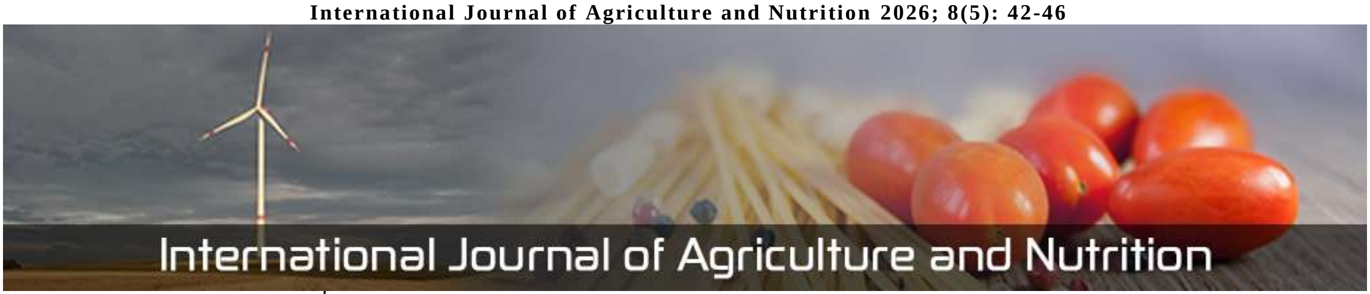

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Paclobutrazol-Mediated Regulation of Growth, Physiology and Yield in Groundnut (*Arachis hypogaea* L.): A Review

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Abstract
Groundnut (*Arachis hypogaea* L.) is an important oilseed crop, yet its productivity is often constrained by excessive vegetative growth, poor source-sink balance, and suboptimal assimilate partitioning. Plant growth regulators, particularly paclobutrazol (PBZ), have emerged as effective tools to regulate plant architecture and improve yield efficiency. PBZ, a triazole-based compound, inhibits gibberellin biosynthesis by blocking ent-kaurene oxidase activity, resulting in reduced stem elongation and compact canopy formation. This physiological modification improves light interception, reduces mutual shading, and enhances radiation use efficiency. In addition, PBZ alters hormonal balance by increasing abscisic acid levels and improving stress tolerance responses. It also enhances chlorophyll content, delays senescence, and stimulates antioxidant enzyme activity, thereby improving photosynthetic efficiency and oxidative stress management. Furthermore, PBZ promotes better source-sink relationships by redirecting assimilates from vegetative to reproductive organs, leading to improved pod development, kernel weight, and harvest index. Enhanced accumulation of osmoprotectants and carbohydrates further supports plant resilience under abiotic stress conditions such as drought. Overall, PBZ contributes to improved dry matter partitioning, photosynthetic performance, and yield stability in groundnut. Although extensive research exists on PBZ in various crops, its integrated physiological and agronomic effects in groundnut remain less comprehensively synthesized. This review highlights the chemical nature, mode of action, and physiological responses of PBZ, emphasizing its potential to enhance productivity and sustainability in groundnut cultivation under changing environmental conditions.

Keywords: Groundnut (*Arachis hypogaea* L.); Paclobutrazol; Plant growth regulator; Gibberellin inhibition; Source-sink relationship; Photosynthesis; Canopy architecture; Yield improvement; Stress tolerance; Dry matter partitioning

Introduction
Groundnut (*Arachis hypogaea* L.) is one of the most important oilseed crops cultivated globally, contributing tiger share to edible oil production, plant protein supply, and livelihood security also in commercial terms in tropical and semi-arid regions. Globally, groundnut is grown on approximately 30-32 million hectares with an annual production of about 50-55 million tonnes, with Asia and Africa as major contributions (Food and Agriculture Organization, 2023). India is one of the leading producers, cultivating groundnut on nearly 5-6 million hectares with a production of around 9-10 million tonnes, although productivity (1800 kg ha^{-1}) finds out to be lower than the global average due to various constraints (Directorate of Economics and Statistics, 2022).
Despite its economic importance, groundnut productivity is often limited by both biotic and abiotic stresses, as well as physiological inefficiencies. Among these, excessive vegetative growth under favorable conditions frequently results in imbalnaced assimilate partitioning, reduced reproductive efficiency and ultimately lower pod yield. The imbalance between source and sink is considered a major physiological bottleneck in realizing higher productivity in groundnut.
The use of plant growth regulators (PGRs) could be an effective approach to manipulate plant growth and improve crop performance. Paclobutrazol (PBZ), a triazole-based PGR, is widely recognized for its ability to inhibit gibberellin biosynthesis, thereby reducing stem

elongation and promoting compact plant architecture (Rademacher, 2015) [12]. In addition to growth regulation, PBZ has been reported to enhance chlorophyll content, improve photosynthetic efficiency, regulate endogenous hormonal balance, and confer increased tolerance to abiotic stresses (Davis *et al*., 1988; Desta *et al*., 2021) [2, 3]. Harnessing role of paclobutrazole could lead to improvements in key yield attributes such as pod number, kernel weight, and harvest index (Barman *et al*., 2017; Lenka *et al*., 2023) [1, 10]. Furthermore, contributes to improved water-use efficiency and resilience under drought-prone conditions, which are common in major groundnut-growing regions.

Although the role of PBZ has been extensively studied in various crops, a comprehensive synthesis of its physiological and agronomic effects specifically in groundnut remains limited. Therefore, the present review aims to critically examine the chemical nature, mode of action, physiological responses, and yield-related impacts of paclobutrazol in groundnut, while integrating supporting evidence from other crop systems to provide a broader understanding of its potential in enhancing productivity and sustainability.

Paclobutrazol: Chemical Nature and Mode of Action

Chemical Nature and Classification

Paclobutrazol (PBZ) is a triazole-based plant growth regulator widely used to modulate plant architecture and improve stress tolerance. Paclobutrazole belongs to the group of substituted triazoles and it has unique characteristics like high stability and longer persistence in plant tissues and soil. Absorption of paclobutrazole primarily occurs through roots and leaves and translocated via the xylem, which enables systemic action within the plant system (Fletcher *et al*., 2000; Desta *et al*., 2021) [4, 3].

Inhibition of Gibberellin Biosynthesis

The inhibition of gibberellins biosynthesis is primary mode of action of paclobutrazole. PBZ blocks the oxidative steps in terpenoid pathway of gibberellin biosynthesis, by inhibiting the ent-kaurene oxidase enzyme, which is a cytochrome P 450- dependent monooxygenase. This leads to reduction in conversion of ent kaurene to ent kaurenoic acid, ultimately lowering the endogenous gibberellin concentrations (Fletcher *et al*., 2000) [4].

The reduction in gibberellin concentration suppresses cell elongation without significantly affecting cell division (which is primarily influenced by cytokinin levels), leading to shorter internodes and compact plant growth. In groundnut, this manifests as reduced plant height, improved canopy structure, and enhanced assimilate allocation toward reproductive organs (Barman *et al*., 2017; Lenka *et al*., 2023) [1,10].

Gibberellins (GAs) are diterpenoid plant growth regulators synthesized through the terpenoid pathway, with geranylgeranyl diphosphate (GGDP) as the precursor.

Gibberellic Acid Biosynthetic Pathway

Geranyl Geranyl Di Phosphate (GGDP)
↓
Ent - Copalyl di Phosphate
↓
Ent -kaurene
↓
Ent kaurenoic acid
↓
GA 12
↓
GA1,3,4

Modulation of Plant Hormonal Balance

Apart from inhibition of gibberellin biosynthesis, paclobutrazol alters the balance of other phytohormones. It has been reported to increase abscisic acid (ABA) levels, which plays a crucial role in stress adaptation by regulating stomatal closure and reducing transpiration losses. Additionally, PBZ may enhance cytokinin activity, promoting cell division and delaying senescence, while modulating ethylene production under stress conditions (Desta *et al*., 2021; Pal *et al*., 2016) [3, 11].

This hormonal modulations may contribute to improved physiological efficiency and resilience in groundnut, particularly under drought and heat stress conditions.

Effects on Metabolic and Enzymatic Activities

Paclobutrazol influences several biochemical and metabolic processes that contribute to improved plant performance. One of the notable effects is the enhancement of chlorophyll content. PBZ also stimulates the activity of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), thereby reducing oxidative damage under stress conditions (Ghadiali *et al*., 2023).

Furthermore, PBZ promotes the accumulation of osmoprotectants such as proline and soluble sugars, which help maintain cellular turgor and enzyme stability during water deficit conditions (Yooyongwech *et al*., 2017). It also improves carbohydrate partitioning by directing assimilates toward sink organs, such as developing pods in groundnut (Hua *et al*., 2014) [6].

Integrated Physiological Outcome in Groundnut

The combined effects of reduced gibberellin activity, altered hormonal balance, and enhanced metabolic efficiency result in a more compact and physiologically efficient plant system. In groundnut, the combinational effect of reduced Gibberellin activity, altered hormonal balance and improved metabolic activity of plant can result in improved source-sink dynamics, better peg penetration, pod to peg ratio and increased pod development.

Physiological Effects of Paclobutrazol in Groundnut (*Arachis hypogaea* L.)

Various physiological effects of Paclobutrazole on Groundnut are discussed hereunder.

Plant Height and Canopy Architecture

The effect on Plant Height and Canopy Architecture are the primary effects of paclobutrazole on Groundnut growth. Paclobutrazol (PBZ) reported to significantly influence plant architecture in Groundnut by inhibiting gibberellin biosynthesis, resulting in reduced stem elongation and shorter internodes. This leads to a compact canopy structure, resulting limitation to excessive vegetative growth with better partitioning efficiency. Studies have consistently reported a marked reduction in plant height following PBZ application, without adversely affecting biomass accumulation (Barman *et al*., 2017; Lenka *et al*., 2023 and Fletcher *et al*., 2000) [1, 10, 4]. The compact canopy enhances light penetration within the crop stand, improving radiation distribution across leaves and reducing mutual shading. This architectural modification is particularly beneficial under high-density planting conditions, where excessive vegetative growth can limit photosynthetic efficiency and reproductive development (Rademacher, 2015) [12].

Leaf Area and Chlorophyll content

PBZ influences leaf development and physiology by increasing chlorophyll content and maintaining functional leaf area for a longer duration. Treated plants often exhibit darker green leaves, indicative of enhanced chlorophyll concentration and delayed senescence (Fletcher *et al*., 2000; Desta *et al*., 2021) [4, 3]. While PBZ may moderately reduce total leaf area due to restricted expansion, it improves the efficiency of the existing leaf area by optimizing leaf orientation, to reduce negative affect of mutual shading.

Dry Matter Accumulation and Partitioning

One of the most significant physiological effects of paclobutrazol (PBZ) in groundnut is its influence on dry matter accumulation and assimilate partitioning. By inhibiting gibberellin biosynthesis and restricting excessive vegetative growth, reduced demand from vegetative sinks, leading to better reproductive translocation. This shift in source-sink dynamics enhances pod development, resulting in improved pod filling, increased kernel weight, and higher harvest index (Hua *et al*., 2014; Barman *et al*., 2017; Lenka *et al*., 2023) [6, 1, 10].

Fletcher *et al*., 2000; Rademacher, 2015 [4, 12], reported that, Triazole-induced growth regulation improves carbon allocation efficiency and biomass partitioning. PBZ has also been shown to influence carbohydrate metabolism by increasing the accumulation of soluble sugars and starch in sink tissues, thereby strengthening sink capacity (Desta *et al*., 2021) [3]. The improved source-sink balance ensures efficient utilization of photosynthates, ultimately contributing to enhanced yield and productivity in groundnut.

Photosynthesis and Carbon Assimilation

The enhancement in chlorophyll content and canopy architecture under paclobutrazol (PBZ) application translates into improved photosynthetic efficiency in groundnut. Increased chlorophyll concentration enhances light-harvesting capacity, while the development of a compact canopy structure facilitates uniform light distribution within the crop stand, thereby reducing mutual shading and improving radiation use efficiency (Fletcher *et al*., 2000; Rademacher, 2015) [4, 12]. In addition, PBZ has been reported to enhance the activity of key photosynthetic enzymes, including ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO), thereby improving carbon fixation efficiency and net photosynthetic rate (Desta *et al*., 2021) [3]. The improved photosynthetic performance is further supported by delayed leaf senescence and sustained functional leaf area, which prolong the duration of assimilate production.

Root Growth and Root-Shoot Ratio

Paclobutrazol (PBZ) application in groundnut has been reported to increased root-shoot ratio. The inhibition of gibberellin biosynthesis suppresses shoot elongation, thereby reducing the assimilate demand of aerial parts and facilitating greater allocation of photoassimilates towards root growth. This shift in biomass partitioning promotes the development of a more extensive and functionally efficient root system, characterized by increased root length, density, and biomass (Fletcher *et al*., 2000; Rademacher, 2015) [4, 12]. Enhanced root architecture improves water and nutrient uptake efficiency, particularly under moisture-limited conditions with better stress resilience. Additionally, PBZ-induced modulation of hormonal balance, including elevated abscisic acid levels, plays a crucial role in root growth regulation and adaptation to drought stress (Desta *et al*., 2021) [3]. The increased root biomass not only enhances resource acquisition but also improves plant anchorage and stability, which attributes to better growth and yield under varying environmental conditions (Ghadiali *et al*., 2023).

Influence of paclobutrazole on various crops.

A wide range of crops are reported to be influenced under effect of paclobutrazole, highlighting persistant nature of it on crops. Evidence from diverse cropping systems further establishes its role in regulating plant architecture, enhancing assimilate partitioning, and improving productivity (Fletcher *et al*., 2000; Desta *et al*., 2021) [4, 3].

Oilseed Crops

In oilseed crops such as soybean and mustard, paclobutrazol application has been reported to reduce excessive vegetative growth and improve reproductive efficiency. Enhanced partitioning of assimilates towards developing seeds, along with an increase in harvest index, has been consistently observed (Kumar *et al*., 2012; Rademacher, 2015) [9, 12]. These responses are alignment with findings of Barman *et al*., 2017; Lenka *et al*., 2023, [1, 10] where PBZ-mediated modulation of source-sink dynamics contributes to improved pod development and yield.

Cereal Crops

In cereals like wheat and rice, paclobutrazol is widely reported to influence as reducing plant height and improving lodging resistance through inhibition of gibberellin biosynthesis (Rademacher, 2015) [12]. This leads to increased harvest index, as assimilates are preferentially allocated to reproductive organs (Hua *et al*., 2014) [6]. These reporting's establish concrete background for studying influence of cereal crops by paclobutrazole.

Horticultural Vegetable Crops

In horticultural vegetable crops such as tomato, brinjal, and chilli, paclobutrazol (PBZ) has been reported and published establishing its effect on modulating vegetative growth by inhibiting gibberellin biosynthesis, resulting in reduced stem elongation and more compact plant architecture (Thomas D. Davis *et al*., 1988; Richard A. Fletcher *et al*., 2000; Wilhelm Rademacher, 2015) [4, 2, 12]. The PBZ acts by enhancing flowering intensity, improving fruit set, and increasing reproductive sink strength, which is attributed to improved assimilate partitioning and altered endogenous hormonal balance.

Furthermore, PBZ-induced increases in chlorophyll content and photosynthetic efficiency contribute to increased crop growth rate, more assimilate partitioning efficiency with better source sink relationships even under stress conditions (Berhanu Desta *et al*., 2021) [3].

Plantation Crops

In perennial plantation crops, particularly mango, paclobutrazol (PBZ) is extensively used to regulate vegetative growth and induce flowering through inhibition of gibberellin biosynthesis, resulting in suppression of excessive vegetative flushes and promotion of reproductive differentiation (Kulkarni, 1988; Yeshitela *et al*., 2004; Rademacher, 2015) [8, 16, 12]. This is attributed to increase in abscisic acid levels and reduced gibberellin activity, which favours floral induction and reproductive development. Additionally, PBZ enhances assimilates accumulation and assimilates partitioning, thereby improving flowering intensity and fruit set. These responses establish strong basis for application of paclobutrazole in plantation crops.

Effect of Paclobutrazol on Growth and Yield Attributes in Groundnut (*Arachis hypogaea* L.)

Paclobutrazol (PBZ) plays a significant role in modulating growth and yield attributes in groundnut through its influence on plant architecture, assimilate partitioning, and hormonal balance.

Influence on Flowering and Reproductive growth

Paclobutrazol (PBZ) has been reported to influence reproductive growth in groundnut by modulating endogenous hormonal balance, primarily through the suppression of gibberellins and the relative enhancement of abscisic acid and cytokinins. These hormonal shifts facilitate the transition from vegetative to reproductive growth, resulting in improved flowering synchronization and increased flower retention. In legumes, regulation of gibberellin activity has been closely associated with enhanced reproductive efficiency and improved flower-to-pod conversion (Rademacher, 2015; Taiz *et al*., 2015) [12, 14]. Studies in groundnut and related crops have indicated that PBZ application improves the proportion of effective flowers that develop into mature pods, primarily due to improved assimilate availability and hormonal regulation (Barman *et al*., 2017; Lenka *et al*., 2023) [1, 10]. Furthermore, triazole-mediated growth regulation has been shown to enhance reproductive sink strength and reduce floral abscission under varying environmental conditions, thereby contributing to yield stability (Davis *et al*., 1988; Sankar *et al*., 2007) [2].

Peg Formation and Pod Development

Peg formation is a critical determinant of yield in groundnut, as successful peg penetration into the soil directly influences pod set. PBZ-induced reduction in vegetative growth improves canopy openness and reduces competition for assimilates, thereby leading to better peg initiation and penetration. Additionally, improved assimilate availability ensures adequate energy supply for pod development. Studies have shown that PBZ application enhances peg-to-pod conversion efficiency, leading to a higher number of well-developed pods per plant (Barman *et al*., 2017; Lenka *et al*., 2023) [1, 10].

Pod Yield and Kernel Yield

The increased pod yield in groundnut as effect of Paclobutrazole is widely reported in many experiments. PBZ-treated plants reported to exhibit increased number of pods per plant, improved pod weight, and higher kernel filling percentage (Barman *et al*., 2017; Lenka *et al*., 2023) [1]. Similar findings across studies indicate that PBZ at optimised doses significantly enhance economic yield without compromising plant health. The improved yield performance is further supported by enhanced photosynthetic capacity and prolonged leaf functional duration (Fletcher *et al*., 2000; Rademacher, 2015) [4, 12].

Harvest Index and Biomass Efficiency

Paclobutrazol application leads to a notable improvement in harvest index by increasing the proportion of economic yield relative to total biomass. The suppression of excessive vegetative growth reduces non-productive biomass accumulation, thereby enhancing biomass-use efficiency, which is a key indicator of crop productivity (Hua *et al*., 2014) [6]. This reflects the effectiveness of PBZ in optimizing carbon allocation within the plant system.

The ability of PBZ to optimize source-sink dynamics and enhance reproductive efficiency underscores its potential as a valuable agronomic tool for improving groundnut productivity (Fletcher *et al*., 2000; Desta *et al*., 2021; Rademacher, 2015) [4, 12, 3].

Conclusion

Paclobutrazol is understood as an effective growth regulator for groundnut (*Arachis hypogaea* L.) through its targeted inhibition of gibberellin biosynthesis and consequent modulation of plant hormonal balance. The resulting alterations in plant architecture, photosynthetic efficiency, root development and assimilate partitioning collectively enhance source-sink relationships and reproductive efficiency. Evidence from groundnut and other crop systems consistently demonstrates that PBZ reduces excessive vegetative growth while promoting pod development, thereby improving yield attributes and harvest index. In addition, PBZ contributes to enhanced tolerance against abiotic stresses through improved physiological and biochemical adjustments. However, variability in response due to genotype, dosage, and other environmental conditions necessitates further refinement of application technology. Future research should focus on optimizing dose-timing combinations, understanding long-term soil and environmental impacts, and integrating PBZ use within sustainable crop management practices. Overall, PBZ has potential as a strategic tool for improving productivity and resilience in groundnut cultivation systems.

Table 1: Compilation of information on Paclobutrazole usage in various crops.

Crops	Typical Dosage	Stage of Application	Primary Effects	Physiological Basis	Key References
Cereal Crops: Rice, Wheat, Maize	50-100 ppm (foliar) or 200-400 g a.i. ha⁻¹	Early vegetative stage (tillering)	Reduced plant height, improved lodging resistance	GA inhibition leads to reduced internodal elongation; improved assimilate partitioning	Kamran *et al*., 2017; Rademacher, 2015 [7, 12]
Oilseed Crops: Groundnut, Soybean, Mustard	50-150 ppm (foliar spray)	25-35 DAS or early flowering	Reduced vegetative growth, improved pod/seed development	Enhanced source-sink balance; improved assimilate translocation	Barman *et al*., 2017; Lenka *et al*., 2023 [1, 10]
Vegetable crops: Tomato, Brinjal, Chilli, Pepper	25-75 ppm (foliar spray)	Pre-flowering or early flowering	Compact growth, increased flowering and fruit set	Hormonal modulation, increased chlorophyll	Davis *et al*., 1988 [2]; Fletcher *et al*., 2000; Desta *et al*., 2021 [4, 3]
Fruit & Plantation Crops: Mango, Citrus, Apple, Guava	1-5 g a.i. per tree (soil drench) or 500-1000 ppm (foliar)	Post-harvest or pre-flowering	Flower induction, control of vegetative flush	Increased carbohydrate accumulation; hormonal shift	Kulkarni, 1988; Yeshitela *et al*., 2004 [8]
Ornamental crops	50-200 ppm (foliar or drench)	Active vegetative growth	Growth retardation, improved plant form	Reduced cell elongation; increased chlorophyll	Rademacher, 2015 [12]

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