. The restrictive effect on plant height and width is the most characteristic response of plants to PBZ. This phenomenon is supported by Ahmad et al. [15], who studied *Helianthus annuus* and *Zinnia elegans*, and Wu et al. [7], who investigated *Paeonia lactiflora*. Paclobutrazol (PBZ) is a plant growth retardant that inhibits gibberellin biosynthesis, thereby reducing cell elongation and vegetative growth [25,26]. In this process, while vegetative growth is limited—as observed by Ghosh et al. [10] in *Jatropha curcas*—the plant acquires a much more compact form alongside height reduction, as identified by Mansuroğlu et al. [8] in *Consolida orientalis*. Although the numerical decreasing trend observed in the plant width of *S. compacta* depending on increasing PBZ doses in both soil drench and foliar spray applications was found to be statistically non-significant, it demonstrates the optimization of plant volume, drawing a parallel with the findings of canopy width reduction (14.72%) reported by Wu et al. [7] in *Paeonia lactiflora*. This narrowing trend remained more limited compared to the radical diameter reduction of 32–43% reported by Ahmad et al. [15] in their study on *Zinnia elegans*. This indicates that while the height of the *S. compacta* plant decreases, it largely maintains its capacity to fill the pot surface.

The reduction of plant height in *S. compacta* from 30.1 cm in the control group to a range of 5.0–6.0 cm (an 80% decrease) via the drench method is in full agreement with the findings of Karagüzel et al. [16], who reported that drench applications highly suppressed plant height and internode length in *Lupinus varius*, and Park and Faust [17], who stated that this method was effective in limiting stem elongation in *Petunia hybrida*. Similarly, Al-Khassawneh et al. [21] reported that the drench application of PBZ was much more effective in limiting plant height in *Iris nigricans* compared to the spray application. When the temporal change in plant height of *S. compacta* was examined, it was observed that the growth curve of PBZ-treated plants reached a plateau at a much earlier stage than the control group. The finding that the foliar spray application in *S. compacta* remained more limited in height control compared to the drench method can be explained by the weak penetration of the spray into plant tissues, as noted by Al-Khassawneh et al. [21] for *Iris nigricans*, and the fewer barriers to growth regulator entry in roots compared to leaves, as emphasized by Taha and Sorour [18] for *Pentas lanceolata*. Furthermore, the fact that the primary transport of PBZ occurs through the xylem supports the drench application in providing more effective growth limitation [18]. Additionally, Million et al. [27] reported that the efficacy of PBZ in *Petunia hybrida* and *Brassica oleracea* species can vary significantly depending on the physical and chemical properties of the growing medium.

The increase in stem diameter despite the reduction in plant height in *S. compacta* is consistent with the finding that PBZ limits vegetative growth to induce a more compact form and redirects nutrients toward lateral development, as stated by Wu et al. [7] in their study on *Paeonia lactiflora*. This morphological change is also in full agreement with the results reported by Karagüzel et al. [16] in *Lupinus varius*, where stem diameter significantly increased with increasing doses. The thickening of the stem enhances the mechanical resistance of the plant, supporting the compact plant form emphasized by Ahmad et al. [15] in *Zinnia elegans*, as seen in the case of *Paeonia lactiflora* by Wu et al. [7], and minimizes the risk of bending and lodging due to the increase in stem diameter, as noted by Mansuroğlu et al. [8] in *Consolida orientalis*.

The statistical increase in both stem and root fresh weights caused by increasing PBZ doses in *S. compacta* diverges sharply from the findings of "dwarfism-induced biomass reduction" commonly encountered in the literature. In our study, high-rate increases were recorded, particularly in the soil drench application, reaching 86% for stem fresh weight and 132% for root fresh weight. Similarly, no statistically significant decrease was detected in dry weights; on the contrary, numerical increases of up to 18% in stem dry weight and 43% in root dry weight were observed compared to the control group. These results obtained in *S. compacta* largely overlap with the root development findings reported by Taha and Sorour [18] on *Pentas lanceolata*. The aforementioned researchers reported that root dry weight increased significantly (between 61% and 95%) as the PBZ concentration increased, and that the drench application was much more effective than the spray in promoting root weight. However, regarding stem (shoot) dry weight, in contrast to *S. compacta*, Taha and Sorour [18] reported that PBZ application significantly reduced stem dry weight in *Pentas lanceolata*. Furthermore, Ahmad et al. [15] reported that PBZ applications reduced fresh weight by 37–47% and dry weight by 46–57% in *Zinnia elegans*, and led to a loss of 22% in fresh weight and 28% in dry weight in *Helianthus annuus*. In the present study, unlike these literature data, it is observed that *S. compacta* not only increased root weight but also maintained its stem weight.

Paclobutrazol (PBZ) applications in *S. compacta* induced characteristic changes in leaf number and area depending on the application method. The continuous increasing trend observed in both the main stem and total leaf number with increasing doses in soil drench applications provided the plant with a fuller vegetative mass in addition to its compact form. This finding diverges positively from the general PBZ effects reported in the literature. Indeed, Ribeiro et al. [19], in their study on eight different genotypes of *Capsicum annuum*, reported that the effect of PBZ varies according to genetic structure, with the number of leaves decreasing compared to the control group in seven of the genotypes examined. Similarly, Parlakova Karagöz et al. [20] reported that PBZ doses significantly reduced leaf number compared to the control in a foliar spray study on *Gypsophila bicolor*. While the limitation of the total leaf number by the foliar spray application in *S. compacta* overlaps with the findings of these researchers, the promotion of leaf number by the soil drench method reveals the success of this method in increasing vegetative density in *S. compacta*. It was determined that leaf length values decreased with increasing doses in both application methods (soil drench and foliar spray) in *S. compacta*. This situation showed a marked similarity with the findings obtained by Ribeiro et al. [19] in their study on *Capsicum annuum*. The aforementioned researchers reported that leaf length showed the highest values in the control group in six out of the eight genotypes they examined. The findings obtained regarding leaf width in *S. compacta* revealed both consistent and contrasting results with general trends in the literature. Ribeiro et al. [19] reported that leaf width decreased compared to the control group in six genotypes in their study on eight different genotypes of *Capsicum annuum*. In *S. compacta*, while the highest dose of soil drench application (2.500 mg a.i./plant) reduced leaf width compared to the control—consistent with that article—none of the doses in the foliar spray application narrowed the leaf width compared to the control; on the contrary, they exhibited mathematically higher values. The fact that the same result was not obtained for all genotypes in the study by Ribeiro et al. [19] (no change in two out of eight genotypes) confirms that the effect of PBZ on leaf morphology can vary depending on the application method and genetic structure. In *S. compacta*, the highest leaf area values were obtained in the control group for both soil drench and foliar spray applications, and leaf areas gradually decreased in parallel with the increase in PBZ doses. These findings are in full agreement with similar studies in the literature. Indeed, Taha and Sorour [18], in their research on *Pentas lanceolata*, found that plants in the control group had higher leaf area values than those treated with PBZ in both application methods. Similarly, Wu et al. [7] reported that PBZ application reduced leaf area by 10.90% compared to the control group in *Paeonia lactiflora*. It was determined that foliar-applied PBZ doses in *S. compacta* increased leaf thickness compared to the control group, whereas soil-applied doses decreased leaf thickness relative to the control. Among these findings, the foliar spray application showed similarity with the results of Wu et al. [7], who reported that PBZ increased leaf thickness by 18.18% compared to the control group, while the soil drench application contrasted with the findings of the researchers regarding the decrease observed relative to the control group.

In *S. compacta*, it was determined that foliar spray applications of PBZ shortened (accelerated) the time from planting to first flowering compared to the control group, whereas soil drench applications delayed flowering by extending this duration. These findings significantly overlap with similar method-based variations reported in the literature. Indeed, Mansuroğlu et al. [8], in their study on *Consolida orientalis*, reported that spray applications shortened the time to first flowering relative to the control group. Similarly, Karagüzel et al. [16] found that spray applications in *Lupinus varius* promoted flowering and reduced the duration; however, the 2.500 mg a.i. soil drench application—identical to the highest dose in our study—markedly delayed the time to first flowering. Conversely, Al-Khassawneh et al. [21] recorded a different trend in *Iris nigricans*, reporting that all spray applications extended the time to first flowering, while only low doses (0.25 and 1 mg/L) of soil drench applications shortened this period by a few days. In *S. compacta*, this delay effect followed a much more radical course in drench-treated plants, limiting the flowering percentage to levels of 20–23%. The suppression of floral induction and the extension of the vegetative phase by PBZ through the inhibition of gibberellin biosynthesis are cited in the literature as the primary reasons for such morphological changes [11]. In the study, it was determined that PBZ treatments applied to *S. compacta* delayed flowering by 10–15 days. This delay can be explained by the plant strengthening its vegetative structures and redirecting energy resources toward the stem and root systems prior to floral bud initiation. From the perspective of landscape applications and commercial production scheduling, although this duration extends the time to market for *S. compacta*, it possesses the potential to minimize losses during transportation due to the more robust and compact plant form. Particularly in intensive landscape designs, such control over the flowering period offers a strategic advantage for optimizing the aesthetic longevity of the plant and creating a phased visual presentation with species that bloom at different intervals.

When the total number of inflorescences per plant in *S. compacta* was examined, the PBZ spray application increased the number of inflorescences compared to the control, whereas the soil drench method reduced it. The fact that PBZ doses in both application methods led to reductions in inflorescence diameter, inflorescence length, flower dimensions, and peduncle length, as well as decreases in the number of flowers per inflorescence, while thickening the peduncle at high doses, proves that the plant redirected its assimilates toward forming more compact structures. When these findings are compared with the literature, although the reduction in inflorescence length of *S. compacta* shows similarity with the results of Karagüzel et al. [16] on *Lupinus varius*, our finding regarding the decrease in inflorescence diameter contrasts with the increase identified by those researchers. In contrast, the data we obtained are in full agreement with the findings of Mansuroğlu et al. [8], who reported that both inflorescence length and width (diameter) decreased with PBZ in *Consolida orientalis*. This situation confirms that the dimensional contractions observed in *S. compacta* are supported by similar species and application results in the literature, and that the plant reached the targeted compact form. The increase in leaf color saturation (Chroma) and the observed darkening (lower L* value) can be attributed to the modulatory effect of PBZ on chlorophyll biosynthesis and leaf anatomy. It is well-documented that triazole compounds, such as PBZ, stimulate the production of the phytyl side chain—a fundamental component of chlorophyll—and increase cytokinin levels, which in turn delay chlorophyll degradation (senescence) [14]. The inhibition of gibberellin biosynthesis through PBZ application [14], combined with the reduction in leaf area, leads to a 'more densely packed' arrangement of chloroplasts per unit leaf area. This structural modification results in an enhancement of both chlorophyll synthesis and its concentration per unit area [20,28]. Furthermore, the reduced cell volume induced by PBZ facilitates a 'concentrating effect', where chlorophyll becomes more intensely localized within the cells [18]; this physiological shift ultimately leads to a decrease in leaf lightness (L*), resulting in a visually darker green foliage [20].

It was determined that the Chroma (C*) value, which expresses leaf color saturation in *S. compacta*, reached its highest level at the maximum paclobutrazol (PBZ) dose, particularly in the soil drench application. This finding is in full agreement with the data of Bañón et al. [22], who studied *Dianthus caryophyllus* and reported that both soil and foliar PBZ applications increased color saturation in the leaves. In contrast, our finding contradicts the results of Parlakova Karagöz et al. [20], who reported that PBZ doses decreased the Chroma value in their study on *Gypsophila bicolor*, and Mansuroğlu et al. [8], who detected a similar decrease in Chroma values with foliar PBZ applications in *Consolida orientalis*. On the other hand, it was observed that leaf lightness (L*) values in *S. compacta* exhibited different responses depending on the application method. Although not statistically significant, a numerical increasing trend in L* values (a brighter appearance) was detected in the drench application compared to the control, while these values decreased (a darker appearance) in the foliar spray application. This decrease observed in the spray application is similar to the findings of Bañón et al. [22], Parlakova Karagöz et al. [20], and Mansuroğlu et al. [8], who all reported a reduction in leaf lightness. However, the increasing trend in the drench application indicates that *S. compacta* acquired a more radiant leaf appearance by reflecting more light in this method, unlike other species, and thus diverges uniquely from the literature. In our study, it was found that the leaf hue angle (h°) value decreased in the soil drench application, while it remained stable and similar to the control group in the foliar spray application. Similarly, Parlakova Karagöz et al. [20] also found that PBZ doses reduced the hue angle compared to the control. However, this situation differs from Bañón et al. [22], who reported that the hue angle increased relative to the control, particularly in soil applications. The different results identified by researchers prove that PBZ can cause species-specific shifts in the leaf color spectrum depending on the method and application dose. The pink-lilac hues of *S. compacta* flowers are likely associated with anthocyanins and flavonoids, which are the primary pigments determining flower color in many ornamental species. As reported by Wu et al. [7] for *Paeonia lactiflora*, anthocyanin content is a decisive factor for flower shades, and the shifts in color values identified in our study suggest that PBZ may modulate these secondary metabolic pathways. The shifts in Chroma and Hue values identified in *S. compacta* indicate that PBZ modulates the secondary metabolic flux toward the flavonoid pathway. It has been suggested that the effect of paclobutrazol on flower color can be explained by its indirect or limited impacts on certain enzymes involved in anthocyanin biosynthesis, as proposed in the literature [11].

When the effects of paclobutrazol (PBZ) applications on flower color in *S. compacta* were examined, it was determined that both lightness (L*) and hue angle (h°) values increased compared to the control group in both application methods (drench and spray). Although these changes in the lightness (L*) level of the flowers were not statistically significant, the observed numerical increasing trend shows a parallel with the findings of Bañón et al. [22] obtained from soil drench applications on *Dianthus caryophyllus*. However, this situation contrasts with the findings of Mansuroğlu et al. [8] on *Consolida orientalis*, who detected who detected a decrease in the lightness (L*) value of flowers. The increasing trend of hue angle (h°) values identified with PBZ applications in the soil drench method for *S. compacta* is in harmony with Bañón et al. [22], who reported higher hue angle values in flowers with the soil application method. In the foliar spray method for *S. compacta*, it was found that the low-dose PBZ application yielded the highest hue value; however, with increasing doses, this value fell below that of the control group. This finding shows similarity at high doses with the data of Mansuroğlu et al. [8] on *Consolida orientalis*, who found that foliar PBZ applications directly reduced the hue angle compared to the control group. This situation proves that *S. compacta* flowers maintain their visual quality by exhibiting a reaction that is both brighter and more stable and vivid in terms of color tone against PBZ applications. Regarding the Chroma (C*) values, which express the color saturation of the flowers, a distinct difference was detected depending on the application method. In the foliar spray application, it was determined that the highest dose of 2.500 mg a.i. PBZ increased the Chroma value compared to the control, giving the flowers a more vivid appearance; conversely, the 1.250 mg a.i. dose reduced this value below the control group. In the soil drench application, it was found that the Chroma value decreased at all doses. Interestingly, contrary to these findings in *S. compacta*, Bañón et al. [22] reported that the Chroma value generally decreased at most PBZ doses in foliar applications, while it increased compared to the control at most doses in soil drench applications. On the other hand, the trend of Chroma reduction we identified in the drench method overlaps with the findings of Mansuroğlu et al. [8], who reported a similar decrease. This situation demonstrates that to achieve maximum flower vividness in *S. compacta*, not only the method but specifically the high-dose spray application is a decisive factor.

Positive correlations among the growth characteristics of *S. compacta* reflect the developmental harmony and allometric growth balance between plant organs. Specifically, the strong positive relationship between plant height and internode length proves that the primary mechanism of height reduction is inherently linked to the shortening of internodes. The positive interaction between leaf count and stem diameter indicates that increased photosynthetic capacity is allocated toward stem durability. Similarly, the positive link between stem weight and root mass suggests that PBZ treatments maintain the physiological balance between the shoot and root systems while dwarfing the plant, thereby supporting overall plant health. These findings are in parallel with the balanced morphological development principle emphasized by Mansuroğlu et al. [8]. In contrast, the negative correlations identified reveal the regulatory effect of PBZ in reshaping the plant architecture. The inverse relationship—where parameters such as stem diameter, leaf count, and root weight increase as plant height decreases—confirms that vertical growth energy is suppressed and redirected toward radial expansion and the root system. This redirection of nutrients toward stem durability (carbohydrate re-allocation), rather than vertical elongation, leads to the formation of a more compact and physically stress-resistant plant form. These results are in full agreement with the findings of Karagüzel et al. [16], who reported that growth regulators promote secondary thickening in stem tissues and enhance mechanical strength.

From the perspective of experimental plant biology, the obtained results support the contention that PBZ acts not merely as a morphological growth retardant in *S. compacta*, but also as an assimilate partitioning regulator that governs the allocation of resources between vegetative and reproductive organs [6,10,14]. In the context of *S. compacta*, the results demonstrating reduced plant height alongside an increased number of inflorescences via foliar application support the potential of paclobutrazol to enhance flowering by restricting vegetative growth and altering assimilate distribution [6]. This reflects an effect of redistributing assimilates and directing the majority toward reproductive development [10], as well as the function of paclobutrazol as a potent modulator by increasing the allocation of assimilates to the economically significant parts of the plant [14].

5 Conclusion

This dwarfing study conducted on *S. compacta*, a natural species, holds strategic importance for integrating the species into the ornamental plants sector and standardizing its cultural practices. In light of the findings obtained, the following conclusions have been drawn and recommendations developed:

- ***Most Effective Application Strategy***: Regarding plant height control and achieving the ideal compact form, the soil drench application exhibited statistically superior success compared to the foliar spray. This method radically shortened internode length, ensuring that the plant remained in a durable, stable, and non-lodging structure suitable for pot cultivation.
- ***Growth and Form Management***: While plant height and lateral branch length decreased in parallel with the increase in paclobutrazol (PBZ) dosage, the increase in stem diameter enhanced the mechanical resistance and visual fullness of the plant. This outcome fully meets the demand for the "short and compact form" preferred in floral and landscape designs.
- ***Production Schedule and Flowering***: It was determined that PBZ applications extended the period from planting to first flowering (delayed flowering). To compensate for this delay when targeting peak market demand, it is critical for growers to advance their production schedules by approximately 10–15 days to ensure the timely market presentation of the species. Furthermore, this delay assumes an advantageous commercial character as the plant becomes more resilient to transportation stress.
- ***Visual Quality and Aesthetic Parameters***: The treatments did not impair the primary color hue or lightness of the leaves and flowers. To enhance the visual quality and leaf appeal of *S. compacta* in plant design, the soil drench method at a dose of 2.500 mg a.i. is recommended, as it imparts higher lightness and color saturation to the foliage. For flower aesthetics, while the 2.500 mg a.i. foliar spray stood out for providing the highest color saturation (Chroma), the use of the foliar spray method with dose optimization is advised when the goal is to maintain the balance of ideal color hue (Hue) and lightness.
- ***Scientific and Commercial Contribution***: By providing comprehensive data on the cultural management of *S. compacta*, about which limited information is available, this study serves as a model for the economic integration of similar natural species as potted ornamental plants or seasonal flowers. Due to its low labor cost and high efficacy, PBZ doses applied via the soil drench method are particularly recommended to producers seeking to maximize plant quality.

In conclusion, the multifaceted contribution of growth regulators—not only to height reduction but also to root development, stem stability, and color quality—has rendered *S. compacta* a high-potential material for modern ornamental plant cultivation and landscape architecture.

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References

1. Singh AK, Singh R, Kumar R, Gupta AK, Kumar H, Rai A, et al. Evaluating sustainable and environment friendly growing media composition for pot mum (*Chrysanthemum morifolium* Ramat.). Sustainability. 2023;15(1):536. [CrossRef].
2. Davis P, Mill R, Tan K. Flora of Turkey and East Aegean Islands (Supplement). Vol. 10. Edinburgh, UK: University Press; 1998.
3. Davis PH, Cullen J, Coode MJE. Flora of Turkey and the East Aegean Islands. Vol. 2. Edinburgh, UK: Edinburgh University Press; 1998.
4. Kosa S, Karaguzel O. Effects of seed age, germination temperature, gibberellic acid and stratification on germination of *Silene compacta*. Pak J Bot. 2020;52(3):901–8. [CrossRef].
5. Yilmaz H, Yilmaz H. Use of native plants in landscape planning of roadside banks under extreme climatic conditions in eastern Anatolia, Turkey. Int J Biodivers Sci Manag. 2009;5(2):102–13. [CrossRef].
6. Yeshitela T, Robbertse PJ, Stassen PJC. Paclobutrazol suppressed vegetative growth and improved yield as well as fruit quality of 'Tommy Atkins' mango (*Mangifera indica*) in Ethiopia. N Z J Crop Hortic Sci. 2004;32(3):281–93. [CrossRef].
7. Wu Y, Liu J, Zhao D, Tao J. Effect of paclobutrazol application on plant growth and flower quality in herbaceous peony. Phyton. 2022;91(9):2017–32. [CrossRef].
8. Mansuroğlu S, Karagüzel O, Ortaçeşme V, Sayan MS. Effect of paclobutrazol on flowering, leaf and flower colour of *Consolida orientalis*. Pak J Bot. 2009;41:2323–32.
9. Graebe JE. Gibberellin biosynthesis and control. Annu Rev Plant Physiol. 1987;38:419–65. [CrossRef].
10. Ghosh A, Chikara J, Chaudhary DR, Prakash AR, Boricha G, Zala A. Paclobutrazol arrests vegetative growth and unveils unexpressed yield potential of *Jatropha curcas*. J Plant Growth Regul. 2010;29(3):307–15. [CrossRef].
11. Rademacher W. Growth retardants: effects on gibberellin biosynthesis and other metabolic pathways. Annu Rev Plant Physiol Plant Mol Biol. 2000;51:501–31. [CrossRef].
12. Wilkinson RI, Richards D. Effects of paclobutrazol on growth and flowering of *Bouvardia humboldtii*. HortScience. 1987;22(3):444–5. [CrossRef].
13. Haldankar PM, Thorat VB, Mayekar AJ, Khirsagar PJ, Korake GN, Khandekar RG. Effect of paclobutrazol and post flowering foliar sprays of nutrients for accelerating harvesting of jackfruit. Indian J Hortic. 2014;71(4):476–80.
14. Desta B, Amare G. Paclobutrazol as a plant growth regulator. Chem Biol Technol Agric. 2021;8(1):1. [CrossRef].
15. Ahmad I, Whipker BE, Dole JM, McCall I. Paclobutrazol and ancymidol lower water use of potted ornamental plants and plugs. Eur J Hortic Sci. 2014:318–26. [CrossRef].
16. Karagüzel O, Baktir I, Cakmakci S, Ortacesme V. Growth and flowering responses of *Lupinus varius* L. to paclobutrazol. HortScience. 2004;39(7):1659–63. [CrossRef].
17. Park J, Faust JE. Fertilization and paclobutrazol application for sustainable production and post-production performance of *Petunia*. HortTechnology. 2023;33(2):225–32. [CrossRef].
18. Taha A, Srour M. Effect of paclobutrazol and its method of application on the growth of *Pentas lanceolata* plants. J Adv Agric Res. 2016;24(4):686–703. [CrossRef].
19. Ribeiro WS, Carneiro CD, França CD, Pinto CMF, Lima PCC, Finger FL, et al. Paclobutrazol application in potted ornamental pepper. Hortic Bras. 2019;37(4):464–8. [CrossRef].
20. Parlakova Karagöz F, Dursun A, Kotan MM. Determining of the effects of paclobutrazol treatments on seedling height control of wild *Gypsophila bicolor* (Freyn & Sint.) Grossh. Not Bot Horti Agrobo. 2023;51(2):12913. [CrossRef].
21. Al-Khassawneh NM, Karam NS, Shibli RA. Growth and flowering of black iris (Iris nigricans Dinsm.) following treatment with plant growth regulators. Sci Hortic. 2006;107(2):187–93. [CrossRef].

22. Bañón S, González A, Cano EA, Franco JA, Fernández JA. Growth, development and colour response of potted *Dianthus caryophyllus* cv. Mondriaan to paclobutrazol treatment. Sci Hortic. 2002;94(3–4):371–7. [CrossRef].
23. Yadaw A, Prasad VM, Bahadur V. Differential effect of different methods of applying paclobutrazol on *Calendula* (*Calendula officinalis* L.) in prayagraj climatic condition. Int J Plant Soil Sci. 2023;35(17):391–7. [CrossRef].
24. Syngenta. Bonzi: Ornamental Growth Regulator (Product Label). 17 Feb 2025. [cited 2026 Jan 5]. Available from: https://www.syngentaornamentals.co.uk/sites/g/files/kgtney951/files/media/document/2025/02/17/Bonzi%20Label.pdf.
25. Orozco-Meléndez LR, Hernández-Rodríguez OA, Cruz-Álvarez O, Robles-Hernández L, Ávila-Quezada GD, Chavez ES, et al. Paclobutrazol and its use in fruit production: A review. Phyton. 2022;91(1):1–12. [CrossRef].
26. Chen CH, Lin SY, Chen CM. Enhancing ornamental qualities of southern highbush blueberry container plants with paclobutrazol in subtropical climates. Sci Hortic. 2025;340:113928. [CrossRef].
27. Million JB, Barrett JE, Nell TA, Clark DG. Influence of media components on efficacy of paclobutrazol in inhibiting growth of broccoli and *Petunia*. HortScience. 1998;33(5):852–6. [CrossRef].
28. Khalil IA. Chlorophyll and carotenoid contents in cereals as affected by growth retardants of the triazole series. Cereal Res Commun. 1995;23:183–9.