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The Utilization of Plant Growth Regulators (PGRs) in Agricultural Application and The Effecting Mechanisms

Tarımsal Uygulamalarda Bitki Büyüme Düzenleyicilerinin (BBD) Kullanımı ve Etki Mekanizmaları

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ABSTRACT

Plants, which lack a sophisticated endocrine system, utilize growth regulators (phytohormones) naturally produced within their bodies to grow, develop, and respond to environmental factors. Many physiological processes in plants occur under the control of hormones that are continuously interacting with each other in a balance. Plant growth regulators are classified into two main categories: growth simulators (e.g auxin, gibberellic acid, cytokinin.) and growth inhibitors (e.g. absisic acid ethylene). They play a role in various processes such as plant elongation, branching, germination, fruit growth, flowering, cell division, root development, and stress responses. This article provides a detailed examination of how plant growth regulators are used in agriculture and their effects on physiological processes. Research on these regulators is of great importance for agricultural productivity and sustainability. They enhance plant growth, improve stress resistance, leading to higher yields and increase product quality. Additionally, they offer opportunities for multiple harvests with shorter growth periods and optimize resource use. Thus, while the economic benefits are provided, environmental impacts are also minimized. Such research contributes to the development of innovative agricultural techniques, playing a critical role for increasing global food demand, ensuring food security.

Keywords: Agriculture, Growth inhibitors, Growth simulators, Plant growth regulators

ÖZ

Gelişmiş bir endokrin sistemi olmayan bitkiler, büyümek, gelişmek ve çevresel faktörlere yanıt oluşturmak için vücutlarında doğal olarak ürettikleri büyüme düzenleyicilerini (fitohormon) kullanmaktadırlar. Bitkide meydana gelen fizyolojik süreçlerin birçoğu bir denge içerisinde birbirileriyle sürekli etkileşim halinde olan hormonların kontrolünde gerçekleşmektedir. Bitki büyüme düzenleyicileri büyümeyi teşvik edenler (örn; oksin, giberellin, sitokinin, …) ve büyümeyi baskılayanlar (örn; absisik asit, etilen) olmak üzere iki ana kategoriye ayrılır. Bitki uzaması, dallanma, çimlenme, meyve büyümesi, çiçeklenme, hücre bölünmesi, kök gelişimi ve stres yanıtları gibi süreçlerde etkilidirler. Bu yazı, bitki büyüme düzenleyicilerinin tarımda nasıl kullanıldığını ve fizyolojik süreçlerde nasıl etki gösterdiğini detaylı bir şekilde ele almaktadır. Bu bağlamda, bitki büyüme düzenleyicileri üzerine yapılan araştırmalar, tarımsal verimlilik ve sürdürülebilirlik açısından büyük önem taşımaktadır. Bu düzenleyiciler, bitkilerin daha hızlı ve sağlıklı büyümesini sağlayarak verimi artırır, stres faktörlerine karşı direnci güçlendirir ve ürün kalitesini iyileştirir. Ayrıca, daha kısa yetişme süreleriyle birden fazla hasat imkanı sunar ve kaynak kullanımını optimize eder. Bu sayede, ekonomik kazanç sağlanırken, çevresel etkiler de minimize edilir. Yenilikçi tarım tekniklerinin geliştirilmesine katkı sunan bu araştırmalar, gıda güvenliğini artırarak, dünya nüfusunun artan gıda talebini karşılamada kritik bir rol oynar.

Anahtar Kelimeler: Tarım, Büyüme engelleyicileri, Büyüme uyarıcıları, Bitki büyüme düzenleyicileri

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Introduction

In the physiological processes of plants, numerous chemical compounds that act as stimulators or inhibitors of growth have been identified, with their chemical structures varying. These compounds, referred to as phytohormones when naturally produced by plants, are produced in low concentrations as signaling molecules within plants. They play crucial roles in plant development and growth (Binici et al., 2022; Çakir et al., 2021; Köksal, 2012; Mundiyara et al., 2020). Understanding these regulators and their mechanisms of action is essential for obtaining higher quality, more productive, and stress-tolerant crops. This article aims to provide informative insights into plant growth regulators, their applications in agriculture with advancing technologies, and their effects on physiological processes.

Growth Regulators

External factors such as light, air, water, and various nutrients significantly influence plant growth and development. In addition to these, internal chemical factors also play a role. Plant growth regulators (PGRs) that regulate plant growth are known as plant growth substances. These regulators can be effective in the tissues where they are produced and can be transported to different parts or tissues of the plant, maintaining their effectiveness in other tissues as well. PGRs influence plant development from germination through to harvest and even post-harvest stages (Kumlay & Eryiğit, 2011). They play important roles in germination, organ development, seed maturation, storage, stress response, and other functional processes (Figure 1) (Amoanimaa-Dede et al., 2022). Auxins, gibberellin (GA), cytokinin (CK), abscisic acid (ABA), and ethylene are among the most important regulators known to influence plant growth, yield, and various physiological responses. Jasmonic acid, salicylic acid, brassinosteroids, strigolactones, and polyamines are also considered plant regulators (Amoanimaa-Dede et al., 2022). Growth regulators can be classified into two main categories: those that promote growth and those that inhibit it (Figure 1) (Kumlay & Eryiğit, 2011). They can also be categorized based on their origin as endogenous (produced with in plants) and exogenous (applied externally) regulators.

Growth Simulators

Growth-promoting regulators primarily include auxins (IAA), gibberellins (GAs), and cytokinins (CKs), which regulate key vegetative processes such as elongation, branching, and organogenesis. The concentrations of these three regulators increase during early fruit development and pollination/fertilization. Strigolactones and brassinosteroids are also included in this group (Srivastava & Handa, 2005; Sezgin & Kahya, 2018).

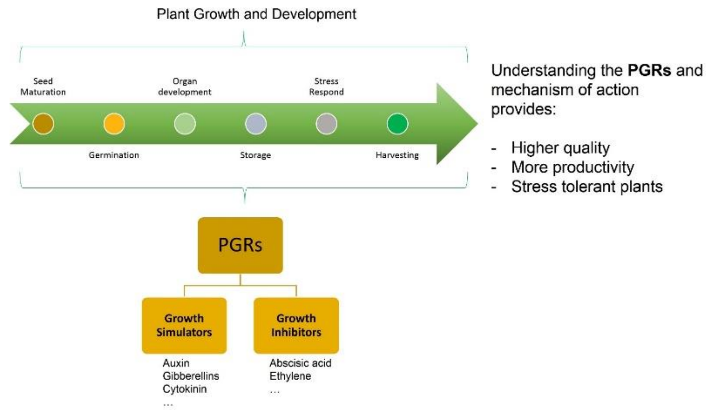

Figure 1.
Classification and function of plant growth regulators (PGRs)

Auxin, first discovered and identified chemically in rice, is one of the most effective hormones in plant growth and development and has been extensively studied. Active forms of auxins include Indole-3-acetic acid (IAA), 4-chloroindole-3-acetic acid (4-Cl-IAA), and phenylacetic acid (PAA), while inactive precursors include Indole-3-pyruvic acid (IPyA), Indoleacetamide (IAM), Indole-3-acetaldoxime (IAOx), Indole-3-acetonitrile (IAN), and Indole-3-acetaldehyde (IAAld). Auxins conjugated with amino acids and sugars, such as Indole-3-butyrate (IBA) and Methyl-IAA (MeIAA), are known as storage forms. Both natural and synthetic forms of auxins are available. Synthetic auxins such as 2,4-dichlorophenoxyacetic acid (2,4-D), 1-naphthaleneacetic acid (NAA), and 4-amino-3,5,6-trichloropicolinic acid (picloram) stimulate the auxin response (Köksal, 2012; Korasick et al., 2013). Auxins are synthesized in high amounts in the apical meristems of plant tissues and are transported to lower tissues, significantly influencing cell elongation and proliferation. They play crucial roles in growth, phototropism, gravitropism, branching, and embryonic pattern formation (Çatak & Atalay, 2020; Liu & Li, 2023; Sezgin & Kahya, 2018). Auxins produced in the apical bud inhibit the growth of lateral buds, allowing the plant to grow with a single main stem. This inhibition mechanism is known as apical dominance. When auxin production stops or the apical bud is removed, the number of branches increases (Çetin, 2002; Rademacher, 2015). Auxins also interact with other compounds to alleviate stress conditions during many abiotic stress processes (Sabagh et al., 2021). When auxin levels are low, plant growth slows, and the number of leaves increases (Çatak & Atalay, 2020).

Gibberellins (GAs), named after the fungus *Giberella fujikuroi* that causes disease in rice, have been extensively studied since 1956, leading to in the isolation of over 50 GAs (Köksal, 2012). According to Sezgin and Kahya (2018), more than 126 forms of GAs exist. GAs, which are predominantly tetrasubstituted diterpenoid compounds, play roles in various physiological processes including photosynthesis, flowering, leaf development, germination, seed dormancy, and cell division. Gibberellic acid (GA_3) is one of the most produced and used GAs associated with these processes (Amoanimaa-Dede et al., 2022; Kaynak & İmamgiller 1997). Typically synthesized in roots, young leaves, and embryos, GAs affect fruit growth and seedless fruit formation. Excessive application of GAs can cause increased plant height, while insufficient application results in dwarf plants (Çatak & Atalay, 2020).

Cytokinins (CKs), distinct from auxins and GAs, were first identified in coconut milk and later isolated from fish sperm in 1995. CKs promote cell division in tissue cultures and have similar chemical structures to kinetin, which was isolated in 1964 from corn kernels and named Zeatin (Köksal, 2012). CKs are involved in processes such as germination, increasing root and shoot biomass, bud development, enhancing antioxidant capacity, stimulating root and shoot development, leaf expansion, delaying senescence, and promoting chlorophyll synthesis. Unlike auxins, they primarily stimulate root formation rather than shoot development (Çatak & Atalay, 2020; Çetin, 2002; Sabagh et al., 2021). CKs also play a role in plant defense mechanisms (Martineau et al., 1994). Their most effective function is known to be in cell division. Natural and synthetic derivatives of CKs include Zeatin, Dihydrozeatin, Isopentyladenine, Dimethyladenine, Kinetin, Benzyladenine, and Benzimidazole (Çetin, 2002). CKs are closely related to nitrogen metabolism, performing their functions mainly in roots (Sakikabara et al., 2016).

Growth Inhibitors

Growth inhibitors are substances that play inhibitory roles in physiological and biochemical processes related to growth and development. ABA and ethylene are well-known growth inhibitors (Çetin, 2002).

ABA is one of the most recognized growth inhibitors, synthesized in almost all plant tissues, with its quantity varying according to environmental conditions. It is produced in fresh leaves, root tips, buds, and seed embryos. ABA is involved in seed and bud dormancy, preventing seed germination, and promoting stomatal closure under extreme weather conditions, thus preventing leaf, flower, and fruit drop. By regulating stomatal closure, ABA helps conserve water during drought conditions (Çatak & Atalay, 2020; Kaynak & Ersoy, 1997).

Ethylene, despite having a more complex chemical structure compared to other regulators, has a simpler structure and is in a gaseous form at normal temperatures. It is synthesized in ripe fruits, aged leaf tissues, and flowers. Ethylene influences various processes such as seed germination, leaf and fruit abscission, and fruit ripening. It is also activated under biotic and abiotic stress conditions. Its gaseous form allows it to spread easily in the environment and affect other plants. For example, ethylene released by one plant can induce flowering in another or cause nearby fruits to ripen (Çatak & Atalay, 2020; Keskin, 2012).

Utilization Areas of Growth Regulators

The primary applications of plant growth regulators include accelerating ripening, enhancing germination capacity, stimulating or delaying flowering, increasing seed production, improving fruit size, enhancing disease resistance, extending fruit shelf life, preventing fruit drop, breaking dormancy, controlling weeds, and promoting organ development in tissue culture studies (Algül et al., 2016). Similar synthetic derivatives of the growth regulators mentioned above are available. These regulators can be used in agricultural production either by direct application or through natural plant enhancement. For example, synthetic auxin derivatives are known to be effective in weed control (Çatak & Atalay, 2020). Synthetic growth stimulants like NAA, used as a substitute for IAA, have been utilized to thin fruit sets and thus produce larger and higher-quality fruits. They are also known to be used in promoting rooting in cuttings (Kaynak & Ersoy, 1997).

GA_3 is employed in viticulture and some pear varieties for seedless production, in artichokes to promote early maturation, and in strawberries to increase fruit size (Kaynak & İmamgiller, 1997). Many plants enter a period of dormancy after completing their bud growth phases. Various chemicals are used to shorten or eliminate this period. In a study on potatoes, GA application was shown to break dormancy, emphasizing that the hormone should primarily act on the buds of the tubers. Additionally, the effectiveness of GA on potato tubers was found to depend more on the treatment duration than on the GA concentration (Alexopoulos et al., 2008). Despite being an important food source, chestnut trees may exhibit low productivity due to producing fewer female flowers and more male flowers. Consequently, a study investigating flower buds before and after winter indicated that high GA concentrations break bud dormancy and promote male flower bud development, while low GA levels combined with high jasmonic acid concentrations affect female flower bud formation (Cheng et al., 2022).

Short internodal distances are caused by a mutation in a gene that inhibits GA activity or effectiveness. This genetic dwarfism can be completely resolved with GA application. Additionally, plants rich in GA have longer internodes (Feucht & Watson, 1958). For tea quality, which is significantly affected by leaf integrity, obtaining varieties suitable for mechanical harvesting is crucial. A study with seven tea varieties showed a positive correlation between internode length and bud and leaf integrity, with a strong relationship between GA_3 levels and internode length (Luo et al., 2023).

In a study, external applications of IAA, ABA, and GA_3 to *Nitraria tangutorum* shrubs at doses of 10 mg L^{-1}, 150 mg L^{-1}, and 200 mg L^{-1}, respectively, resulted in increased osmotic regulatory compounds and antioxidant enzyme activities in the plants. This aimed to enhance tolerance to stress factors and improve environmental adaptation (Didi et al., 2022).

Plant tissue culture studies are among the most common areas for using plant hormones. CKs are frequently used in tissue and meristem cultures. In tissue cultures, CKs and auxins are typically used together. When auxins are used in higher amounts than CKs, root formation is stimulated, while excess CKs over auxins result in shoot and leaf formation in callus tissues. When used in similar ratios, they promote the formation of callus tissues (Çatak & Atalay, 2020; Köksal, 2012).

Ethylene, used as a ripening hormone, is also employed in post-harvest technologies to preserve many garden products and as a stress hormone. Ethylene exhibits physiological effects when present in concentrations above 10 ppm in the air. Ethylene production accelerates under stress conditions, with the highest levels detected near plant death (Çatak & Atalay, 2020). On the other hand, during drought conditions, synthesis of another hormone, ABA, increases, and external application of low amounts of ABA is known to reduce plant transpiration (Aslam et al., 2022).

Dosages of external applications of plant growth regulators are crucial. For instance, it has been shown that horizontal gene transfer of antibiotic resistance genes in bacteria is stimulated by IAA and GA_3. The study reported that reactive oxygen species (ROS) formation was induced, changes occurred in cell membrane permeability, and these regulators increased the frequency of gene transfer at specific concentrations (Zhao et al., 2023). This situation leads to an increase in resistant pathogens. It indicates the need for controlled and careful use of PGRs.

The Effect Mechanism of Growth Regulators

The growth and development processes of plants involve complex mechanisms. Therefore, it is challenging to explain which vital functions are affected by chemical stimulators or inhibitors. Understanding how hormones function requires examining the expression of genes in relevant signaling pathways. Cells have specific binding sites, and the presence of these sites is crucial for a hormone's recognition by the cell (Bruinsma, 1985; Keskin, 2012). Each hormone or group of hormones has distinct formation, transport, and effects. Hormones that have similar or opposing effects always maintain a balance (Aydoğdu & Boyraz, 2005). Growth regulators have the ability to activate and block genes and their compounds (Köksal, 2012). The perception of hormones occurs through various ligands and receptors (Sabagh et al., 2021). For example, ethylene binds to receptors in the ER (endoplasmic reticulum) via diffusion across the cell membrane, activating the *EIN3 (ethylene-insensitive 3*) transcription factor. The expression of genes involved in the constitutive triple response, characterized by thick, short stems, and horizontal growth, is stimulated by this TF. *EIN3* directly activates *Ethylene Response Factor (ERF)* genes, aiding in the plant's survival under mechanical stress and other extreme conditions (Keskin, 2012; Tipu & Sherif, 2024). Another example is that ABA interacts with receptors associated with G-proteins in the plasma membrane of plant cells. The activation of G-proteins initiates the synthesis of secondary messengers such as Ca^{+2} ions and ROS (reactive oxygen species), which in turn trigger protein phosphorylation and result in changes in gene expression. Effective responses to various stress conditions arise from these changes in gene expression. ABA application alters cytosolic Ca^{+2} concentrations, leading to the closure of stomata (Keskin, 2012).

Genes like *Aux/IAA* and *DR12* encode proteins with nuclear localization signals and constitute a gene family involved in auxin responses (Srivastava and Handa, 2005). Mutations in the *DR12* gene cause changes in seed and seedling development, fruit cell division, and result in phenotypes such as upward curling leaves, high chlorophyll content, unripe fruit conditions, and irregular fruit formation. These conditions are thought to be due to auxin and CK responses, indicating that *DR12* affects hormonal responses (Martineau et al., 1994; Srivastava & Handa, 2005).

Starch stored in the endosperm is reduced to simple sugars via enzymatic pathways during germination and is transported to the embryo as an energy source. In the germination environment, the seed swells with water, and GA is synthesized in the embryo. GA is transported to the layer surrounding the endosperm, where it facilitates the movement of starch by inducing the formation of amylase and protease enzymes (Karakurt et al., 2010). The role of GA in this enzymatic effect is controlled by genes. Genes responsible for enzyme synthesis become active in the presence of GA (Boyraz et al., 2019).

An increase in auxin levels in plants stimulates ethylene production, which then inhibits the effects of auxin, thereby slowing down plant growth (Çatak & Atalay, 2020). Ethylene, the primary regulator of fruit ripening, causes the breakdown of cell walls, leading to reduced fruit firmness and changes in color, thereby facilitating ripening (Tipu & Sherif, 2024).

Growth regulators also respond under stress conditions. For example, auxins interact with stress response signaling components such as Ca^{+2} and ROS. During nutrient deprivation, they play a role in stimulating root development to enhance the uptake of essential nutrients like N, P, and K from the soil. For instance, the nitrate transporter gene *NRT1-1* stimulates the downward movement of auxins, reducing their accumulation in lateral roots (Sabagh et al., 2021).

Hormonal changes induced by pathogen-host interactions or other stress factors in plants can be controlled through the application of external growth regulators. This approach can also enhance the host's activity against pathogens. For example, the destruction of the host cell wall by enzymes such as pectinase, hemicellulose, and protease from pathogens facilitates pathogen development within the plant. By altering the solubility of pectin with auxins, the damage to pectin structures by pathogen enzymes is prevented, leading to the development of resistant plants (Aydoğdu & Boyraz, 2005). Auxins are also thought to influence phenol metabolism, thereby contributing to disease resistance.

Under stress conditions, growth regulators play regulatory roles in processes such as ROS scavenging, effective photosynthesis, stress protein accumulation, and other crucial metabolic processes. PGRs manage defense responses through synergistic and antagonistic activities known as crosstalk. They balance the negative effects of stress conditions by interacting with various compounds such as nitrates, H_2O_2, ROS, and NO^- (Sabagh et al., 2021).

Conclusion

PGRs play a critical role in plant growth and development processes. Particularly, growth regulators such as auxins, GAs, and CKs promote plant growth and enhance productivity. Additionally, the potential of plant growth regulators to increase plant resilience under environmental stress conditions is of great significance. However, effective use of these regulators requires determining the correct dosages and careful application. Future research should continue to improve the understanding of these regulators' mechanisms and their more effective use in agricultural practices. Studies like these are essential for supporting sustainable agriculture, enhancing agricultural productivity, and promoting environmental sustainability.

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