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Balancing Ornamental Performance through Different Paclobutrazol Application Strategies in Container-Grown *Rhododendron ponticum* L.

Ümmü Özgül Karagüzel^{1,*}, Hatice Filiz Boyacı¹, Sümeyye İslam¹, Songül Yıldız², Bahadır Altun³ and Ergül Erkut¹

¹Department of Horticulture, Faculty of Agriculture, Recep Tayyip Erdoğan University, Rize, Türkiye

²Department of Plant and Animal Production, Pazar Vocational School, Recep Tayyip Erdoğan University, Rize, Türkiye

³Department of Horticulture, Faculty of Agriculture, Ahi Evran University, Kırşehir, Türkiye

*Corresponding Author: Ümmü Özgül Karagüzel. Email: ozgul.karaguzel@erdogan.edu.tr

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ABSTRACT: *Rhododendron ponticum* L. is a native evergreen ornamental shrub with considerable potential for landscape use and container production. Achieving compact, marketable plants while maintaining overall plant quality is an important production objective. Although the growth-regulating effects of paclobutrazol (PBZ) have previously been reported in rhododendrons, most studies have focused on PBZ concentration or single application methods, whereas comparative evaluation of practical application strategies under container production has received relatively little attention. Therefore, this study compared five PBZ application strategies, namely root dip, substrate drench, foliar spray, substrate drench with manual pinching, and foliar spray with manual pinching, each applied at five PBZ concentrations (0, 1.25, 2.5, 5.0, and 10.0 mg L⁻¹), in container-grown *Rhododendron ponticum*. Plant height, leaf number, leaf length, stem diameter, and floral bud occurrence were evaluated. Application strategy significantly affected plant height, leaf number and leaf length, whereas PBZ concentration and the application strategy × concentration interaction were significant only for leaf length. Effect-size estimates indicated larger application-strategy effects than PBZ-concentration effects for plant height, leaf number, and stem diameter, whereas leaf length also showed substantial concentration and interaction effects. Plant height ranged from 2.27 to 6.63 cm, while stem diameter ranged from 1.67 to 4.03 mm. Floral buds were present in all non-pinched substrate drench treatments, with 100% occurrence at 0–5.0 mg L⁻¹ and 67% occurrence at 10.0 mg L⁻¹, but were absent from all treatments combining foliar spray with manual pinching. Principal component analysis (PCA) explained 56.9% of the total variation and separated the evaluated treatments according to their morphological responses. Overall, application strategy was the dominant source of variation for several vegetative traits, while leaf length showed a more complex response involving both PBZ concentration and the application strategy × concentration interaction. Among the evaluated strategies, substrate drench without manual pinching provided the most favourable balance between vegetative growth control and floral bud occurrence, suggesting that this strategy may represent an effective approach for producing high-quality container-grown *Rhododendron ponticum*.

KEYWORDS: *Rhododendron ponticum*; paclobutrazol; plant growth regulator; manual pinching; ornamental quality

1 Introduction

Container-grown ornamental shrubs constitute an important segment of the nursery industry because they can be produced and marketed throughout the year, transported efficiently, and used directly in urban landscapes, gardens, and interior or exterior planting schemes [1–4]. Their commercial value depends

on both flowering performance and plant form. Compact, uniform, and well-proportioned plants are generally preferred, whereas excessive shoot elongation reduces visual quality, increases space requirements during production and transport, and may necessitate repeated pruning before marketing [5,6]. Therefore, growth management practices that restrict excessive vegetative development without reducing ornamental performance are essential in container nursery production.

Species of the genus *Rhododendron* are among the most valuable woody ornamentals because of their evergreen foliage, attractive flowers, long ornamental period, and adaptability to different landscape conditions [7–9]. Native *Rhododendron* species also represent important genetic resources for breeding, conservation, and the development of plant material adapted to regional environmental conditions [9]. *Rhododendron ponticum* L., naturally distributed in the Black Sea region, has considerable potential as a container-grown ornamental shrub. Under restricted container conditions, however, vigorous shoot extension may result in elongated and uneven plants, reducing visual balance and increasing the need for corrective pruning during production.

Paclobutrazol (PBZ) is a triazole-type growth retardant widely used to control shoot elongation in ornamental crops. It restricts gibberellin biosynthesis, thereby reducing cell elongation and internode extension [10–12]. Depending on species, dose, and application method, PBZ may also influence stem development, biomass distribution, water relations, and flowering responses [11–13]. The growth-regulating effects of PBZ in rhododendrons have been documented since the early 1990s. Studies have shown that PBZ can reduce shoot growth and modify flowering in different *Rhododendron* cultivars, although the magnitude and persistence of these responses vary according to cultivar, concentration, developmental stage, and application method [14–16].

The route of PBZ application is particularly important because it affects absorption, movement within the plant, and the duration of growth control. Substrate drench treatments generally provide sustained root uptake, whereas foliar sprays may produce more variable responses because their effectiveness depends on leaf surface characteristics and environmental conditions during application [13,17]. Application to rooted cuttings before transplanting may also provide residual growth control after plants are transferred to larger containers [16]. Despite these differences, previous studies on *Rhododendron* have largely focused on concentration responses or individual application techniques rather than comparing several commercially applicable application strategies under the same production conditions [14–16].

Manual pinching is another common nursery practice used to remove apical dominance and modify subsequent shoot development. Its effects on vegetative growth and flowering have been investigated in several ornamental species, either alone or in combination with growth retardants [18–21]. In *Rhododendron* and azalea, removal of the shoot apex has been shown to promote lateral shoot development and to be associated with changes in endogenous hormones involved in apical dominance [22]. GA-inhibiting growth regulators such as PBZ, on the other hand, restrict shoot elongation and may also influence subsequent floral development, with responses depending on treatment conditions and plant developmental stage [23,24]. Thus, combining pinching with PBZ may modify both shoot architecture and floral development, rather than simply producing an additive reduction in plant size. However, combining manual pinching with PBZ does not necessarily improve all components of ornamental quality. Greater restriction of shoot growth may be accompanied by delayed or reduced reproductive development, depending on the timing of pinching and the stage of floral initiation. Therefore, for commercial *Rhododendron* production, the smallest plant is not necessarily the most desirable; rather, the practical objective is to obtain adequate compactness while maintaining floral buds and subsequent flowering potential.

Comparative information on commercially applicable PBZ application strategies for container-grown *Rhododendron ponticum* remains limited, particularly regarding their ability to balance vegetative growth regulation with floral bud development. Addressing this knowledge gap is important for identifying practical growth management strategies that improve ornamental quality under container production conditions. Therefore, this study aimed (1) to evaluate the morphological responses of container-grown *R. ponticum* to five PBZ application strategies across a concentration gradient of 0–10 mg L⁻¹ and (2) to identify the strategy that provides the most favorable balance between compact plant form and floral bud occurrence under greenhouse conditions.

2 Materials and Methods

2.1 Plant Material and Growing Conditions

The experiment was conducted under greenhouse conditions from March to November 2025 at the Faculty of Agriculture, Recep Tayyip Erdoğan University, Rize, Türkiye. The rooted cuttings used in this study were derived from multiple mother plants originating from three naturally occurring populations of *Rhododendron ponticum* L. in Rize Province, Eastern Black Sea region, Türkiye. Cuttings were collected from these natural populations in November 2023 and used to establish rooting experiments. Successfully rooted cuttings obtained from these experiments were subsequently used as plant material for the present PBZ experiment conducted in 2025. The three source populations were Hoşdere, Ardeşen (41°06′39.078″ N, 41°01′55.409″ E; 508 m a.s.l.), Derecik Village, Çayeli (40°59′15.9″ N, 40°41′38.1″ E; 460 m a.s.l.), and Akpınar, Hemşin (41°02′46.682″ N, 40°54′36.991″ E; 494 m a.s.l.). Prior to treatment application, only healthy and morphologically uniform rooted cuttings of comparable size and developmental stage were selected. Rooted cuttings showing weak growth or markedly different development were excluded. The selected plants were then randomly assigned to the treatment groups to reduce variation in the initial plant material.

Rooted cuttings were transplanted into 2 L plastic pots containing a 2:1 (v/v) mixture of TS 4 Ericaceous + GreenFibre (Recipe 254; Klasmann-Deilmann GmbH, Germany) and horticultural-grade perlite. According to the manufacturer's specifications, the commercial substrate had a pH (H₂O) of 4.8 and contained no starter fertilizer. No supplemental fertilizer was applied during the experimental period. All plants were grown in the same substrate mixture and maintained under the same cultivation conditions throughout the experiment. Plants were grown in a polyethylene-covered greenhouse under natural photoperiod conditions. The mean daily air temperature inside the greenhouse ranged from 15 to 22°C, and relative humidity ranged from 60% to 75%. Environmental conditions were monitored continuously using HOBO data loggers (Onset Computer Corporation, Bourne, MA, USA). Plants were manually irrigated approximately every 2–3 days to maintain the substrate near field capacity.

2.2 Experimental Design and Treatments

The experiment was arranged as a split-plot design with three blocks (replications). Within each block, the five PBZ application strategies were assigned to five main plots because the strategies required different application procedures. Each main plot was divided into five subplots corresponding to the five PBZ concentrations (0, 1.25, 2.5, 5.0, and 10.0 mg L⁻¹). Each subplot consisted of five plants and constituted one experimental unit. Thus, each block contained 25 experimental units (125 plants), and the entire experiment comprised 75 experimental units and 375 plants. The five application strategies were randomized among the main plots within each block, and the five PBZ concentrations were independently randomized among the subplots within each main plot.

Five PBZ application strategies were evaluated: root dip (RD), substrate drench (SD), foliar spray (FS), substrate drench combined with manual pinching (SD+P), and foliar spray combined with manual pinching (FS+P). Each strategy was tested at 0, 1.25, 2.5, 5.0, and 10.0 mg L⁻¹ PBZ, resulting in 25 treatment combinations. Each experimental unit consisted of five plants; thus, each treatment combination included 15 plants across the three replications.

The strategies represented nursery practices differing in PBZ uptake route and canopy management. This design enabled direct comparison of complete production programmes rather than PBZ concentration alone.

2.3 PBZ Application Strategies

Root-dip treatments were applied in March 2025, immediately before transplanting. The SD, SD+P, FS, and FS+P treatments were applied approximately 30–35 days after transplanting, in April 2025, when the plants had reached the 5–6-leaf stage.

Root Dip (RD): Before transplanting, the root systems of rooted cuttings were immersed completely in PBZ solutions for 3.5 h. This exposure period falls within the range of prolonged PBZ immersion periods previously evaluated in cutting material, including woody cuttings [25–27]. Cuttings were transplanted immediately after treatment.

Substrate Drench (SD): At the 5–6-leaf stage, 50 mL of PBZ solution was applied directly to the substrate surrounding each non-pinched plant.

Substrate Drench with Manual Pinching (SD+P): Plants were pinched at the 5–6-leaf stage, leaving four basal leaves. PBZ solution was then applied as a substrate drench.

Foliar Spray (FS): At the 5–6-leaf stage, PBZ solution was sprayed uniformly onto the adaxial and abaxial leaf surfaces of non-pinched plants until runoff during the early morning.

Foliar Spray with Manual Pinching (FS+P): Plants were pinched as described for SD+P, after which PBZ solution was applied immediately as a foliar spray until runoff.

PBZ Concentrations: Paclobutrazol (Cultar 250 g L⁻¹ SC; Syngenta) was diluted with distilled water to prepare solutions containing 0, 1.25, 2.5, 5.0, or 10.0 mg L⁻¹ PBZ. Tween 20 (0.1%, v/v) was added only to foliar spray solutions as a non-ionic surfactant. For the 0 mg L⁻¹ treatments, the same application procedures were followed without PBZ. Root-dip control plants were immersed in distilled water for 3.5 h, while substrate-drench controls received 50 mL of distilled water. Foliar-spray controls were treated with distilled water containing 0.1% (v/v) Tween 20 until runoff. For the SD+P and FS+P controls, plants were manually pinched as described above and then received the respective PBZ-free drench or foliar-spray treatment.

2.4 Data Collection

Morphological evaluations were performed 12 weeks after PBZ application using all plants within each experimental unit. Plant height (cm) was measured vertically from the substrate surface to the highest point of the plant canopy. Because several leaves were horizontally or obliquely oriented, this vertical plant-height measurement was independent of individual leaf length; consequently, leaf length could exceed plant height. Stem diameter (mm) was measured at the basal portion of the main stem with a digital caliper. Leaf number was determined by counting all fully expanded leaves per plant. Leaf length (cm) was measured on three fully expanded leaves selected from the middle portion of each plant, and the mean was used for analysis. Floral bud occurrence was expressed as the percentage of plants bearing at least one visible floral bud in each experimental unit. Floral buds were distinguished from vegetative buds by their rounded, swollen morphology.

2.5 Statistical Analysis

Data were analyzed by analysis of variance (ANOVA) for a split-plot design using JMP software (Version 13.0; SAS Institute Inc., Cary, NC, USA). Replication was included as a random effect, application strategy as the main-plot factor, PBZ concentration as the subplot factor, and their interaction as fixed effects. Application strategy was tested against the whole-plot error term (replication $\times$ application strategy), whereas PBZ concentration and the application strategy $\times$ PBZ concentration interaction were tested against the subplot residual error. When significant differences were detected, means were compared using the least significant difference (LSD) test at $p \leq 0.05$. For application strategy, comparisons were made among the overall means of the five strategies. When the interaction between application strategy and PBZ concentration was significant, PBZ concentrations were compared separately within each application strategy. To compare the magnitude of treatment effects, partial eta-squared (η^2) was calculated from the F statistic and its numerator and denominator degrees of freedom (df) as $\eta^2 = (F \times df_1) / [(F \times df_1) + df_2]$. Pearson correlation analysis and principal component analysis (PCA) were performed using standardized trait data. Hierarchical clustering of standardized treatment means was conducted using Euclidean distance and Ward's linkage method. Floral bud occurrence was recorded as a binary variable (presence/absence) and is presented descriptively; therefore, no inferential statistical analysis was performed for this trait.

3 Results

3.1 Effects of PBZ Application Strategy and Concentration on Vegetative Growth

Application strategy significantly affected plant height, leaf number, and leaf length, whereas its effect on stem diameter was not significant ($p = 0.0517$). PBZ concentration significantly affected only leaf length and the application strategy $\times$ PBZ concentration interaction was also significant only for leaf length (Table 1). Effect-size estimates supported the ANOVA results. Application strategy showed larger partial eta-squared values than PBZ concentration for plant height ($\eta^2 = 0.801$ vs. 0.101), leaf number ($\eta^2 = 0.681$ vs. 0.125), and stem diameter ($\eta^2 = 0.654$ vs. 0.054). For leaf length, application strategy also showed a large effect ($\eta^2 = 0.728$), while PBZ concentration ($\eta^2 = 0.390$) and the application strategy $\times$ concentration interaction ($\eta^2 = 0.554$) also showed substantial effects.

Table 1: Effects of paclobutrazol application strategy and concentration on vegetative growth and floral bud occurrence of container-grown *Rhododendron ponticum* L.

Application Strategy	PBZ (mg L ⁻¹)	Plant Height (cm)	Leaf Number (plant ⁻¹)	Leaf Length (cm)	Stem Diameter (mm)	Floral Bud Occurrence (%)
Root dip	0.00	6.10a	4.00a	8.33a	1.93a	100
	1.25	5.27a	5.33a	7.33ab	2.47a	100
	2.50	5.20a	6.00a	8.70a	2.87a	0
	5.00	5.47a	5.00a	7.47ab	2.93a	0
	10.00	4.70a	3.67a	6.13b	3.00a	0
Substrate drench (without pinching)	0.00	3.93a	3.67a	9.03ab	3.97a	100
	1.25	6.63a	4.00a	9.53a	2.53a	100
	2.50	5.20a	5.00a	7.10c	3.63a	100
	5.00	5.13a	4.00a	8.03bc	2.67a	100
	10.00	3.57a	6.00a	8.27abc	4.03a	67
Foliar spray (without pinching)	0.00	4.97ab	5.33a	6.37b	2.00a	100
	1.25	3.47ab	3.67a	9.60a	2.23a	100
	2.50	4.30ab	4.67a	6.73b	1.67a	67
	5.00	4.50ab	4.33a	6.70b	2.90a	100
	10.00	3.93ab	4.67a	6.17b	2.24a	67

Table 1: Cont.

Application Strategy	PBZ (mg L ⁻¹)	Plant Height (cm)	Leaf Number (plant ⁻¹)	Leaf Length (cm)	Stem Diameter (mm)	Floral Bud Occurrence (%)
Substrate drench + manual pinching	0.00	3.10b	3.00a	7.00b	2.37a	67
	1.25	3.07b	3.67a	8.53a	2.87a	0
	2.50	4.13b	4.67a	6.80b	2.87a	0
	5.00	2.47b	3.67a	7.10b	3.00a	0
	10.00	2.63b	3.67a	7.13ab	2.83a	0
Foliar spray + manual pinching	0.00	3.50b	3.33a	6.97a	2.73a	0
	1.25	3.40b	4.33a	6.53a	3.07a	0
	2.50	3.07b	3.33a	6.77a	2.87a	0
	5.00	2.27b	4.00a	5.73a	2.60a	0
	10.00	3.53b	3.67a	6.93a	2.87a	0
Application-Strategy Means						
Application Strategy	Plant Height (cm)		Leaf Number (plant ⁻¹)		Stem Diameter (mm)	
Root dip	5.35a		4.80a		2.64a	
Substrate drench (without pinching)	4.89a		4.53a		3.37a	
Foliar spray (without pinching)	4.23ab		4.53a		2.21a	
Substrate drench + manual pinching	3.08b		3.73b		2.79a	
Foliar spray + manual pinching	3.15b		3.73b		2.83a	
LSD ($p \leq 0.05$)	1.17		0.79		—	
Source of Variation	df	Plant Height	Leaf Number	Leaf Length	Stem Diameter	
Application strategy	4	8.03**	4.27*	5.35*	3.78ns	
Whole-plot error (replication $\times$ application strategy)	8	—	—	—	—	
PBZ concentration	4	1.12ns	1.43ns	6.41***	0.57ns	
Application strategy $\times$ PBZ concentration	16	1.30ns	1.66ns	3.11**	0.99ns	
Subplot residual error	40	—	—	—	—	

Note: Different letters indicate significant differences according to the LSD test ($p \leq 0.05$). For plant height and leaf number, letters compare application-strategy means; for leaf length, letters compare PBZ concentrations within each application strategy (LSD = 1.41). No significant differences were detected for stem diameter. Values presented for the measured traits in the ANOVA table are F-ratios. * $p \leq 0.05$, ** $p \leq 0.01$, and *** $p \leq 0.001$; ns, not significant. Floral bud occurrence was evaluated descriptively. PBZ: Paclobutrazol, df: degrees of freedom.

Representative plant responses are shown in Fig. 1.

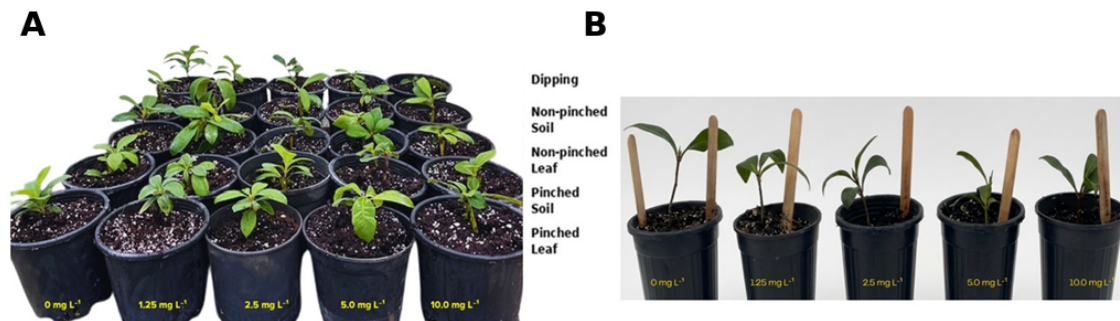


Figure 1: Representative responses of container-grown *Rhododendron ponticum* to PBZ application strategies and concentrations at the end of the study (November 2025). (A) Plant responses to PBZ concentrations of 0, 1.25, 2.5, 5.0, and 10.0 mg L⁻¹. (B) Plants subjected to the five PBZ application strategies.

Plant height ranged from 2.27 to 6.63 cm. The tallest plants occurred with substrate drench without pinching at 1.25 mg L⁻¹, whereas the shortest plants occurred with foliar spray plus manual pinching at 5.0 mg L⁻¹. No consistent concentration-dependent pattern was observed for plant height.

Leaf number ranged from 3.00 to 6.00 leaves per plant. The highest values occurred with root dip at 2.5 mg L⁻¹ and substrate drench without pinching at 10.0 mg L⁻¹, whereas the lowest value occurred in

the untreated substrate-drench-plus-pinching treatment. Application strategy was significant, but PBZ concentration was not.

Leaf length was the only trait significantly affected by PBZ concentration and by the application strategy $\times$ concentration interaction. The greatest leaf length (9.60 cm) occurred with foliar spray without pinching at 1.25 mg L⁻¹, followed by substrate drench without pinching at the same concentration (9.53 cm). The shortest leaves (5.73 cm) occurred with foliar spray plus manual pinching at 5.0 mg L⁻¹.

Stem diameter ranged from 1.67 to 4.03 mm. The greatest value occurred with substrate drench without pinching at 10.0 mg L⁻¹, whereas the smallest value occurred with foliar spray without pinching at 2.5 mg L⁻¹. Neither application strategy nor PBZ concentration significantly affected stem diameter.

Floral bud occurrence differed clearly among application strategies. In the root-dip treatment, floral buds were present in all plants at 0 and 1.25 mg L⁻¹, but were absent at concentrations of 2.5 mg L⁻¹ and above. In contrast, substrate drench without pinching maintained 100% floral bud occurrence from 0 to 5.0 mg L⁻¹, with 67% occurrence at 10.0 mg L⁻¹. Foliar spray without pinching showed a more variable response, whereas no floral buds occurred in any treatment combining foliar spray with manual pinching.

3.2 Principal Component Analysis

The first two principal components explained 56.9% of the total variation, with PC1 accounting for 34.7% and PC2 for 22.2% (Fig. 2). Plant height, floral bud occurrence, leaf length, and leaf number were positively associated with PC1, whereas stem diameter was more strongly associated with PC2. Treatments containing manual pinching were generally positioned on the negative side of PC1, consistent with lower plant height and floral bud occurrence. Substrate drench without pinching was associated with greater stem diameter and floral bud occurrence.

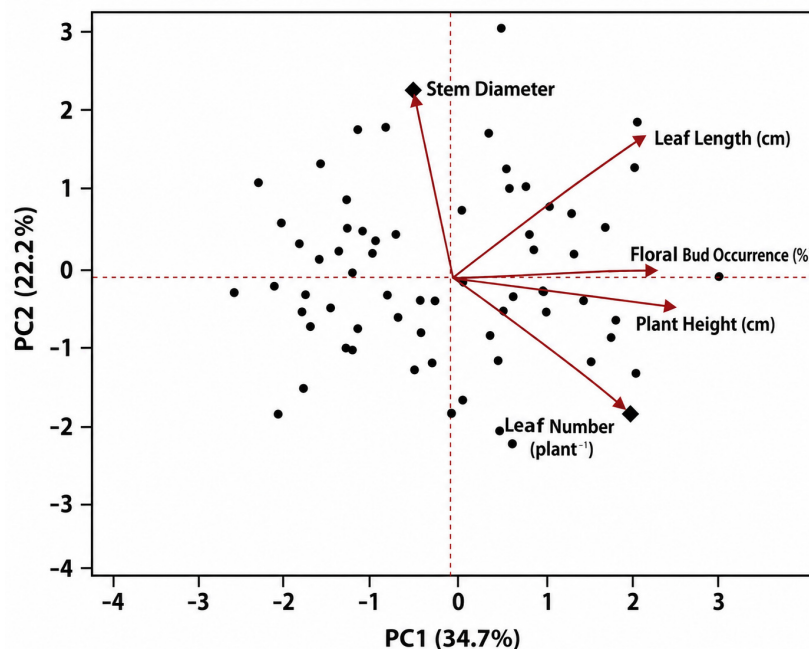


Figure 2: Principal component analysis biplot showing relationships among measured traits and PBZ treatment combinations. PC1, principal component 1; PC2, principal component 2.

3.3 Correlation and Hierarchical Clustering Analyses

Pearson correlation analysis showed positive relationships among plant height, leaf number, leaf length, and floral bud occurrence. Plant height was correlated with leaf number ($r = 0.364$), leaf length ($r = 0.303$), and floral bud occurrence ($r = 0.315$). Leaf number was correlated with leaf length ($r = 0.354$) and floral bud occurrence ($r = 0.336$), while leaf length showed a moderate positive correlation with floral bud occurrence ($r = 0.414$).

Stem diameter showed weak correlations with plant height ($r = 0.095$), leaf number ($r = -0.097$), leaf length ($r = 0.109$), and floral bud occurrence ($r = 0.079$). The hierarchical clustering heatmap suggested that treatment combinations tended to group primarily according to application strategy, although partial overlap among application strategies was observed across PBZ concentrations (Fig. 3).

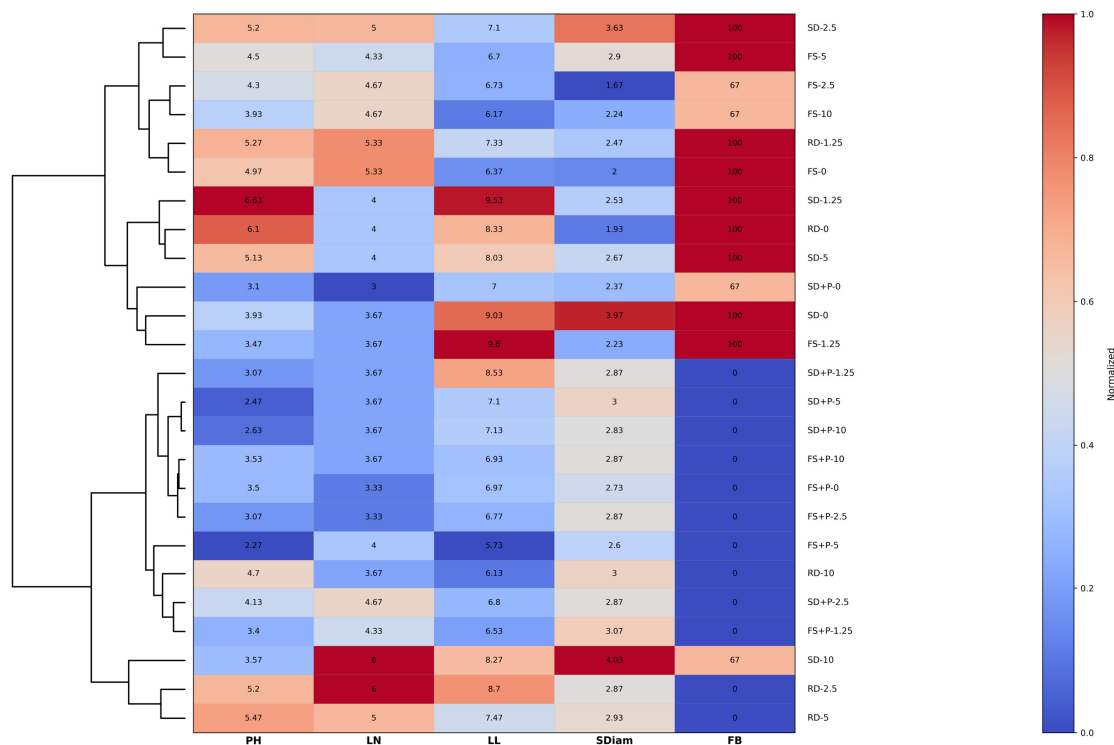


Figure 3: Hierarchical clustering heatmap of morphological traits in container-grown *Rhododendron ponticum* under different PBZ application strategies and concentrations. Cell values represent treatment means, and colours indicate standardized values. Hierarchical clustering was performed using Euclidean distance and Ward's linkage method. RD, root dip; SD, substrate drench; FS, foliar spray; SD+P, substrate drench + pinching; FS+P, foliar spray + pinching. PH, plant height; LN, leaf number; LL, leaf length; SDiam, stem diameter; FB, floral bud occurrence.

4 Discussion

Producing compact, floriferous and visually balanced container-grown shrubs remains one of the principal objectives of modern ornamental nursery production because plant architecture directly influences production efficiency, transportation, post-production handling and commercial value. In woody ornamentals, excessive vegetative growth reduces canopy symmetry, increases pruning requirements and limits market quality, whereas excessive growth suppression may adversely affect flowering and overall ornamental performance. Consequently, the objective of chemical growth regulation is not simply to minimize shoot elongation but to achieve an appropriate balance between vegetative compactness and

reproductive development. Paclobutrazol (PBZ), a triazole-derived growth regulator, has therefore become one of the most extensively used compounds for controlling plant architecture because it inhibits gibberellin biosynthesis, restricts cell elongation and modifies several developmental processes including branching, stem development and flowering [10,11,28,29]. Numerous investigations have demonstrated the effectiveness of PBZ in ornamental and woody species; however, the magnitude and persistence of its effects vary considerably according to species, developmental stage, substrate characteristics, environmental conditions and, importantly, the method of application [13,17,30]. Recent work in woody seedlings further shows that PBZ-based growth-retardant treatments can markedly alter plant architecture and biomass allocation, underscoring the continued relevance of PBZ for growth regulation in woody plant production [31].

Among ericaceous ornamentals, *Rhododendron* species are particularly valuable because of their evergreen foliage, attractive floral display and extensive landscape use. Nevertheless, vigorous shoot elongation frequently reduces plant compactness during container production, making growth regulation an important cultural practice. Early studies demonstrated that PBZ effectively reduced shoot extension and altered flower development in *Rhododendron* cultivars, although treatment responses depended on cultivar, concentration and application timing [14–16,32]. Despite these important contributions, previous investigations generally focused on individual application methods or concentration responses, whereas direct comparisons among commercially applicable strategies, including root dipping, substrate drenching, foliar spraying and combinations with manual pinching, remain scarce. The present study extends previous research by evaluating these practical nursery strategies simultaneously. Partial eta-squared estimates indicated that application strategy had a larger effect than PBZ concentration on plant height, leaf number, and stem diameter. Leaf length differed from this general pattern: although application strategy showed a large effect, PBZ concentration and particularly the application strategy $\times$ concentration interaction also had substantial effects. These results indicate that the relative importance of application strategy and concentration was trait dependent rather than uniform across all vegetative responses.

Previous studies have shown that root-absorbed PBZ is transported mainly through the xylem and can inhibit gibberellin biosynthesis in actively growing tissues. Substrate drench application may provide more persistent exposure through continued root absorption, whereas the response to foliar application depends on factors such as droplet retention and cuticular penetration [10,11,13,17]. These differences may help explain why the same PBZ concentration can produce different responses depending on the application strategy. However, PBZ uptake, transport, and endogenous hormone levels were not measured in the present study. In our study, plant height did not decrease consistently with increasing PBZ concentration. Under substrate drench, for example, plant height increased from 3.93 cm in the control to 6.63 cm at 1.25 mg L⁻¹ PBZ. Since the overall effect of PBZ concentration on plant height was not significant, this difference should not be interpreted as a growth-promoting effect of PBZ and may instead reflect variation among plants. A clear dose-dependent reduction in plant height is not always observed with PBZ, and increasing the concentration beyond a certain level may produce little or no further reduction in plant height [11,15].

The responses of leaf development further demonstrate that the physiological effects of PBZ cannot be explained solely by changes in stem elongation. Although leaf number differed significantly among application strategies, PBZ concentration alone did not consistently influence leaf production, indicating that the evaluated treatments affected leaf initiation to a much lesser extent than vegetative extension. This observation agrees with previous reports showing that triazole growth regulators predominantly suppress cell elongation while having relatively limited effects on organ initiation, thereby allowing acceptable canopy density to be maintained even in compact plants [5,10,11]. Similar responses have been reported

in calendula and herbaceous peony, and have also been summarized across ornamental crops [12,33,34]. For container-grown ornamental shrubs, preservation of foliage density is commercially advantageous because compact plants with well-developed canopies generally possess greater aesthetic value than plants exhibiting severe vegetative suppression accompanied by sparse foliage.

Unlike leaf number, leaf length was significantly influenced by both PBZ concentration and the interaction between concentration and application strategy, demonstrating that leaf expansion was considerably more sensitive to differences in PBZ uptake. Since final leaf size is determined primarily by cell expansion rather than cell initiation, reductions in endogenous gibberellin activity are expected to influence leaf elongation more directly than leaf production [10,11]. The present findings therefore agree well with the established physiological mode of action of PBZ. Nevertheless, the significant interaction observed for leaf length indicates that increasing PBZ concentration alone does not adequately explain treatment responses. Instead, concentration effects varied among application strategies. Differences in absorption efficiency and persistence between substrate drench and foliar PBZ applications reported in previous studies may help explain this pattern [13,17], although PBZ uptake and persistence were not measured in the present study.

Stem diameter responded differently from the remaining vegetative characteristics. Although some variation was observed among application strategies, the effect was not statistically significant ($p = 0.0517$). PBZ concentration and the interaction between concentration and strategy were also not significant. Similar observations have been reported in numerous woody ornamentals where PBZ effectively restricted shoot elongation without proportionally reducing radial stem growth [10–12]. In some species, PBZ has even been associated with increased stem thickness due to reduced longitudinal growth and redistribution of assimilates towards radial development [27,30]. Maintenance of adequate stem diameter is particularly important for container-grown shrubs because stronger stems improve resistance to mechanical damage during handling, transportation and retail display. Therefore, application strategies that simultaneously restrict excessive shoot elongation while maintaining stem robustness provide greater commercial value than treatments producing extremely compact but structurally weaker plants.

Among all measured characteristics, floral bud occurrence represents the most important criterion from a commercial perspective because the market value of flowering shrubs ultimately depends on reproductive performance rather than vegetative compactness alone. Floral bud occurrence differed markedly among application strategies. In the root-dip treatment, floral buds were present in all plants at 0 and 1.25 mg L⁻¹, but were absent at 2.5 mg L⁻¹ and higher concentrations. In contrast, substrate-drenched plants maintained 100% floral bud occurrence from 0 to 5.0 mg L⁻¹, and floral buds were still present in 67% of plants at 10.0 mg L⁻¹. This contrasting response suggests that the effect of PBZ on floral bud development depended not only on concentration but also on the application method. No floral buds were observed in plants receiving foliar spray together with manual pinching, further showing that greater vegetative growth restriction was not necessarily associated with better reproductive performance. Previous studies in rhododendrons have similarly shown that the effects of PBZ on growth and flowering vary with application method, concentration, and treatment conditions [14–16]. Previous studies have also suggested a relationship between triazole growth regulators and floral development [11,12], but the physiological basis of this response was not examined in the present study.

The contrasting reproductive responses observed among application strategies may largely reflect differences in PBZ availability throughout the production period. Root-applied PBZ remains available within the substrate and is absorbed continuously by developing roots, thereby providing relatively stable growth regulation over an extended period. Conversely, foliar applications rely on a single uptake event and are influenced by leaf morphology, spray coverage, cuticular permeability and environmental conditions

during application [13,17]. These differences in PBZ uptake may help explain the contrasting floral bud responses among application strategies [10,16]. However, the underlying physiological changes were not measured in the present study, so this interpretation should be regarded as a possible explanation rather than a demonstrated mechanism.

The complete absence of floral buds following foliar spray combined with manual pinching deserves particular attention. The timing of pinching may have contributed to this response. If pinching coincided with, or occurred close to, floral bud initiation, removal of the shoot apex and the subsequent development of lateral shoots could have affected floral bud formation. Similar effects of pinching on shoot development have been reported in other ornamental species [18–20]. Foliar PBZ application may also have contributed to the observed response. Previous studies have associated PBZ responses with changes in endogenous growth regulators [11,12], but hormone levels were not measured in the present study. In addition, pinching was included as part of the combined application strategy rather than tested as an independent factor. Therefore, the individual contributions of pinching timing, foliar PBZ application, and possible hormonal changes cannot be separated from the present data. These explanations should be regarded as possible mechanisms rather than confirmed causes. Further studies examining floral initiation over time together with endogenous hormone levels would help clarify why floral buds were absent under FS+P.

The multivariate analyses provided an integrated interpretation of the relationships among the measured morphological characteristics and further strengthened the conclusions derived from the univariate analyses. Principal component analysis (PCA) successfully summarized the overall variation among treatments, with the first two principal components explaining more than half of the total variability observed in the dataset. This indicates that the selected morphological variables adequately described the major treatment responses and confirms that plant architecture in container-grown *Rhododendron ponticum* is governed by the combined interaction of multiple vegetative and reproductive traits rather than by a single morphological parameter. Similar applications of PCA in ornamental horticulture have demonstrated its value for reducing complex morphological datasets into biologically meaningful components, facilitating identification of the traits contributing most strongly to treatment discrimination [35,36].

The PCA biplot showed that plant height, leaf length, and floral bud occurrence loaded positively on PC1, whereas stem diameter was more strongly associated with PC2. Thus, the first two components distinguished variation in stem diameter from the pattern represented by plant height, leaf length, and floral bud occurrence. This finding has important practical implications because it demonstrates that the most compact plants were not necessarily those exhibiting the greatest flowering potential. Similar trade-offs between vegetative growth suppression and reproductive performance have previously been reported in rhododendrons and other woody ornamentals treated with triazole growth regulators [12,14,16]. Consequently, growth management of container-grown rhododendrons should focus on maintaining a suitable balance between compact growth and flowering rather than simply maximizing growth suppression. In azalea, compact and well-branched plants with satisfactory flowering are considered desirable quality characteristics [37]. Commercial quality standards for azalea also consider characteristics such as bud distribution, flowering stage, and general appearance [38]. The morphological traits and floral-bud occurrence measured in this study therefore provide useful information on these commercially relevant characteristics, although they do not cover all aspects of ornamental quality. Additional measurements, including biomass allocation, chlorophyll content, and standardized assessments of phytotoxicity and overall ornamental quality, could be included in future studies.

Pearson correlation analysis showed weak-to-moderate positive relationships among plant height, leaf number, and leaf length ($r = 0.303\text{--}0.364$). Comparable relationships among vegetative traits have

been reported in woody ornamental plants treated with growth regulators [5,10,30]. In the present study, the correlations describe statistical associations only and do not establish a hormonal basis for those relationships. Floral bud occurrence was also positively correlated with the vegetative traits, although the coefficients were only moderate ($r = 0.315\text{--}0.414$). Therefore, none of these traits alone showed a close relationship with floral bud occurrence. The moderate correlations indicate that floral bud occurrence was not closely associated with any single vegetative trait measured in this study. Because endogenous hormones and carbohydrate status were not measured, their possible contribution cannot be evaluated from the present data. Stem diameter showed only weak correlations with the other traits ($r = 0.079\text{--}0.109$). Taken together, the correlations indicate that vegetative growth and floral bud occurrence were related to some extent, but vegetative compactness alone did not adequately reflect floral bud occurrence.

The heatmap analysis complemented both PCA and Pearson correlation by illustrating treatment-dependent clustering of morphological responses. Treatments sharing similar application strategies tended to cluster more closely than treatments receiving similar PBZ concentrations, indicating that application method contributed to the overall pattern of treatment responses. Such clustering patterns have frequently been reported in multivariate analyses of horticultural experiments because integrated responses generally reflect simultaneous changes in several correlated traits rather than isolated variation in individual variables [3,31,32]. The multivariate analyses were generally consistent with the treatment patterns observed in the univariate analyses.

Collectively, the findings of this study indicate that successful PBZ use in container-grown *Rhododendron ponticum* should not be evaluated solely according to reductions in plant height. These observations agree with previous studies emphasizing that optimization of PBZ application requires consideration of uptake dynamics, plant developmental stage and production objectives rather than concentration alone [12,13,16,17].

To our knowledge, relatively few studies have simultaneously compared root dipping, substrate drenching, foliar spraying and integrated pinching strategies within a single experimental framework for container-grown *Rhododendron ponticum*. Future studies incorporating endogenous hormone profiling, carbohydrate dynamics and molecular analyses of floral induction would further clarify the physiological mechanisms responsible for the contrasting responses observed among application strategies.

These findings provide practical information on the morphological and floral-bud responses of container-grown *R. ponticum* to the evaluated PBZ application strategies and concentrations. Overall, the present findings show that responses to PBZ were associated with both application strategy and concentration, with their relative contributions varying among traits. Effect-size estimates indicated a larger contribution of application strategy than PBZ concentration alone to the measured vegetative traits, while the strategy $\times$ concentration interaction was particularly important for leaf length. These results emphasize the need to consider application method, concentration, and their interaction when developing PBZ management practices for container-grown *R. ponticum*. Further studies across multiple growing seasons would be valuable to determine whether the relative responses to PBZ application strategies observed in this study remain consistent under different seasonal conditions.

5 Conclusion

Paclobutrazol effectively regulated vegetative growth in container-grown *Rhododendron ponticum*. However, plant responses varied with application strategy and concentration. Partial eta-squared estimates showed larger application-strategy effects than PBZ-concentration effects for plant height, leaf number,

and stem diameter. Leaf length showed a more complex response, with substantial effects of application strategy, PBZ concentration, and their interaction.

Clear differences were also observed in floral bud occurrence. Substrate drench without manual pinching maintained floral buds across all PBZ concentrations, with 100% occurrence up to 5.0 mg L⁻¹ and 67% at 10.0 mg L⁻¹. In contrast, no floral buds were observed when foliar spray was combined with manual pinching. This shows that greater growth suppression was not necessarily accompanied by better flowering performance. Among the strategies tested, substrate drench without pinching gave a favourable balance between vegetative growth control and floral bud occurrence.

Within the PBZ concentration range evaluated in this study (0–10 mg L⁻¹), the findings indicate that application strategy, concentration, and their interaction should be considered together when PBZ is used for growth regulation in container-grown *R. ponticum*.

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