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PACLOBUTRAZOL AND ITS IMPACT ON GROWTH AND PHYSIOLOGY IN VARIOUS CROPS : A REVIEW

Kamrul Nissa*[1], Rajender Sharma[2], Narender Kumar Bharat[1], Devender Kumar Mehta[2] and Anubhav Thakur[1]
[1]Department of Seed Science Technology
[2]Department of Vegetable Science
Dr. Yashwant Singh Parmar University of Horticulture and Forestry,
Nauni, Solan, Himachal Pradesh-173230, India
*Corresponding author E-mail: kamrulnissa579@gmail.com
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ABSTRACT

Growth retardants are essential tools in modern agriculture and horticulture, helping regulate excessive vegetative growth, improve crop yield, enhance stress tolerance and optimize overall plant quality. Paclobutrazol (PBZ) is among the most extensively utilized synthetic growth retardants, recognized for its ability to regulate plant growth without interfering with developmental processes or causing phytotoxicity. This compound is chemically described as β-(4-chlorophenyl)methyl-α-(tert-butyl)-1H-1,2,4-triazole-1-ethanol. PBZ suppresses gibberellin biosynthesis by inhibiting the transformation of ent-kaurene into ent-kaurenoic acid leads to a significant reduction in shoot elongation. Moreover, It regulates the signaling pathways of other plant hormones, including cytokinins and abscisic acid, thereby further influencing plant growth and development. Paclobutrazol has been extensively studied for its diverse applications across various crops. In fruit crops, it restricts excessive vegetative growth, induces early flowering, enhances fruit set, manages biennial bearing and facilitates high-density planting systems. In vegetable and field crops, it reduces plant height, increases stress tolerance, enhances chlorophyll content, prevents lodging, minimizes disease incidence and improves seed yield and quality. In floricultural crops, it is primarily used for height control and increased plant compactness as well as enhancing their ornamental value. Given its wide-ranging benefits, paclobutrazol has emerged as a valuable growth regulator for improving plant architecture, productivity and stress resilience. However, its precise application rates and effects vary depending on crop species, environmental conditions and agronomic practices. This review compiles and analyzes research findings on the impact of paclobutrazol across multiple crop species, highlighting its role in sustainable agriculture and efficient crop management.
***Keywords* :** Paclobutrazol, Crop, Growth, Physiology.

Introduction

In India, plant growth retardants are used to a limited extent, whereas in many other countries, they have been incorporated as key elements in contemporary farming systems. The American Society for Horticultural Sciences identifies chemical growth regulation as one of the eight key research priorities in horticultural science. The development of several highly effective growth retardants in recent years has significantly enhanced the potential applications of chemical growth regulation in horticulture (Yadav *et al*., 2025). Synthetic substances called plant growth retardants shorten plant shoots without altering their developmental patterns or posing any phytotoxicity risks. This is mostly accomplished by decreasing cell elongation as well as decreasing the rate of cell division.

For the time being, plant growth inhibitors are categorized into four primary groups based on their modes of action. The first group comprises onium compounds, including chlormequat chloride, mepiquat chloride, chlorphonium and AMO-1618- which act initially on gibberellin (GA) biosynthesis by inhibiting cyclase enzymes such as copalyl diphosphate synthase and ent-kaurene synthase. The second group consists of nitrogen-containing heterocyclic compounds like ancymidol, flurprimidol, tetcyclacis, uniconazole-P, paclobutrazol and inabenfide. These function by obstructing cytochrome P450-dependent monooxygenases, thereby preventing the oxidation of ent-kaurene to ent-kaurenoic acid. The third category includes synthetic analogs of 2-oxoglutaric acid, notably acylcyclohexanediones such as prohexadione-Ca, trinexapac-ethyl and daminozide, which inhibit 3β-hydroxylase enzymes and consequently block the formation of bioactive gibberellins from their inactive precursors. The fourth group involves 16,17-dihydro-GA5 derivatives, which structurally resemble gibberellin precursors and are thought to competitively interfere with the same dioxygenase enzymes (Rademacher, 2000). Physiologically, these growth regulators primarily restrict vegetative expansion by reducing plant height, internodal growth, and leaf surface area, while concurrently intensifying chlorophyll content in leaves. Notably, they do not alter the number of internodes or leaves formed. Furthermore, they tend to stimulate root development, leading to an increased root-to-shoot biomass ratio (Tesfahun, 2018; Kuchenbuch and Jung, 1988).

Paclobutrazol (PBZ), a bioregulator was initially introduced in 1986 and brought to the market by ICI Agrochemicals, which later became a part of syngenta (Orozco-Melendez *et al.*, 2022). Paclobutrazol, a compound consisting of a β-(4-chlorophenyl) methyl group attached to an α-(1,1-dimethyl)-substituted 1H-1,2,4-triazole ring linked to an ethanol moiety is a major growth retardant which exists under multiple commercial names including PP 333, cultar, bonze, sadabahar, parley and clipper etc (Desta and Amare 2021). It has a molecular weight of 293.8, a chemical formula of $C_{15}H_{20}ClN_3O$, a melting point ranging from 165°C to 166°C, a density of 1.22 g per ml and a water solubility of 35 mg per L. It contains hydrophilic regions, making it partially polar while also displaying hydrophobic properties (Jiyang *et al.*, 2019).

PBZ is a non-polar molecule known for its broad-spectrum effects, primarily transported through the xylem, though its movement can also occur via the phloem depending on the method of application. The molecule contains two chiral centers (asymmetric carbons), resulting in two distinct pairs of enantiomers i.e. [(2R, 3R) & (2S, 3S)] and [(2S, 3R) & (2R, 3S)]. Of these stereoisomers, those with the 2S and 3S configurations exhibit greater efficacy in inhibiting gibberellin biosynthesis, while the 2R and 3R isomers degrade at a faster rate (Wu *et al.*, 2015). PBZ acts within the terpene biosynthetic pathway as illustrated in Figure- 1, by blocking the synthesis of gibberellins. Specifically, it targets and inhibits ent-kaurene oxidase, the enzyme responsible for converting ent-kaurene into ent-kaurenoic acid. This inhibition leads to increased activity of geranylgeranyl reductase and phytoene synthase, enzymes that play key roles in the biosynthesis of chlorophyll and abscisic acid, respectively (Luo *et al.*, 2019).

By restricting gibberellin production, paclobutrazol effectively regulates the growth of various horticultural crops. Due to its ability to inhibit shoot elongation even at relatively low concentrations, it is considered more potent than most other growth retardants. The most prominent physiological effects of paclobutrazol on plants include reduced height, decreased lodging, increased compactness, and enhanced greenery due to a higher chlorophyll concentration per unit leaf area, along with improved seed set (Gilley and Fletcher 1997). Widely recognized for its growth-inhibiting properties across various plant species, PBZ-treated plants typically exhibit a more compact and shorter stature. Additionally, PBZ induces morphological and anatomical modifications in leaves, which vary depending on factors such as species, developmental stage, rate of application as well as method of application (Sebastian *et al.*, 2002). Additionally, PBZ inhibits activity in the shoot apical meristem i.e., the region responsible for initiating leaf primordial by interfering with hormonal signals essential for cell division. Consequently, plants treated with PBZ develop stems that maintain the same number of internodes, but these internodes are shortened. Despite this reduction in length, cell division persists resulting in thicker stems (Fletcher *et al.* 2000), which may be attributed to the increased formation of palisade and spongy cell layers, as reported by Jaleel *et al.* (2007). PBZ application is also linked to a thicker layer of epicuticular wax in leaves (Jenks *et al.* 2001) and enlargement of epidermal, mesophyll as well as bundle sheath cells (Burrows *et al.*, 1992). In addition to reducing plant height, PBZ prevents lodging, enhances productivity, lowers evapo-transpiration and also mitigates moisture stress by increasing relative water content by optimizing leaf area

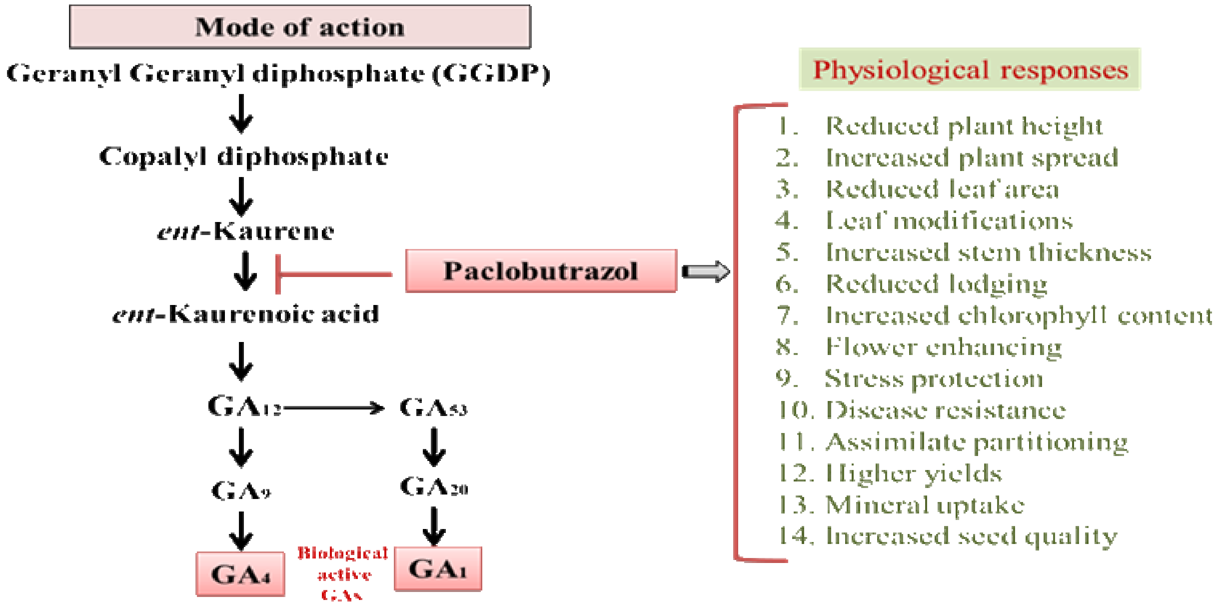

Fig. 1: Mode of action and physiological responses of paclobutrazol in various crops

Paclobutrazol (PBZ) influences both vegetative growth and flowering processes by modulating the balance of key plant hormones, including gibberellins (GAs), abscisic acid (ABA) and cytokinins (CKs). It exerts its effects through the isoprenoid biosynthetic pathway, where it inhibits the synthesis of gibberellins and simultaneously promotes increased cytokinin levels. The blockage of GA production causes precursor molecules in the terpenoid pathway to accumulate, which subsequently enhances the biosynthesis of ABA (Lal *et al.,* 2023). Elevated cytokinin concentrations contribute to increased chloroplast size and chlorophyll accumulation, and they also suppress apical dominance, leading to the proliferation of lateral shoots and a broader plant architecture. By restricting GA-mediated control of cell expansion, PBZ also supports continued chlorophyll synthesis, resulting in a greater chlorophyll density and a visibly greener leaf canopy compared to untreated controls. Additionally, the greening effect may be explained by the disruption of GGPP (geranylgeranyl pyrophosphate) conversion into ent-kaurene within the GA biosynthesis pathway. Since GGPP is a precursor for several compounds including chlorophyll, carotenoids, and tocopherols, its diversion toward chlorophyll synthesis increases pigment content (Kamran *et al.,* 2020). Consequently, the intensified leaf greenness observed following PBZ application is likely due to both enhanced chlorophyll production and denser chloroplast distribution within the leaf tissue.

Paclobutrazol also helps the plants become more resilient to both abiotic and biotic stresses. It minimizes various economically damaging fungal infections and functions as a highly effective systemic fungicide (Desta and Amare, 2021). The 2R and 3R enantiomers of paclobutrazol are particularly known for their potent antifungal activity and most potent suppressor of the 14α-demethylation process in plant systems (Burden *et al.* 1987). The selective activity of specific triazole isomers in inhibiting gibberellin biosynthesis as well as sterol biosynthesis could explain the reduction in disease incidence (Lenton, 1994). This inhibition might have disrupted sterol biosynthesis, leading to disordered membrane functions due to the accumulation of 14 α-methylsterols and a concurrent decline in ergosterol content, thereby inhibiting fungal growth (Haughan *et al.*, 1989). Moreover, PBZ enhances the detoxification of reactive oxygen species (ROS) and boosts antioxidant levels during stress and the ageing process (Rady and Gaballah, 2012). ROS detoxification mechanism is present in all plant species involving enzymes such as superoxide dismutase (SOD), catalase (CAT) and peroxidase (POX). The PBZ-induced increase in these enzymes helps mitigate the effects of ageing in plants.

Triazole compounds are believed to help protect cellular membranes from oxidative stress and lipid peroxidation under adverse environmental conditions by enhancing the tissue's natural defense responses against reactive oxygen species (Fletcher and Hofstra, 1990; Fletcher *et al.,* 2000). In addition, paclobutrazol is known to trigger a range of metabolic and biochemical changes that improve a plant's ability to withstand stress, which includes the development of seeds with elevated levels of antioxidant enzymes. This review examines how paclobutrazol influences crop growth, productivity and physiological adaptations across different plant species.

Effect of paclobutrazol on growth and physiology in vegetable crops

Across various vegetables, paclobutrazol emerged as a powerful tool for optimizing growth and productivity. It primarily inhibits gibberellin biosynthesis, leading to reduced internodal elongation, compact plant growth and improved resource allocation. In crops like tomatoes, peppers and onions, PBZ application enhances flowering, fruit set and seed production by promoting reproductive growth over vegetative growth. Specifically, in onions PBZ reduces seed scape height, minimizes lodging and enhances seed yield & quality (Kumar *et al.,* 2016). Its mode of action includes inhibition of energy transport to mitochondria and blocking gibberellin biosynthesis. As a result, cell elongation is restricted, leading to reduced above-ground growth while simultaneously enhancing photosynthesis and mineral uptake. This ultimately leads to a substantial enhancement in the overall yield of various root crops (Jabir *et al*., 2017).

Prior investigations have highlighted the beneficial impact of PBZ treatment on various root crops, such as carrots and potatoes, improving both yield and overall plant quality. Additionally, it improves drought resistance, enhances chlorophyll content and delays senescence, contributing to better crop quality and yield stability. The exploration of role of paclobutrazol in vegetables began with Globerson *et al*. (1989), who discovered that spraying onions with 100 ppm PP 333 reduced seed stalk length by 20-30%. Soaking bulbs in 500 ppm further decreased stalk length but inhibited leaf growth, causing plants to dry prematurely. Setia *et al*. (1995) advanced the research in *Brassica carinata*, finding that foliar application of PP 333 decreased plant height increased branching and boosted seed yield through higher siliquae production and prolonged leaf retention. In potatoes, Tsegaw *et al*. (2005) explored anatomical changes induced by paclobutrazol treated plants exhibited thicker stems, larger vascular bundles, and increased chlorophyll content, resulting in sturdier, more efficient growth. Tekalign and Hammes (2005) expanded this work in Ethiopia, applying paclobutrazol as a foliar spray or soil drench. They observed enhanced photosynthesis, reduced plant height, and lower transpiration rates, alongside increased chlorophyll levels. Years later, Ashrafuzzaman *et al*. (2009) also investigated PBZ at 0, 20, 40 and 80 ppm on onions. They found that 80 ppm PBZ significantly reduced plant height, leaves per plant, tillers per bulb, seed stalk height and seed yield, while also lowering umbel size, flower count, and fruit set. Tuna (2014) found that PBZ (40 mg L^{-1}) enhanced chlorophyll, carotenoids, and antioxidants in tomato seedlings. Mutlu and Agan (2015) demonstrated that PBZ (5-15 ppm) reduced plant height by 25-50% in ornamental peppers, increased chlorophyll content, and delayed fruit set, suggesting it could replace pinching in greenhouse production. Kumar *et al*. (2016) studied onions and revealed that PBZ at 100 ppm significantly reduced seed scape height while increasing scape diameter, umbel size, seed setting, and seed yield. PBZ also improved seed quality by increasing 1000 seed weight, chlorophyll and seed antioxidant content. After that, Mabvongwe *et al*. (2016) found that early PBZ application in potatoes reduced stem length, tuber count and sugar content but increased starch content and yield. Grossi *et al*. (2017) observed in ornamental peppers that PBZ (30-150 mg L^{-1}, foliar; 5-60 mg L^{-1}, soil drench) reduced plant height and diameter by 10-65%, while increasing leaf chlorophyll, though higher doses caused phytotoxicity. Phasri *et al*. (2019) applied PBZ (50 ppm) to Jerusalem artichoke, resulting in compact plants with improved inulin content and decreased flowers. Araujo *et al*. (2020) discovered that PBZ treatment (1.0-100 mg/litre) on potatoes decreased plant height & stem length by 18%, leading to denser planting and higher yields. However, its application requires precise dosage and timing to avoid negative effects on plant metabolism and productivity.

Impact of paclobutrazol on growth and physiology in fruit crops

Over the past decade, PBZ application has become a standard practice in fruit tree cultivation, yielding various effects (Orozco-Melendez 2021). Perennial fruits such as avocado, litchi, mango, citrus, temperate fruits and nuts are often affected by the intricate challenge of alternate bearing or cropping periodicity, coupled with inconsistent and erratic flowering patterns. These physiological constraints contribute to a substantial reduction in their yield potential (Kishore *et al*., 2015). Hence, paclobutrazol exhibits great potential in controlling flowering, improving yield and regulating vegetative growth in fruit crops. Paclobutrazol is known as a versatile plant growth regulator that inhibits excessive vegetative growth, stimulates flowering encouraging, early fruit production, managing biennial bearing and enabling the establishment of high-density plantations in several fruit crops (Gollagi *et al*., 2019). The following is a summary of multiple research efforts on the impact of paclobutrazol on the growth and physiology of fruit crops:

Table 1 : Impact of different doses and concentration of paclobutrazol in fruit crops

Sr. No	Fruit crop	Dose	Effect	References
1.	Apple 'Golden delicious'	1500-3000 ppm	Reduction of shoot growth	Greene (1982)
2.	Apple seedlings	500 ppm	Reduction in shoot length	Quinlan and Richardson (1984)
3.	Apple 'MM.106'	250 mg/ tree	Reduction in number of total shoots and buds	Khurshid *et al*. (1997)
4.	Sweet cherry	1.6 g a.i./ tree	Vegetative growth Reduction	Webster (1986)
5.	Mango	12, 10 & 8 g a.i./tree	Reduction in vegetative growth, length of reproductive shoots and canopy size, while enhancing fruit set and controlling panicle length.	Nafeez *et al*. (2010)
6.	Mango 'Tommy Atkins'	8.25 g a.i. /tree	Reduced canopy size, vegetative growth and reproductive shoot flush length while regulating fruit set and panicle length.	Teferi *et al*. (2010)
7.	Mango 'Langra'	6 g a.i./ tree	Enhanced total chlorophyll, α-amylase activity and caretonoids	Singh and Saini (2001)
8.	Mango	1.0 g a. i. m/canopy 20-40 g/ tree	Growth reduction, flower induction, increased yield as well as sex ratio	Burondkar and Gunjate (1993)
9.	Plum 'Santa Rosa'	500 ppm	Reduced shoot growth and increased fruit weight	Jindal and Chandel (1996)
10.	Pear 'Gala'	0.15 g a.i. /tree	Higer fruit yield	Ratna and Bist (1997)
11.	Strawberry 'Selva'	100 mg/l	Vegetative growth was reduced and highest vitamin C was obtained	Abdollahi *et al*. (2010)
12.	Jackfruit 'Eviarc Sweet'	1 g a.i./meter of canopy diameter	Higher female inflorescence production.	Lina and Protacio, 2015
13.	Pineapple	150 mg L^{-1}	Extended harvesting time and increased produce.	Antunes *et al*. (2008)
14.	Litchi	5 g /m^2 plant spread	Restricted vegetative growth and enhanced flowering	Faizan *et al*. (2000)
15.	Avocado	1.0 %	Increased yield	Salazar-Garcia *et al*. (2013)
16.	Cashew nut	1-3 g /plant	Growth regulation and nut yield	Meena *et al*. (2014)
17.	Guava	1.0 g /plant	Yield improvement	Brar and Bal (2011)
18.	Mexican lime	15 g a.i./ plant	Enhanced flowering	Medina-Urrutia and Buenrostro-Nova (1995)
19.	Mandarin	1.0-2.0 g /plant	Growth Regulation	Dos Santos *et al*. (2004)
20.	Apricot	0.5-2.0 g a.i/ plant	Reduced growth, boosted flowering, and enhanced yield	Arzani and Roosta (2004)

The data presented in the table clearly demonstrates the widespread use of paclobutrazol across various fruit crops that can increase both fruit quality and fruit yield, but there is cases of its residual effects, which may negatively impact consumer health. Moreover, it has been associated with environmental pollution, particularly affecting soil and groundwater (Wang *et al*., 2019).

Impact of paclobutrazol on growth and physiology in floricultural crops

In floriculture, paclobutrazol is used to effectively control the plant growth, ensuring compact, well-structured plants ideal for commercial markets. It also enhances flowering, improves flower quality and optimizes resource allocation, leading to increase in plant spread as well as duration of flowering along with higher yields. Various studies collectively highlighted the role of paclobutrazol in controlling plant height, enhancing branching and improving aesthetics in floricultural crops. Fahl *et al*. (1985) studied the impact of paclobutrazol on chrysanthemum plants, finding that all concentrations reduced plant height, with 45 ppm showing the most significant reduction. Hong *et al*. (1986) and Hendriks (1987) demonstrated that paclobutrazol applied at 50 ppm successfully reduced the height of geranium plants, with further studies showing a reduction in shoot growth by 5-45% with single and double treatments. Maus (1987) investigated the effects of paclobutrazol (50, 100, 200 ppm) and uniconazole on Hibiscus rosa-sinensis, revealing that both treatments reduced plant height, promoted side shoots, and increased leaves and flowers per plant. High-intensity green colour was also observed in treated plants. Adriansen (1988) observed that a single drench of 40 ppm paclobutrazol was better than two foliar sprays in reducing the height of Pelargonium zonale. In a series of experiments, Kristensen and Adriansen (1988) explored the effects of various growth regulators on *Hebe × franciscana* cv. Variegata, discovering that paclobutrazol at 10 mg L^{-1} significantly enhanced inflorescence production, branch growth and controlled height. Farthing and Ellis (1990) tested cycocel and paclobutrazol on *Pelargonium zonale* cv. Ringo Scarlet, finding both growth regulators effectively reduced height while promoting branching and regulating vegetative growth. Wang and Blessington (1990) applied paclobutrazol and uniconazole to *Codiaeum variegatum* and *Plectranthus australis*, with paclobutrazol promoting short stems in croton and severely stunted growth in Swedish ivy even at low doses. Latimer (1991) evaluated paclobutrazol on marigold, zinnia and impatiens, reporting height reduction in zinnia and decreased shoot dry weight in marigold, though no significant effect on final height. Holcomb and Gohn (1995) recommended a 2 ppm drench of paclobutrazol for compact poinsettia plants.

Building on the further understanding of paclobutrazol role in controlling plant growth, Auda *et al.* (2002) explored its effects along with mepiquat chloride and chlormequat on *Barleria cristata*, the Philippine violet shrub. Their study revealed that a 150 ppm paclobutrazol treatment and a 2000 ppm chlormequat application resulted in the best outcomes, reducing vegetative growth and encouraging abundant flowering. Similarly, Niu *et al.* (2002) conducted two experiments to examine paclobutrazol's impact on poinsettias, finding that applications starting immediately after short days and continuing until one week before anthesis significantly reduced plant height and bract area. The second experiment showed that a sub-application of paclobutrazol at 2 mg per litre reduced height & bract area by 23 %, suggesting that delaying drench applications helps to prevent unwanted reductions in bract size. After that, Singh and Bist (2003) evaluated paclobutrazol impact on the growth and flowering of "Gruss-a-Teplitz" roses, finding that higher dosages (20-40 mg $plant^{-1}$) reduced plant height but increased flower production. Similarly, Chen *et al.* (2004) demonstrated that paclobutrazol & uniconazole decreased plant height & inflorescence diameter in *Ixora duffii*, while advancing flowering. Karaguzel *et al.* (2004) observed that paclobutrazol shortened flowering time and increased flower number in *Lupinus varius*, with lower doses promoting growth and higher doses controlling height and inflorescence size. Abou-Dahab and Habib (2005) showed that paclobutrazol and pinching enhanced lateral growth and flower production in *Barleria cristata*, especially at 200 ppm. Misra *et al.* (2005) found that paclobutrazol enhanced early flowering in *Rosa damascena* and increased flower count when combined with $ZnSO_4$. Later on, Ranwala *et al.* (2005) studied the impact of paclobutrazol, uniconazoleand ancymidol as pre-plant bulb treatments on hybrid lilies and found that combining uniconazole and paclobutrazol effectively reduced plant height. Nazarudin *et al.* (2007) applied paclobutrazol to *Syzygium campanulatum* and observed a significant reduction in plant height and leaf area, with lasting effects for up to five months. Sharma *et al.* (2009) found that paclobutrazol (25 ppm) as a pre-plant dip in *Star Gazer* lilies led to earlier bud initiation, more flowers and prolonged flowering. Mansuroglu *et al.* (2009) noted that paclobutrazol reduced vegetative growth in *Consolida orientalis*, with higher concentrations improving flower number and stem diameter.

Various studies conducted in 2010 examined the impact of paclobutrazol on plant growth regulation. Currey and Lopez investigated the impact of pre-plant paclobutrazol bulb dips on *Lilium longiflorum* (easter lily), finding that plant height at flowering was reduced by 15-26%, with the highest concentration (120 mg L^{-1}) meeting commercial height requirements. Latimer and Freeborn tested uniconazole and paclobutrazol on *Lilium lancifolium* and *Lilium aurelianense*, discovering that paclobutrazol dips were more effective in reducing plant height, especially at higher concentrations. Schnelle and Barrett studied paclobutrazol liner dips on bedding plants (*Impatiens walleriana*, *Petunia × hybrida*, and *Scaevola aemula*), showing that a 2 mg per litre, significantly reduced plant height. Shahrokhi *et al.* focused on turf grass, finding that a 40 mg L^{-1} concentration of paclobutrazol effectively controlled plant height during all stages of vegetative growth. Afterwards, Mishra and Yadava (2011) investigated the effect of paclobutrazol applied through root dips, drenches or foliar sprays on China aster, finding that higher concentrations reduced flower size and stalk length, while 25 ppm increased flower yield. Rathore *et al.* (2011) studied the impact of paclobutrazol and pinching on marigold, concluding that 100 ppm enhanced water content, reduced plant height and boosted flower production. Wahyuni *et al.* (2011) tested paclobutrazol, gibberellic acid, and day length on cornflower and redmaids, finding that paclobutrazol at 0.25 mg plant^{-1} created compact plants but reduced inflorescence production. Ghait *et al.* (2012) evaluated paclobutrazol on hibiscus, noting reductions in plant height & leaf area, alongside increased leaf nutrient content & chlorophyll. Likewise, Youssef and Abd-El-Aal (2013) observed that paclobutrazol and cycocel treatments significantly reduced plant height and leaf area in *Tabernae montana*, while increasing the number of branches and leaves per plant. Lenzi *et al.* (2015) applied paclobutrazol to *Dianthus* hybrids and noted a reduction in plant height by up to 55 %, without affecting the number or size of inflorescences, though leaf greenness was improved. Heikal (2017) demonstrated that paclobutrazol inhibited growth in Sanchezia shrub, with higher doses causing the greatest reduction, while lower doses increased chlorophyll and mineral content in leaves. Kasim *et al*., (2018) reported that paclobutrazol spraying on *Salvia splendens* resulted in reduced height and increased chlorophyll content, showcasing its potential for growth regulation.

In a series of experiments to study the role of paclobutrazol (PBZ) in flower crops, Xia *et al.* (2018) applied PBZ to herbaceous peony and found that a 100 mg ml^{-1} dose significantly reduced plant height while enhancing leaf greenness and chlorophyll content. Similarly, Li *et al.* (2020) studied PBZ's effects on *Cymbidium hybridum* (orchid) and observed that concentrations of 300 mg L^{-1} promoted flower bud differentiation and reduced plant height, with lower concentrations stimulating antioxidant enzyme activity. In another experiment, Demir and Celikel (2021) immersed *Narcissus tazetta* (daffodil) bulbs in paclobutrazol and found that a 200 mg L^{-1} treatment resulted in a 59% decrease in plant height, reduced leaf area and increased leaf thickness. Furthermore, Malik *et al.* (2021) found that paclobutrazol (60 ppm) combined with cycocel (200 ppm) resulted in shorter plants, fewer leaves and earlier flowering in Asiatic lilies, alongside higher bulb yield and larger bulb diameter. Noor *et al.* (2022) applied foliar sprays of PBZ on *Hibiscus rosa-sinensis*, with 100 ppm PBZ enhancing plant characteristics such as more leaves, branches, flowers and higher chlorophyll content. Karagoz *et al.* (2023) applied different concentrations of PBZ to regulate seedling height in *Gypsophila bicolor*, with 1.5 mg per litre paclobutrazol reducing plant height while impacting leaf number. These studies highlight the role of paclobutrazol in improving growth control and promoting desired characteristics in floricultural crops.

Impact of paclobutrazol on the growth and physiological responses of field crops

According to earlier research, paclobutrazol serves as a highly effective plant growth regulator enhancing crop structure, reducing lodging, enhanced antioxidant activity and maximizing yield potential in field crops. A series of studies highlighted the significant effects of paclobutrazol on field crops. Hunter (1984) investigated its impact on ryegrass and found that it reduced lodging by restricting stem elongation and strengthening basal internodes, leading to increased seed weight, fertile tillers, and spikelets per spike. The study also noted that paclobutrazol's effects varied with growth stage, promoting tillering in the vegetative phase and increasing florets per spikelet when applied during floret initiation. Similarly, Ozmen *et al.* (2003) observed that barley seedlings treated with 40 mg paclobutrazol had shorter shoots, a higher root-to-shoot ratio & elevated levels of SOD, carotenoids, and chlorophyll. Likewise, Mansour *et al.* (2010) assessed sunflower production and reported that applying 2000 ppm paclobutrazol resulted in the shortest plants. Gomez *et al.* (2011) investigated the impact of paclobutrazol (PBZ) on quinoa and found that PBZ decreased plant height, increased seed yield, & decreased leaf area index while enhancing SPAD values and specific leaf weight. Xu *et al.* (2013) studied PBZ application on *Jatropha curcas* and observed improved reproductive growth, increased fruit load, and reduced vegetative growth, including shorter new branches. Hua *et al.* (2014) explored PBZ's role in optimizing canola height for mechanical harvesting, revealing that application at a 10 cm stalk height reduced plant height by 27% and boosted seed yield by 21%. The study linked yield improvement to enhanced branching ability and efficient carbohydrate utilization.

In various experiments conducted in 2015, the role of paclobutrazol (PBZ) in improving crop architecture, reducing lodging, and enhancing yield was extensively studied. Koutroubas and Damalas found that repeated PBZ applications in sunflower reduced plant height by up to 14.4% while increasing achene yield by 25%. Similarly, Kuai *et al.* (2015) demonstrated that PBZ foliar sprays at 150 and 300 mg L^{-1} in rapeseed significantly improved lodging resistance. Though seed number per pod decreased, an increase in pod count and seed weight contributed to higher yields. Yuan *et al.* (2015) examined PBZ in flax and discovered that early applications at the seedling and rapid growth stages effectively reduced plant height. Following that, Syahputra *et al.* (2016) examined the impact of different paclobutrazol concentrations on rice, finding that higher PBZ levels reduced plant height and leaf area while enhancing lodging resistance, spikelet number, grain filling, and overall yield. Barman *et al.* (2018) evaluated PBZ in groundnut, showing that double sprays of 250 ppm significantly decreased plant height by 28% while improving pod number, dry pod yield, and economic returns. Kamran *et al.* (2018) investigated PBZ application methods in maize, revealing that both seed-soaking and seed-dressing improved culm strength, increased lignin accumulation in basal internodes, and reduced lodging risk. Furthermore, the application of PBZ increased the activity of important enzymes like 4-coumarate CoA ligase (4CL), phenylalanine ammonia-lyase, peroxidase, and cinnamyl alcohol dehydrogenase, which improved the structural integrity of the stalks and increased lignin synthesis. According to their results, PBZ at 300 mg L^{-1} or 3.5 g kg^{-1} efficiently improved plant architecture, strengthened stalks, and increased enzymatic activity for increased yield. Mepiquat chloride and paclobutrazol were tested on paddy in recent studies by Mukherjee (2020), who discovered that both decreased internode and culm length while increasing culm diameter. Mepiquat chloride at 50 g a.i. ha^{-1} and paclobutrazol at 25–50 g a.i. ha^{-1} produced the highest grain yield, indicating better plant architecture and less lodging. In groundnut, Goswami *et al.* (2022) found that paclobutrazol at 150 ppm applied twice resulted in higher dry matter and pod yield, with up to an 18% increase over the control. Panda *et al.* (2023) applied paclobutrazol to chickpea at different concentrations, concluding that it reduced plant height and delayed flowering, with 35 ml ha^{-1} providing the highest yield, demonstrating its potential in modifying reproductive phenology and boosting yields. Similarly, Sarkar (2023) examined PBZ's impact on sunflower (*Helianthus annuus* L.), finding that PBZ-treated plants exhibited a compact stature with dark green leaves and increased chlorophyll and carotenoid content, although plant height was significantly reduced with no notable change in stem girth. Zhao *et al.* (2023) also investigated the role of PBZ in peanut cultivation. They discovered that applying PBZ decreased lodging by increasing chlorophyll content and reducing plant height. A 100 mg L^{-1} application of PBZ was the best combination for optimizing peanut yield.

Impact of paclobutrazol on growth and physiology in herbs

Plants like sweet basil and *Ocimum sanctum* (holy basil) are significantly impacted by paclobutrazol (PBZ) in terms of their growth and antioxidant qualities. In *Ocimum sanctum*, PBZ enhances the plant's free radical scavenging ability and boosts antioxidant levels, including enzymes like SOD, CAT, and ascorbate peroxidase (APX) (Nair *et al*. 2009). In sweet basil, PBZ regulates plant height and improves decorative qualities, with higher concentrations (10 or 20 ppm) leading to more compact, bushy plants and increased leaf chlorophyll content (Kurniawati *et al*., 2023).

Conclusion

Paclobutrazol serves as a reliable growth suppressant with broad applicability in horticulture and agriculture, significantly improving plant architecture, stress resilience, and yield quality across various crop species. Its ability to regulate gibberellin biosynthesis, influence other phytohormones and optimize vegetative growth makes it a valuable tool for enhancing productivity and resource efficiency in modern farming systems. However, despite its numerous benefits, concerns regarding its residual accumulation in soil and potential environmental impact necessitate further investigation. Future research should focus on optimizing application rates for different crops and environmental conditions to maximize benefits while minimizing any adverse effects. Additionally, exploring PBZ alternatives with lower environmental impact, integrating its use with sustainable agricultural practices, and assessing its long-term physiological and ecological effects will be crucial for ensuring its continued effectiveness in precision agriculture. Moreover, advancements in nanotechnology and formulation techniques could enhance PBZ efficiency and reduce its environmental footprint

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