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Emerging Trends in Plant Growth Regulators: Innovations and Applications

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The review offers a comprehensive and illuminating summary of the most recent developments in the area of plant growth regulators (PGRs). The purpose of this research is to investigate the rapid advancements and uses of plant growth regulators (PGRs), which are vital instruments for maximizing the growth and productivity of plants. A wide variety of novel PGR compounds and technologies have been created as a result of recent breakthroughs. These new technologies and compounds provide considerable enhancements over the conventional methods. This discusses important discoveries such as innovative synthetic plant growth regulators (PGRs) and biostimulants that improve plant growth, resistance to stress, and crop output. Specifically, it investigates the manner in which these improved PGRs are developed to target certain physiological processes, which ultimately results in treatments that are more precise and successful in crop management. In addition, the study investigates the role that developing technologies play in the implementation of PGRs. These technologies include smart delivery systems and precision agricultural methods, which make it possible to adjust treatments to the individual requirements of plants and the circumstances of their environments. Additionally, the incorporation of PGRs into agricultural operations that are environmentally responsible. It highlights the potential for these advances to help to environmentally friendly agriculture by lowering the dependency on chemical inputs and enhancing the efficiency with which resources are used. The significance of these technological developments in solving global concerns such as climate change and food security is emphasized in the article. The revolutionary effect that new PGR technology have had on contemporary agricultural practices. This article highlights the potential for these technologies to improve crop productivity and promote sustainable agriculture practices by providing a detailed review of current developments and the practical consequences of those trends.

Keywords: PGR; crop; food; plants; growth; treatments.

1. INTRODUCTION

Plant growth regulators (PGRs), also known as plant hormones, are a diverse group of organic compounds that regulate various aspects of plant growth and development. These substances, which occur naturally within plants or are synthetically produced, play crucial roles in coordinating physiological processes and responses to environmental stimuli. Unlike nutrients, which primarily contribute to the structural and functional components of plants, PGRs specifically influence plant behaviours at the molecular and cellular levels [1].

The primary classes of PGRs include auxins, gibberellins, cytokinins, abscisic acid, and ethylene, each with distinct functions and mechanisms of action. Auxins are pivotal in regulating cell elongation, root initiation, and apical dominance, which influences how plants grow towards light and establish root systems [2]. Gibberellins are involved in processes such as seed germination, stem elongation, and flowering, promoting cell division and growth in various plant tissues. Cytokinins, on the other hand, primarily stimulate cell division and shoot formation, affecting the balance between shoot and root growth and influencing leaf senescence [3]. Abscisic acid (ABA) is crucial for managing plant responses to environmental stressors, including drought and salinity. It promotes stomatal closure to conserve water and helps plants adapt to adverse conditions by regulating gene expression related to stress tolerance [4]. Ethylene, another key PGR, regulates fruit ripening, flower senescence, and responses to mechanical stress. It acts as a signalling molecule, orchestrating various developmental processes and stress responses. PGRs can be classified based on their origin and chemical structure [5]. Endogenous PGRs are naturally occurring within plants and are synthesized in specific tissues, where they exert localized effects. These include auxins, gibberellins, cytokinins, ABA, and ethylene. Exogenous PGRs, in contrast, are applied externally to influence plant growth and development. They include synthetic analogues of natural hormones or entirely new compounds designed to mimic or alter hormonal activity [6].

The effects of PGRs are mediated through complex signalling pathways and interactions with plant receptors. Once a PGR binds to its specific receptor, it triggers a cascade of biochemical events that ultimately result in the desired physiological response. For example, auxins influence gene expression by modulating the activity of transcription factors, leading to changes in cell elongation and differentiation [7]. The application of PGRs has profound implications for agriculture and horticulture. By manipulating PGR levels, farmers and growers can achieve desired plant characteristics such as increased yield, improved fruit quality, and enhanced resistance to diseases and pests [8]. For instance, synthetic auxins are used to regulate fruit setting and prevent premature fruit drop, while gibberellins are applied to extend the growing season and increase crop size. Plant growth regulators are essential for controlling and optimizing plant growth and development [9]. Their ability to influence a wide range of physiological processes makes them valuable tools in agriculture and plant science. Understanding the functions and mechanisms of PGRs enables researchers and practitioners to harness their potential for improving crop productivity, managing plant health, and addressing challenges in modern agriculture [10].

2. OVERVIEW OF PLANT GROWTH REGULATORS

Plant growth regulators (PGRs), commonly referred to as plant hormones, are integral to the regulation of plant growth and development. These chemical substances, whether naturally occurring within plants or synthetically applied, orchestrate a wide array of physiological processes, enabling plants to adapt, thrive, and reproduce [11]. The primary classes of PGRs include auxins, gibberellins, cytokinins, abscisic acid, and ethylene. Each class plays a distinct role in regulating growth, development, and responses to environmental stimuli [12].

2.1 Auxins

Auxins are perhaps the most well-known group of plant hormones and play a central role in various growth processes. These hormones are primarily synthesized in the apical meristems—the growing tips of roots and shoots [12]. Auxins influence plant growth through several mechanisms:

Cell Elongation: Auxins promote cell elongation by loosening the cell wall, allowing cells to expand. This process is critical for stem growth and root development. By regulating the direction and rate of elongation, auxins enable plants to adapt to environmental conditions such as light and gravity [13].

Apical Dominance: Auxins are involved in apical dominance, where the main shoot suppresses the growth of lateral buds. This ensures that the plant grows taller rather than wider, which is advantageous for competing for light [14].

Root Development: Auxins stimulate the formation of lateral roots, which enhances the plant’s ability to absorb water and nutrients from the soil. This is particularly important for young plants as they establish their root systems [15].

Fruit Development: Auxins are also critical in fruit development, where they can influence fruit set and prevent premature fruit drop. Synthetic auxins are often used in agriculture to manage these processes and improve yield [16].

2.2 Gibberellins

Gibberellins are another crucial class of PGRs that regulate various growth and developmental processes. They are synthesized in young tissues and act primarily on the following:

Seed Germination: Gibberellins help break seed dormancy and promote germination by stimulating enzymes that mobilize stored nutrients in seeds. This is essential for the successful establishment of new plants [17].

Stem Elongation: These hormones promote cell division and elongation in stems, leading to increased plant height. This effect is particularly noticeable in crops where increased stem length can improve light capture and yield [18].

Flowering and Fruit Development: Gibberellins influence the timing of flowering and can enhance fruit development. They are often used in horticulture to synchronize flowering and increase fruit size [19].

Growth Regulation: By promoting cell elongation and division, gibberellins contribute to overall plant growth and can be used to control plant size and shape [20].

2.3 Cytokinins

Cytokinins are key regulators of cell division and differentiation. They are synthesized in the roots and transported to other parts of the plant. Their main functions include:

Cell Division: Cytokinins stimulate cell division, leading to the development of new shoots and leaves. This is essential for the growth of plant organs and overall plant vigour [21].

Shoot Formation: By promoting the formation of new shoots, cytokinins balance growth between roots and shoots. This is crucial for maintaining healthy plant architecture and productivity [22].

Leaf Senescence: Cytokinins delay leaf senescence, which prolongs the lifespan of leaves and improves photosynthesis. This effect can enhance plant productivity and quality [23].

Root Growth Interaction: The interaction between cytokinins and auxins regulates root and shoot growth. Proper balance between these hormones is essential for optimal plant development [24].

2.4 Abscisic Acid (ABA)

Abscisic acid is a hormone primarily involved in stress responses and developmental processes. It is synthesized in response to environmental stressors and regulates several key functions:

Water Stress Management: ABA plays a crucial role in managing water stress by promoting stomatal closure. This reduces water loss during drought conditions and helps plants conserve moisture [25].

Seed Dormancy: ABA induces seed dormancy, preventing premature germination and ensuring that seeds remain viable until conditions are favourable for growth [26].

Stress Tolerance: ABA enhances the plant's ability to withstand various stress conditions, including high salinity and low temperatures. It regulates gene expression related to stress tolerance and adaptive responses [27].

Growth Regulation: In addition to its role in stress responses, ABA can inhibit growth under unfavourable conditions, allowing plants to redirect resources towards survival rather than growth [28].

2.5 Ethylene

Ethylene is a gaseous hormone that regulates a range of developmental processes and stress responses. Its effects include:

Fruit Ripening: Ethylene is well known for its role in fruit ripening. It accelerates the maturation of fruits, leading to changes in colour, texture, and flavour. This is a critical process for agricultural and horticultural industries [29].

Flower Senescence: Ethylene influences flower senescence, leading to the aging and eventual shedding of flowers. This helps regulate the timing of reproduction and seed production [30].

Stress Responses: Ethylene is involved in plant responses to mechanical stress, such as wounding and overcrowding. It helps plants adapt to physical damage and optimize growth conditions [31].

Growth Regulation: Ethylene can influence plant growth by promoting or inhibiting certain processes, such as root growth and cell elongation. Its effects are context-dependent and vary based on environmental conditions [32].

3. INNOVATIONS IN PGRS

Plant growth regulators (PGRs) are pivotal in modern agriculture and horticulture, offering tools to optimize plant growth, development, and stress responses. As research and technology advance, innovative approaches to PGRs are emerging, reshaping how we manage and enhance plant growth [33]. These innovations encompass new synthetic compounds, biostimulants, nanotechnology, and advanced application techniques, each contributing to more effective and sustainable agricultural practices.

3.1 Novel Synthetic PGRs

Recent advancements in synthetic chemistry have led to the development of novel PGRs that offer improved efficacy and specificity compared to traditional compounds. These innovations aim to enhance the precision of plant growth regulation and address specific agricultural needs.

Enhanced Auxins: Synthetic auxins, such as 2, 4-D have been refined to offer greater control over weed management and crop development. Newer formulations are designed to minimize environmental impact and reduce off-target effects, making them more effective in controlling unwanted vegetation without harming crops [34].

Advanced Gibberellins: New gibberellin analogues have been developed to improve their effectiveness in promoting seed germination, stem elongation, and flowering. These advanced compounds are tailored to specific crops and growth conditions, enhancing yield and quality [35].

Targeted Cytokinins: Innovative cytokinins with enhanced stability and bioactivity are being used to optimize shoot development and delay leaf senescence. These new compounds offer more precise control over plant growth and productivity, particularly in high-value crops [36].

3.2 Biostimulants

Biostimulants are a class of substances that enhance plant growth and stress tolerance through mechanisms beyond traditional hormonal effects. Recent advancements in biostimulant technology have led to the development of more effective and sustainable products [37].

Natural Biostimulants: Extracts from natural sources, such as seaweed, algae, and microbial products, have gained popularity for their ability to improve plant health and resilience. These biostimulants work by modulating plant metabolism, enhancing nutrient uptake, and promoting growth under stress conditions. For instance, seaweed extracts are known to improve drought tolerance and enhance root development [38].

Synthetic Biostimulants: Recent innovations in synthetic biostimulants focus on creating compounds that mimic the effects of natural substances while offering enhanced stability and effectiveness. These synthetic biostimulants are designed to improve plant growth and stress tolerance in a more controlled manner, providing consistent results across different environments [39].

3.3 Nanotechnology in PGRs

Nanotechnology has introduced a new dimension to plant growth regulation, offering novel approaches to PGR delivery and effectiveness.

Nano-Encapsulation: Nano-encapsulation techniques involve enclosing PGRs in nanoparticles, allowing for controlled release and targeted delivery. This method enhances the efficiency of PGR applications by reducing losses and improving uptake by plant tissues. For example, nano-encapsulated auxins can be delivered directly to the root zone, promoting more uniform and effective growth [40].

Nano-Particles for Targeted Delivery: Nanoparticles can be engineered to deliver PGRs to specific plant tissues or organs. This targeted approach ensures that the hormones are applied precisely where needed, minimizing waste and maximizing their effects. Nano-structured PGRs can also improve the stability and longevity of the compounds, leading to longer-lasting benefits [41].

Smart Delivery Systems: Advanced nanotechnology has led to the development of smart delivery systems that respond to environmental stimuli. These systems release PGRs in response to factors such as temperature, pH, or moisture, providing dynamic and adaptive regulation of plant growth [42].

3.4 Precision Agriculture and PGR Application

The integration of precision agriculture technologies with PGR application has transformed how growth regulators are used in farming. Precision agriculture leverages data-driven approaches to optimize PGR use, leading to more efficient and sustainable practices.

Remote Sensing and GPS: Remote sensing technologies, such as satellite imagery and drones, are used to monitor plant health and growth in real-time. By integrating this data with GPS mapping, farmers can apply PGRs more precisely, targeting specific areas that need intervention. This approach reduces waste, minimizes environmental impact, and improves the effectiveness of PGR applications [43].

Variable Rate Application: Variable rate technology (VRT) allows for the application of PGRs at varying rates across a field based on real-time data. This technique ensures that PGRs are applied in optimal quantities, tailored to the specific needs of different areas within a field. VRT improves resource use efficiency and enhances crop performance [44].

Decision Support Systems: Advanced decision support systems use data analytics and modelling to guide PGR application decisions. These systems integrate information on weather, soil conditions, and plant health to recommend the best timing and dosage of PGRs. This data-driven approach enhances the precision and effectiveness of growth regulation [45].

3.5 Sustainable and Eco-Friendly Innovations

Sustainability is a key focus in the development of new PGR technologies. Innovations are increasingly aimed at reducing the environmental impact of PGRs and promoting eco-friendly practices.

Reduced Chemical Inputs: Innovations in PGRs are focusing on minimizing the use of synthetic chemicals by developing more efficient and targeted compounds. For example, advanced formulations with lower application rates can achieve the desired effects with reduced environmental impact [46].

Biodegradable PGRs: Research into biodegradable PGRs aims to create compounds that break down naturally in the environment, reducing the risk of accumulation and pollution. These biodegradable products offer a more sustainable alternative to traditional PGRs, aligning with eco-friendly agricultural practices [47].

Integrated Pest Management: The use of PGRs in conjunction with integrated pest management (IPM) practices promotes sustainable agriculture by reducing the reliance on chemical pesticides. PGRs that enhance plant resistance to pests and diseases can complement IPM strategies, leading to healthier and more resilient crops [48].

Table 1. Review of literature

Crop	PGR Used	Effects/Applications	References
Wheat	Gibberellins (GA3)	Increases stem elongation, enhances grain yield, promotes seed germination.	Ali & Ahmad [4], Hedden & Thomas [36]
Rice	Nano-PGRs	Enhances nutrient uptake, reduces chemical inputs, improves water efficiency, and increases yield.	Mahmood & Mathur [57], Hussain & Ali [38]
Tomato	Seaweed extracts	Improves drought tolerance, enhances fruit yield and quality, strengthens stress tolerance.	Crouch & van Staden [19], Ahmad & Rasool [2]
Maize	Auxins (IAA)	Stimulates root growth, improves plant height and leaf area, increases grain production under stress.	Patten & Glick [67], Blum [12]
Cotton	Cytokinins	Delays leaf senescence, enhances boll retention, increases fiber quality, and improves yield.	Roberts & Rajagopal [78], Schaller & Kieber [81]
Soybean	Brassinosteroids (BR)	Promotes stress tolerance, enhances root and shoot development, improves photosynthesis and seed yield.	Bajguz & Piotrowska-Niczyporuk [7], Pharis [46]
Grapes	Ethylene	Induces ripening, increases uniformity in grape clusters, and improves post-harvest quality.	McAtee & Karim [58], Nakashima & Yamaguchi-Shinozaki [62]
Apple	Abscisic acid (ABA)	Promotes fruit ripening, enhances drought tolerance, and improves water-use efficiency.	Wang & Cheng (2020), Vlot & Dempsey [92]
Cucumber	Jasmonic acid (JA)	Enhances defence mechanisms against pests, improves stress tolerance and promotes flower development.	Park & Lee [66], Song & Dai [86]
Banana	Cytokinins	Promotes cell division, increases bunch size, delays leaf senescence, and enhances post-harvest quality.	Oikawa & Takai [65], Kim & Hong [44]
Potato	Gibberellins (GA3)	Stimulates tuber formation, increases tuber size, and enhances overall yield.	Liu & Wang [50], Rajasekaran & Blake [73]
Peppers	Ethylene	Enhances fruit ripening and colouring,	McAtee & Karim [58],

Crop	PGR Used	Effects/Applications	References
		improves post-harvest shelf life, and increases uniformity of ripening.	Wang & Lin (2015)
Strawberry	Auxins (IAA)	Promotes fruit set, increases berry size, and enhances overall fruit yield.	Sugimoto & Sakai [87], Rezaei & Zein [77]
Sugarcane	Gibberellins (GA3)	Improves stem elongation, enhances sugar content, and increases crop yield.	Rasmussen & Andersen [74], Saini & Singh [80]
Tobacco	Abscisic acid (ABA)	Enhances drought resistance, improves leaf quality, and enhances stress tolerance mechanisms.	Kurepin & Pharis [46], Peleg & Blumwald [68]
Citrus	Cytokinins	Increases fruit size, improves flowering, enhances overall fruit quality, and delays senescence.	Schippers [83], Vlot & Dempsey [92]
Chili	Jasmonic acid (JA)	Enhances resistance to fungal infections, promotes flowering, and increases fruit yield under stress.	Schaller & Kieber [81], Qu & Luo [71]
Ginger	Brassinosteroids (BR)	Increases rhizome size, enhances drought and heat tolerance, and improves antioxidant activity.	Bajguz & Piotrowska-Niczyporuk [7], Sharma & Ramawat [84]

Table 2. The use of different PGRs on various vegetables

PGR	Vegetable	Purpose	Examples of Application
Auxins (e.g., IAA, IBA, NAA)	Tomato	Promote rooting, prevent fruit drop	Used in nursery to stimulate root growth in cuttings; applied to flowers to reduce fruit drop.
Gibberellins (GA3)	Cucumber	Promote flowering, increase fruit size	Applied to promote early flowering and increase fruit size in seedless cucumber varieties.
Cytokinins (e.g., BAP, Kinetin)	Lettuce	Delay leaf senescence, promote cell division	Sprayed on leaves to delay yellowing, enhancing shelf life.
Ethylene (Ethrel)	Tomato	Uniform fruit ripening	Applied to induce synchronized ripening for uniform harvest.
Abscisic Acid (ABA)	Spinach	Improve stress tolerance	Used to enhance drought tolerance in spinach, especially under water stress conditions.
Brassinosteroids	Broccoli	Promote growth, enhance stress resistance	Applied to improve cold tolerance and enhance overall plant vigour.
Jasmonates	Peppers	Induce defence mechanisms	Used to increase resistance to pests and diseases in pepper plants.

4. APPLICATIONS OF EMERGING PGR TECHNOLOGIES

Plant growth regulators (PGRs) have long been fundamental in agricultural and horticultural practices for their ability to influence plant growth, development, and responses to environmental stress. The rise of new technologies and innovations in PGRs has expanded their applications, enabling more sustainable, efficient, and targeted approaches to plant management. Emerging PGR technologies are now applied in various sectors, including crop yield enhancement, environmental stress management, post-harvest quality control, pest and disease management, and biotechnological advancements [49]. Below are key applications of these emerging PGR technologies:

4.1 Enhancing Crop Yield and Productivity

One of the most significant applications of PGRs is improving crop yield and quality. Advances in synthetic and natural PGRs allow for precise control over various growth stages, including seed germination, vegetative growth, and fruit development [50].

Auxins: These are used to promote root development, leading to better nutrient uptake and stronger plants. New synthetic auxins offer enhanced control in crops such as maize, wheat, and rice, which are critical for global food security [51].

Gibberellins: These regulators are vital for stem elongation and fruit development. They are applied in sugarcane to increase stalk length and in grapes to improve fruit size, leading to better market quality and higher yields [52].

Cytokinins: Cytokinins delay leaf senescence, thus extending the productive life of crops like lettuce, tobacco, and various vegetables. This results in higher biomass accumulation and extended harvest periods [53].

4.2 Mitigating Environmental Stress

With climate change intensifying the frequency and severity of environmental stressors such as drought, heat, and salinity, PGRs are being leveraged to help plants cope with these challenges.

Abscisic Acid (ABA): ABA is known for its role in enhancing drought tolerance by closing stomata and reducing water loss. Recent applications of synthetic ABA analogs help plants endure prolonged periods of water scarcity, making them highly useful in arid regions where crops like maize, wheat, and soybeans are susceptible to drought [54].

Ethylene Modulators: By controlling ethylene production, plants can better withstand abiotic stresses like extreme temperatures and physical damage. Ethylene inhibitors delay plant senescence and fruit ripening, enabling crops like tomatoes, bananas, and apples to survive harsh conditions [55].

Biostimulants: Natural extracts, such as seaweed, algae, and microbial products, are gaining attention for enhancing stress tolerance. Biostimulants promote root development, improve nutrient uptake, and strengthen plant resilience to environmental stress, benefiting crops like olive trees, grapes, and cereals grown in marginal environments [56].

4.3 Post-Harvest Management and Shelf-Life Extension

Emerging PGR technologies are critical in the post-harvest sector, where they are used to extend the shelf life of produce, reduce waste, and ensure food quality during transport and storage.

Ethylene Inhibitors: Ethylene is a plant hormone that regulates ripening in fruits such as bananas, tomatoes, and avocados. Ethylene inhibitors like 1-Methylcyclopropene (1-MCP) block ethylene receptors, delaying ripening and extending shelf life, which is particularly important for perishable goods in international trade [57].

Post-Harvest Biostimulants: New biostimulant formulations improve the firmness, colour retention, and resistance to decay in fruits like strawberries, cherries, and grapes. These biostimulants are applied immediately after harvest to extend the freshness and quality of the produce [58].

Ripening Control: PGRs are used to synchronize fruit ripening for uniformity in harvest. This is especially useful for crops like tomatoes, where uniform ripening ensures a more efficient harvest process, reducing labour costs and post-harvest losses [59].

4.4 Pest and Disease Resistance

Emerging PGR technologies are playing an increasingly important role in integrated pest management (IPM) by strengthening plant defences against pathogens and pests. PGRs can enhance the plant's natural immunity and reduce dependency on chemical pesticides [60].

Salicylic Acid (SA): This PGR induces systemic acquired resistance (SAR), a plant’s innate defines mechanism against pathogens. Enhanced salicylic acid derivatives are used to bolster resistance in crops like tomatoes, wheat, and rice, reducing susceptibility to common fungal and bacterial infections [61].

Jasmonic Acid: In addition to promoting plant growth, jasmonic acid plays a role in plant defence by activating responses against herbivores and pathogens. Recent innovations have improved the efficacy of jasmonic acid applications, helping crops like cotton and maize resist pest infestations without excessive pesticide use [62].

4.5 Biotechnology and Genetic Engineering

Emerging PGR technologies are instrumental in genetic engineering, helping researchers modify plant growth pathways and develop crops with enhanced traits. Biotechnology applications of PGRs include the manipulation of hormonal pathways to increase plant growth rates, yield potential, and stress tolerance.

CRISPR-Cas9 and PGR Pathways: In genetic engineering, technologies like CRISPR-Cas9 are used to edit genes related to PGR pathways, leading to the development of crops with improved growth characteristics, such as dwarf varieties of rice and wheat, which are less prone to lodging, or drought-resistant maize with enhanced ABA signalling [63].

Transgenic Crops: Biotechnology is also used to develop transgenic plants with overexpressed PGRs, leading to traits such as enhanced disease resistance, higher yields, and extended shelf life. For instance, rice varieties engineered for altered gibberellin production show improved productivity, while transgenic tomatoes with modified ethylene pathways exhibit longer shelf lives and reduced spoilage [64].

4.6 Horticultural Propagation and Seedling Establishment

Horticulture benefits significantly from PGR innovations, especially in plant propagation, rooting, and seedling establishment. This is vital for ornamental plants, nurseries, and the production of high-value crops.

Auxins for Root Development: Auxins like indole-3-butyric acid (IBA) and naphthaleneacetic acid (NAA) are commonly used to stimulate rooting in plant cuttings. This is especially important in ornamental plants, like roses and poinsettias, and fruit trees, where consistent rooting is necessary for large-scale production [65].

Gibberellins for Breaking Seed Dormancy: In species with naturally long dormancy periods, such as grapes, cherries, and certain forest trees, gibberellins are applied to break dormancy and enhance germination rates. This ensures better propagation success and uniform seedling development in nurseries [66].

Cytokinins for Shoot Proliferation: Cytokinins are widely used in tissue culture to promote shoot proliferation in micropropagation. They are essential for propagating plants like orchids and banana trees, where traditional propagation methods are slow or inefficient [67].

4.7 Sustainable Agricultural Practices

Sustainability is a core focus of emerging PGR technologies. New developments are aimed at reducing the environmental footprint of agriculture by minimizing chemical inputs, enhancing resource use efficiency, and promoting eco-friendly alternatives.

Biodegradable PGRs: Research into biodegradable PGRs is increasing, with products that break down naturally in the environment and leave minimal residue. These are especially important in sensitive ecosystems where chemical contamination could disrupt biodiversity [68].

PGRs in Organic Farming: PGRs derived from natural sources, such as plant extracts, seaweed, and beneficial microbes, are being increasingly used in organic farming systems. These biostimulants and natural PGRs improve plant growth and resilience without the use of synthetic chemicals, aligning with the principles of organic and regenerative agriculture [69].

5. CHALLENGES AND FUTURE DIRECTIONS

While the applications of plant growth regulators (PGRs) have shown immense potential in transforming agriculture, horticulture, and biotechnology, several challenges remain that could limit their widespread adoption and effectiveness. Addressing these challenges is essential for ensuring the long-term success and sustainability of PGR technologies [70]. Additionally, emerging trends and research suggest new directions that could further enhance the role of PGRs in modern agriculture. Below are some of the key challenges and future directions for PGR technologies.

5.1 Challenges in the Use of PGRs

Environmental Impact and Residue Concerns: One of the primary challenges of

PGRs, especially synthetic ones, is the potential for environmental contamination. Improper application or overuse can lead to chemical residues in the soil, water, and plants, which may affect non-target organisms and ecosystem health.

Soil and Water Contamination: Some synthetic PGRs may persist in the environment, leading to unintended consequences such as altered soil microbial activity or water pollution. This is a particular concern in regions with intensive agriculture or where PGRs are used extensively [71, 72].

Plant Residues: The potential for chemical residues on food crops is also a concern, especially for consumers demanding organic or chemical-free produce. Regulatory frameworks need to ensure that PGR levels in food products remain within safe limits [73].

5.2 Regulatory Challenges

The regulatory landscape for PGRs can be complex and varies between countries. Different regions have different standards for the approval and use of PGRs, which can hinder the global adoption of certain innovations.

Approval Processes: New PGRs must go through rigorous testing to ensure their safety and efficacy. This can be a time-consuming and expensive process, leading to delays in bringing new products to the market. Additionally, small-scale farmers in developing regions may lack access to these innovative technologies due to regulatory hurdles [74, 75].

International Trade: PGR regulations can also impact international trade, as crops treated with certain PGRs may face restrictions or bans in some markets. This creates challenges for global food supply chains, particularly for countries that rely on exports of PGR-treated produce [76].

5.3 Variable Efficacy across Crop Types and Environments

PGR efficacy can vary depending on the crop type, environmental conditions, and application methods. While PGRs work well in controlled environments, field conditions are often unpredictable, leading to inconsistent results.

Climate Sensitivity: Environmental factors such as temperature, humidity, and soil type can influence how effectively a PGR performs. For example, auxins used for rooting might show excellent results in one region but fail in another due to climatic differences [77].

Crop Specificity: Some PGRs may only be effective for specific plant species or varieties, limiting their broad applicability. This poses a challenge for farmers growing diverse crops, as they may need to invest in multiple PGR formulations, increasing costs and complexity [78].

5.4 High Costs and Accessibility

The cost of developing, producing, and applying PGRs can be prohibitive, particularly for smallholder farmers. Advanced PGR formulations and biotechnological applications, such as CRISPR-modified plants, often require significant investment in both technology and expertise.

Cost of Application: Applying PGRs requires precision, which may involve advanced technologies like drones, sensors, or automated systems. Small-scale farmers may not have access to such technologies, limiting the effectiveness of PGR use [79].

Lack of Knowledge and Training: Farmers may also lack the knowledge and training to properly apply PGRs, leading to misuse or inefficient use, which diminishes their benefits. Training programs and extension services are necessary to ensure that farmers understand how to apply PGRs optimally [80].

5.5 Consumer Acceptance

Consumer attitudes toward PGR-treated crops, particularly those involving synthetic or genetically modified products, can be a barrier to widespread adoption. Many consumers, particularly in developed countries, are becoming increasingly conscious of food safety, environmental impact, and organic labelling.

Perception of Chemicals: Despite the benefits of PGRs, there is often a negative perception of any chemicals applied to crops. Public concerns about food safety and health risks associated with synthetic hormones may limit the market for PGR-treated products [81].

Organic and Sustainable Labels: The rise of the organic and sustainable food movements has led to increased demand for natural alternatives to synthetic PGRs. Farmers may face pressure to use biostimulants or organic PGRs, which are often more expensive or less effective than their synthetic counterparts [82].

6. FUTURE DIRECTIONS OF PGR TECHNOLOGIES

Despite the challenges, ongoing research and innovation in PGR technologies are paving the way for more sustainable, efficient, and widely accepted solutions. Below are some key future directions for PGR technologies.

6.1 Development of Biostimulants and Organic PGRs

One of the most promising areas of future development is the focus on natural PGRs and biostimulants. These products, derived from plant extracts, seaweed, algae, and microbes, offer a more eco-friendly alternative to synthetic PGRs [83].

Natural PGRs: Research into plant-derived PGRs is growing, with the goal of producing hormones that work as effectively as synthetic versions but with fewer environmental and health risks. For example, natural auxins, cytokinins, and gibberellins are being explored for use in organic farming systems [84].

Biostimulants: These are non-hormonal products that enhance plant growth by improving nutrient uptake, stress resistance, and soil health. As consumers and regulators demand more sustainable agricultural practices, the market for biostimulants is expected to grow rapidly [85].

6.2 Precision Agriculture and Digital PGR Applications

The rise of precision agriculture is creating opportunities for more targeted and efficient PGR application. Technologies such as drones, sensors, and artificial intelligence are allowing farmers to apply PGRs more precisely, reducing waste and improving outcomes.

Drone-Based Application: Drones equipped with sensors can monitor plant health and apply PGRs only where and when they are needed, reducing overall usage and minimizing environmental impact [86].

AI-Driven PGR Optimization: Artificial intelligence can analyse data from various sources, such as weather conditions, soil health, and plant growth stages, to recommend optimal PGR dosages and application times. This level of precision ensures maximum efficacy while minimizing resource use [87].

6.3 Biotechnological Integration and Gene Editing

Advances in biotechnology, particularly gene editing tools like CRISPR-Cas9, offer new ways to enhance plant responses to PGRs. By editing the genes responsible for hormone production or signalling, researchers can create crops that are more responsive to PGRs or produce their own hormones in response to environmental cues.

Gene-Edited Crops: Future crops could be engineered to have enhanced hormonal pathways, enabling them to grow faster, resist stress, and produce higher yields without external PGR applications. This could reduce the need for synthetic PGRs while improving crop performance [88].

CRISPR and PGR Pathways: Scientists are already exploring how to modify PGR pathways in crops to optimize growth and yield. For instance, tweaking the gibberellin pathway in rice and wheat has resulted in dwarf varieties that are less prone to lodging, a key concern in grain production [89].

6.4 Sustainable PGR Production

Another future direction is the development of more sustainable production methods for PGRs. This includes using renewable resources, reducing the carbon footprint of manufacturing processes, and creating biodegradable PGR formulations that do not persist in the environment.

Green Chemistry: Researchers are exploring "green chemistry" approaches to produce PGRs with minimal environmental impact. This includes using non-toxic solvents, renewable feedstocks, and energy-efficient processes [90].

Biodegradable PGRs: Innovations in biodegradable PGRs that break down naturally in the soil and water after use will be critical for reducing environmental contamination and ensuring long-term sustainability [91].

Table 3. Sustainable PGR Production

Case Study	Crop	PGR Type	Objective	Application Method	Outcome	Key Benefits
Crop Yield Improvement	Wheat	Synthetic Gibberellins	Enhance grain production	Applied during specific growth stages	Significant increase in grain yield	Higher productivity, improved food security
Stress Tolerance in Vegetables	Tomato	Seaweed Extract Biostimulants	Improve resilience to drought	Foliar application during drought conditions	Higher fruit yield, improved quality	Better stress tolerance, enhanced crop resilience
Sustainable Farming with Nano-PGRs	Rice	Nano-PGRs	Reduce chemical inputs and improve nutrient uptake	Nano-formulations applied to improve nutrient efficiency	Increased yield, reduced environmental impact	Sustainable farming, reduced reliance on chemical fertilizers
Disease Resistance Enhancement	Grapes	Salicylic Acid	Induce systemic acquired resistance to pathogens	Applied preemptively to manage fungal infections	Reduced disease incidence, healthier plants	Reduced chemical fungicide use, eco-friendly disease control
Post-Harvest Quality Control	Bananas	Ethylene Inhibitors (1-MCP)	Delay ripening and extend shelf life	Applied post-harvest to delay ethylene production	Extended shelf life, reduced spoilage	Better storage, reduced food waste

7. CONCLUSION

The evolving field of plant growth regulators (PGRs) represents a significant advancement in modern agriculture, offering solutions to some of the most pressing challenges faced by the industry. PGRs, encompassing both synthetic hormones and natural biostimulants, have proven to be highly effective in regulating plant growth, improving crop yields, enhancing stress tolerance, and promoting sustainable farming practices. As demonstrated through various case studies and practical examples, the application of PGR technologies has allowed farmers and researchers to optimize plant development in ways that were not previously possible. From enhancing grain production in staple crops like wheat to boosting drought resilience in vegetables and promoting sustainable farming with nano-PGRs, these innovations are shaping the future of agriculture. One of the key takeaways from the advancements in PGR technologies is their ability to target specific physiological processes in plants. Whether it's promoting cell division and elongation, delaying senescence, or improving nutrient uptake, PGRs offer a precision-based approach to crop management. This is particularly critical in the context of climate change and global food security. As environmental conditions become more unpredictable, PGRs provide a way for plants to adapt and thrive in adverse conditions, such as drought, salinity, or temperature extremes. By boosting plant resilience, PGRs not only improve yields but also contribute to the overall sustainability of agricultural systems. Moreover, the shift towards natural and sustainable PGRs, such as biostimulants derived from seaweed or microbial extracts, underscores the growing demand for environmentally friendly farming practices. These natural products are increasingly being adopted as alternatives to synthetic chemicals, aligning with consumer preferences for organic and chemical-free produce. Additionally, the integration of cutting-edge technologies like nano-PGRs and precision agriculture tools offers even more efficient and sustainable ways to apply PGRs, reducing chemical inputs and minimizing environmental impact. However, the successful implementation of PGRs is not without its challenges. Regulatory hurdles, particularly in the approval and use of synthetic PGRs, can slow down the adoption of new innovations. Moreover, the cost of PGR technologies, especially advanced formulations such as nano-PGRs, may limit accessibility for small-scale farmers. There is also the issue of consumer perception, with some skepticism surrounding the use of plant hormones in food production. Overcoming these barriers will require ongoing research, education, and policy support to ensure that PGR technologies are accessible, safe, and effective.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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