The Academic
International Journal of Multidisciplinary Research

An Online Peer Reviewed / Refereed Journal
Volume 2 | Issue 11 | November 2024
ISSN: 2583-973X (Online)
Website: www.theacademic.in

Plant Growth Regulators: Mechanisms, Applications, and Advancements in Agricultural Productivity

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ARTICLE DETAILS

Research Paper

Keywords:
Plant Growth Regulators, Auxins, Gibberellins, Cytokinins, Ethylene, Growth Retardants, Crop Yield, Stress Tolerance, Agricultural Productivity, Sustainable Agriculture

DOI;
10.5281/zenodo.14329091

ABSTRACT

Plant Growth Regulators (PGRs) are pivotal in modern agriculture, influencing plant growth, development, and stress response. They consist of natural and synthetic compounds like auxins, gibberellins, cytokinins, ethylene releasers, and growth retardants, each playing distinct roles in modulating plant physiological processes. Auxins primarily enhance root formation and prevent fruit drop, while gibberellins promote stem elongation and fruit enlargement. Cytokinins delay senescence and are vital for cell division, whereas ethylene releasers like ethephon accelerate fruit ripening and abscission. Growth retardants like paclobutrazol control excessive vegetative growth and improve yield quality. PGRs contribute to increased agricultural output by enhancing crop yield, improving fruit quality, and making plants more resilient to environmental stresses such as drought and salinity. This review aims to explore the types, functions, and applications of

PGRs in agriculture, with an emphasis on their role in enhancing crop productivity, stress tolerance, and post-harvest management. Through an analysis of recent research and innovations, this paper highlights the potential of PGRs as an essential tool in sustainable agricultural practices.

1. Introduction:

Agriculture today is confronted with the dual challenge of increasing food production while ensuring sustainability in the face of environmental stresses like climate change, limited natural resources, and growing population demands. **Plant Growth Regulators (PGRs)** have emerged as essential tools in meeting these challenges, enabling farmers to optimize plant growth, development, and resilience.

PGRs are natural or synthetic compounds that influence key physiological processes in plants, such as seed germination, root development, stem elongation, flowering, and fruit ripening. They are categorized into five primary groups: **auxins, gibberellins, cytokinins, ethylene releasers,** and **growth retardants**. Each of these plays a specialized role in plant development. For example, **auxins** promote root initiation and prevent premature fruit drop, while **gibberellins** enhance fruit size and stem elongation. **Cytokinins** are instrumental in delaying leaf senescence and improving post-harvest longevity, and **ethylene releasers** like ethephon are used to synchronize fruit ripening for crops such as bananas and tomatoes. **Growth retardants** help control vegetative growth, especially in tall crops like mango and cotton, enhancing fruit quality and yield.

Beyond improving crop productivity, PGRs are also vital for stress tolerance. Compounds like **brassinosteroids** and **salicylic acid** enhance plant resistance to drought, salinity, and pathogen attacks, making crops more resilient to adverse conditions. By bolstering a plant's natural defenses, PGRs reduce the reliance on chemical fertilizers and pesticides, fostering more sustainable agricultural practices.

PGRs also play a crucial role in post-harvest management, improving the shelf life of fruits and vegetables by controlling ripening and delaying senescence, thus reducing post-harvest losses. This capacity to increase both pre- and post-harvest efficiency makes PGRs indispensable for modern agriculture.

This review will discuss the different types of PGRs, their mechanisms of action, and their applications in enhancing crop yield, quality, and stress tolerance. By understanding the benefits of PGRs, we can better utilize these compounds to promote sustainable agriculture and address the growing global demand for food production.

2. Objectives:

- To review the types and mechanisms of action of plant growth regulators (PGRs).
- To evaluate the role of PGRs in improving crop yield, quality, and stress tolerance.
- To examine recent research and innovations related to the application of PGRs in agriculture.
- To explore sustainable agricultural practices facilitated by PGRs.
- To provide a comprehensive chart of PGRs and their applications across various crops.

3. Literature Review:

The role of Plant Growth Regulators (PGRs) in modern agriculture has been widely studied for their ability to manipulate plant physiology, improve yields, and enhance stress tolerance. Auxins have been extensively used to promote root initiation and prevent premature fruit drop. Research by Jeyakumar et al. (2013) highlights their application in improving fruit retention and size in crops like mangoes and grapes. Gibberellins, particularly GA3, are well-documented for their role in stimulating stem elongation and increasing fruit size, especially in horticultural crops like grapes and citrus (Patel et al., 2020). Cytokinins, as noted by Khan et al. (2019), have proven effective in delaying senescence, promoting cell division, and improving post-harvest longevity of leafy vegetables and ornamental plants.

Ethylene-releasing compounds, such as ethephon, have been shown to synchronize fruit ripening and abscission in crops like bananas, pineapples, and tomatoes (Ali et al., 2020). This controlled ripening improves both harvesting efficiency and market quality. Growth retardants, such as paclobutrazol, are widely used to control vegetative growth and enhance fruit set in crops like mangoes and cotton (Singh et al., 2018).

Additionally, brassinosteroids and salicylic acid have gained attention for their role in increasing plant resistance to abiotic stresses, such as drought and salinity, by improving photosynthesis and nutrient uptake (Zhou et al., 2020). These findings underline the potential of PGRs to improve crop productivity and sustainability in agriculture, making them indispensable for addressing global food security challenges.

4. Mechanisms and Applications of Plant Growth Regulators in Agriculture

4.1. Types and Mechanisms of Action of Plant Growth Regulators (PGRs):

Plant Growth Regulators (PGRs) are categorized based on their specific roles in regulating various plant processes, including growth, development, and stress responses. Below are the key types and their mechanisms of action:

- **Auxins**: Auxins are essential in promoting cell elongation, particularly in young plant tissues. They are involved in the regulation of root development, shoot growth, and phototropism, where plants grow towards light. Auxins such as indole-3-acetic acid (IAA) play a crucial role in root initiation, making them valuable in rooting cuttings for plant propagation. Additionally, auxins help prevent premature fruit drop by maintaining the hormonal balance in fruits, particularly in crops like mango, tomato, and grapes.

- **Gibberellins**: Gibberellins, especially gibberellic acid (GA3), are well known for their role in stem elongation, seed germination, and the promotion of fruit development. These hormones break seed dormancy and are often applied to enhance fruit size and quality in horticultural crops like grapes, citrus, and apples. They also induce rapid growth in cereals by increasing cell division and elongation, making them valuable in boosting yield in grain crops.

- **Cytokinins**: Cytokinins promote cell division (cytokinesis), shoot formation, and delay the process of senescence (aging) in plants. They are used to enhance leaf growth, improve shoot proliferation in tissue cultures, and extend the post-harvest life of leafy vegetables. By delaying senescence, cytokinins improve the visual and nutritional quality of plants, which is particularly important for the commercial value of ornamental and edible crops.

- **Ethylene Releasers**: Ethylene is a gaseous hormone that accelerates fruit ripening and promotes the abscission (shedding) of leaves and fruits. PGRs like ethephon and ethrel release ethylene and are used to synchronize the ripening process in fruits like bananas, tomatoes, and pineapples. These PGRs ensure that crops ripen uniformly, allowing for timely and efficient harvesting. Ethylene also regulates flower formation and is used in crops like cotton to promote shedding of older leaves, enhancing the plant's overall reproductive performance.

- **Growth Retardants**: Growth retardants such as paclobutrazol and chlormequat chloride inhibit excessive vegetative growth by blocking gibberellin biosynthesis. These PGRs are often applied to control plant height, strengthen stems, and promote better fruit set. In mangoes and cotton, for instance, paclobutrazol enhances fruit yield and quality by shifting the plant's energy focus from excessive vegetative growth to reproductive development. Additionally, growth retardants are used to regulate flowering and reduce fruit drop in fruit trees, making them critical for managing fruit load in high-yield orchards.

- **Brassinosteroids**: Brassinosteroids are a class of PGRs that promote cell elongation, enhance photosynthesis, and improve plant tolerance to abiotic stresses such as drought, salinity, and temperature extremes. These PGRs are involved in plant growth regulation and stress management, helping crops to better cope with challenging environmental conditions. Their application is particularly useful in stress-prone areas to sustain crop growth under adverse conditions.

- **Salicylic Acid**: Salicylic acid is a PGR that plays a key role in inducing systemic acquired resistance (SAR), a plant's defense mechanism against pathogens and pests. It also enhances a plant's tolerance to abiotic stresses by improving the antioxidant system, thereby protecting plants from oxidative damage caused by environmental stressors.

- **Jasmonates**: Jasmonates, such as methyl jasmonate, regulate plant responses to biotic stress, such as pest attacks, and abiotic stress, such as drought. They trigger defensive responses that protect plants from pathogens and herbivores. Additionally, jasmonates have been shown to influence processes like root growth, fruit ripening, and senescence.

- **Abscisic Acid (ABA)**: ABA is commonly known for its role in plant responses to environmental stress, particularly drought. It regulates stomatal closure, reducing water loss during times of water scarcity. ABA is also involved in seed dormancy and germination, helping plants adapt to stress conditions by regulating water balance and preserving moisture in the soil.

4.2. Role of PGRs in Enhancing Crop Yield and Quality:

PGRs play a significant role in improving crop yields and enhancing the quality of agricultural products. Their ability to manipulate plant growth, flowering, fruit setting, and ripening is crucial for optimizing productivity:

- **Auxins**: These are extensively used to increase fruit size and ensure proper fruit retention in crops like mangoes, tomatoes, and grapes. By preventing premature fruit drop, auxins ensure that fruits reach maturity and contribute to higher overall yields.

- **Gibberellins**: Gibberellins are applied in horticultural crops to boost fruit size, making them highly valuable in the commercial production of grapes and citrus. In cereals, gibberellins promote faster growth and increase biomass, directly contributing to yield enhancement.

- **Cytokinins**: These are used to promote shoot development and delay leaf senescence, thus increasing the aesthetic and commercial value of ornamental plants. In agriculture, delaying senescence also prolongs the productive life of crops and enhances post-harvest longevity in leafy vegetables.

- **Ethylene Releasers**: Ethylene-releasing compounds like ethephon help in synchronizing fruit ripening, ensuring that crops like bananas, tomatoes, and pineapples ripen uniformly, making harvesting more efficient and profitable.

- **Growth Retardants**: Growth retardants like paclobutrazol are used in mango cultivation to control excessive vegetative growth, encouraging better fruit set and yield. By regulating plant height and shifting energy towards reproductive growth, these PGRs ensure higher quality yields.

4.3. Stress Tolerance:

PGRs are integral to improving plant resilience against environmental stresses:

- **Brassinosteroids** and **salicylic acid** help plants cope with abiotic stress factors like drought, salinity, and extreme temperatures. These PGRs enhance photosynthesis, water use efficiency, and nutrient uptake, allowing plants to maintain growth and productivity even under unfavorable conditions.

- **Jasmonates**: Jasmonates such as methyl jasmonate are used to induce resistance against pests and pathogens, providing a natural alternative to chemical pesticides. These PGRs activate the plant’s defense system, helping it ward off biotic stress while maintaining growth and development.

4.4. Regulation of Flowering and Ripening:

PGRs are essential in controlling the timing and uniformity of flowering and ripening:

- **Gibberellins** and **cytokinins** are widely used to induce flowering in fruit trees such as apples and citrus. These hormones synchronize the flowering process, ensuring better fruit set and higher yields.
- **Ethylene Releasers**: Ethylene plays a pivotal role in regulating fruit ripening. PGRs like ethephon are applied in crops like bananas, tomatoes, and pineapples to induce uniform ripening, ensuring that fruits reach optimal market quality at the same time.

4.5. General Information of PGRs:

PGR Type	Example	Use/Application	Crop Example	Additional Information
Auxins	Indole-3-Acetic Acid (IAA)	Root formation, fruit drop prevention, apical dominance, cell elongation, vascular tissue development	Mango, Tomato, Grapes	IAA is the most common naturally occurring auxin, often involved in cell division and expansion.
	Naphthalene Acetic Acid (NAA)	Root initiation, thinning of flowers and fruits, prevents premature fruit drop	Apples, Pears, Oranges	NAA is synthetic and widely used to encourage root development in plant propagation.
Gibberellins	GA3	Stem elongation, fruit enlargement, germination, breaks dormancy, increases fruit set	Grapes, Citrus, Rice	Gibberellins play a role in mobilizing stored nutrients in seeds during germination.
	GA4+GA7	Increases flower size, enhances fruit quality,	Grapes, Apples	A mixture of GA4 and GA7 is often used to

		promotes internode elongation		improve fruit set and size in commercial crops.
Cytokinins	Benzylaminopurine (BAP)	Cell division, shoot development, delays leaf senescence, promotes nutrient mobilization	Ornamental plants, Vegetables	Cytokinins like BAP are essential in tissue culture for shoot proliferation and regeneration.
	Kinetin	Delays aging in leaves, promotes seed germination, regulates nutrient allocation	Corn, Tobacco, Wheat	Kinetin is a synthetic cytokinin known for its role in cell differentiation and senescence delay.
Ethylene Releasers	Ethephon	Fruit ripening, abscission, flower induction in pineapples, breaks seed dormancy, induces flowering in ornamental plants	Bananas, Pineapple, Tomatoes	Ethephon releases ethylene, which is essential for uniform ripening and flower induction.
	Ethylene Gas	Fruit ripening, flowering, enhances sugar concentration in fruits	Tomatoes, Bananas, Apples	Ethylene is crucial for triggering fruit ripening and is naturally produced by most plants.
Growth Retardants	Paclobutrazol	Controls vegetative growth, enhances flowering, reduces shoot elongation, stress tolerance	Mango, Cotton, Tea	Paclobutrazol inhibits gibberellin biosynthesis, thus controlling excessive vegetative growth.
	Chlormequat Chloride (CCC)	Reduces stem elongation, strengthens plant structure,	Wheat, Barley,	CCC is commonly used in cereals to

		promotes root development	Cotton	prevent lodging by strengthening stems.
Brassinosteroids	24-Epibrassinolide	Stress tolerance (drought, salt), nutrient uptake, enhances growth rate, increases crop yield	Cereals, Legumes, Rice	Brassinosteroids are natural compounds that help plants cope with environmental stress.
	Brassinolide	Increases resistance to environmental stresses, enhances crop quality, regulates growth	Cotton, Vegetables, Rice	Brassinolide improves nutrient absorption and helps in the production of healthier crops.

5. Application of PGRs

PGRs are widely used across various crops to optimize growth and boost productivity. They offer different benefits depending on the specific regulator and the type of crop. Here's a deeper look into the applications:

- **Yield Improvement:**
  - ✓ **Auxins** like Indole-3-Acetic Acid (IAA) are used to stimulate root development, which helps the plant absorb more water and nutrients, leading to healthier growth and higher yields.
  - ✓ **Gibberellins** (GA3) are essential for promoting stem elongation and fruit enlargement. In crops like grapes and citrus, they can increase fruit size and weight, directly contributing to better yields. Gibberellins also help break seed dormancy, ensuring that plants germinate faster and more uniformly.
- **Quality Control:**
  - ✓ **Ethylene releasers** such as Ethephon are widely applied in crops like bananas and tomatoes to ensure uniform ripening. Uniform ripening is crucial for large-scale commercial farming where fruits need to be harvested at the same time for efficient processing and distribution.

This improves the quality and marketability of the produce, as consumers prefer fruits that are uniformly ripened and visually appealing.

- **Stress Management:**
  - ✓ **Brassinosteroids** play a crucial role in helping plants deal with stressful conditions like drought and high salinity. They increase the plant's ability to take up nutrients even in less-than-ideal growing conditions, improving the overall health and resilience of the crop.
  - ✓ **Salicylic Acid** helps plants build stronger defense mechanisms against pathogens and environmental stressors. It is particularly useful in managing diseases and boosting the plant's immunity, enabling crops to survive adverse weather or pest infestations.
- **Post-Harvest Benefits:**
  - ✓ **Cytokinins** delay senescence (the aging process) in plants. This is important for extending the shelf life of crops, particularly leafy vegetables and ornamental plants. By delaying aging, cytokinins help maintain freshness and appearance, which is crucial for both the local and export markets.

6. Conclusion:

Plant Growth Regulators (PGRs) have emerged as critical components in advancing modern agricultural practices, playing a pivotal role in enhancing plant productivity, improving crop quality, and increasing resilience to environmental stresses. These compounds, including auxins, gibberellins, cytokinins, ethylene releasers, brassinosteroids, and salicylic acid, enable farmers to have greater control over various stages of plant growth and development. For example, auxins promote root growth and prevent premature fruit drop, while gibberellins aid in stem elongation and fruit enlargement, leading to better yield outcomes. Ethylene releasers ensure uniform fruit ripening, improving the marketability of crops like bananas and tomatoes, and cytokinins delay senescence, extending the shelf life of perishable produce.

As global agricultural systems face mounting challenges, particularly due to climate change and increasing food demand, PGRs offer a valuable solution by boosting stress tolerance. Compounds like brassinosteroids help plants withstand drought, salinity, and other adverse conditions, ensuring stable yields even under stress. Furthermore, the post-harvest benefits of PGRs, such as maintaining crop freshness and quality, make them indispensable in modern supply chains.

Looking ahead, PGRs will continue to be vital in sustainable farming, enabling more efficient use of resources while ensuring higher productivity. Their ongoing development and optimization, particularly in terms of environmentally friendly formulations and application methods, will help secure a more resilient and sustainable agricultural future.

7. Discussion:

The application of Plant Growth Regulators (PGRs) holds immense potential for addressing future agricultural challenges, but their sustainable use requires careful consideration. One of the key areas for improvement is the development of more eco-friendly PGR formulations that minimize any negative impact on soil health, biodiversity, and overall ecosystem balance. While synthetic PGRs have proven effective, their long-term environmental effects need more research. Natural alternatives, such as PGRs derived from plant extracts or microorganisms, could provide safer, biodegradable options that ensure the same efficacy without harmful residues.

In addition, optimizing application methods for PGRs will be essential for enhancing their efficiency. Current methods often lead to excess use or uneven distribution, potentially causing environmental contamination and increasing costs for farmers. Innovations in precision agriculture, such as targeted spraying through drones, slow-release formulations, or microencapsulation, could ensure that PGRs reach specific plant tissues more effectively. This would not only reduce environmental risks but also increase the cost-effectiveness of PGR use.

Another critical aspect is the integration of PGRs within broader sustainable agricultural practices. As agriculture increasingly shifts toward practices like organic farming, the compatibility of PGRs with these systems will be important. Research must focus on the interaction between PGRs and soil microbiomes, plant health, and long-term productivity to ensure they contribute positively to sustainability goals.

Ultimately, the sustainable and efficient use of PGRs will be vital for improving global food security while addressing the environmental pressures facing modern agriculture.

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