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SIGNIFICANCE AND APPLICATION OF PLANT GROWTH REGULATORS

Plant growth regulators (PGRs) are natural or synthetic compounds that modulate plant growth, development, and stress responses by adjusting endogenous hormone concentrations and influencing signaling pathways. This review examines the roles of key phytohormones which regulate physiological processes and tolerance mechanisms to abiotic stress. Abscisic acid emerges as the principal stress-responsive hormone, governing stomatal closure, water balance maintenance, and osmotic adjustment under adverse conditions. Auxins regulate cell elongation, vascular differentiation, and root architecture, with their homeostasis being significantly altered under environmental stress. Cytokinins promote photosynthetic efficiency and delay senescence, while gibberellins control stem elongation, seed germination, and flowering induction. Jasmonates contribute to both biotic and abiotic stress defense through activation of antioxidant systems and stomatal regulation. The review also examines how humic substances function helping plants better tolerate stress by improving nutrient absorption, activating antioxidant systems, and influencing auxin-like activity. Humic acids interact with root cells, influence ion absorption, and mitigate oxidative damage caused by reactive oxygen species under stress conditions. Practical applications of PGRs in agriculture are discussed, including their use in promoting flowering, fruit development, vegetative propagation, and yield enhancement. The integration of PGRs with biostimulants and microbial inoculants represents a promising strategy for sustainable crop production under increasingly challenging environmental conditions. Future research directions emphasize molecular approaches for optimizing hormonal manipulation and developing stress-resilient crop varieties.

Keywords: plants, growth regulators, phytohormones, humic substances.

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Өсу реттегіштердің маңызы және оларды қолдану

Өсімдіктердің өсу реттегіштері (ӨР) – эндогендік гормондардың концентрациясын реттеу және сигнал беру жолдарына әсер ету арқылы өсімдіктердің өсуін, дамуын және стресске реакциясын модуляциялайтын табиғи немесе синтетикалық қосылыстар. Бұл шолуда негізгі фитогормондардың – абсциз қышқылының, ауксиндердің, цитокининдердің, гиббереллиндердің, жасмонаттардың – өсімдіктердің өсу процестерін реттеудегі және абиотикалық стресстерге, соның ішінде құрғақшылыққа, тұздылыққа, экстремалды температураға және ауыр металдардың ластануына төзімділікті қамтамасыз етудегі рөлі қарастырылады. Абсциз қышқылы леп тесіктердің жабылуын, су балансын сақтауды және қолайсыз жағдайларда осмостық реттеуді реттейтін стресске жауап беретін негізгі гормон ретінде пайда болады. Ауксиндер жасушалардың созылуын, тамырлардың дифференциациясын және тамыр архитектурасын реттейді, олардың гомеостаздары қоршаған ортаның күйзелісі кезінде айтарлықтай өзгереді. Цитокининдер фотосинтездің тиімділігіне ықпал етеді және қартаюды кешіктіреді, ал гиббереллиндер сабақтың ұзаруын, тұқымның өнуін және гүлдену индукциясын бақылайды. Жасмонаттар антиоксидантты жүйелерді белсендіру және стоматологиялық реттеу арқылы биотикалық және абиотикалық стресстен қорғауға ықпал етеді. Шолу гуминді заттардың қоректік заттардың антиоксиданттық ферменттерді белсендіру және ауксинге ұқсас дабыл беру жолдарын модуляциялау арқылы өсімдіктердің стресске төзімділігін арттыруға қабілетті табиғи биостимуляторлар ретіндегі рөлін одан әрі зерттейді. Гумин қышқылдары тамыр жасушаларымен әрекеттеседі, иондардың сіңуіне әсер етеді және стресс жағдайында реактивті оттегі түрлерінің тотығу зақымдануын азайтады. Ауыл шаруашылығындағы ӨР-дің практикалық қолданылуы, оның ішінде гүлденуді, жемістердің дамуын, вегетативті көбеюін және өнімділікті арттыруда қолданылуы талқыланады. ӨР-ді биостимуляторлармен және микробтық егу құралдарымен біріктіру барған сайын күрделі экологиялық жағдайларда тұрақты өсімдік шаруашылығының перспективалы стратегиясын білдіреді. Болашақ зерттеу бағыттары гормоналды манипуляцияны оңтайландырудың және стресске төзімді дақылдардың сорттарын дамытудың молекулалық тәсілдеріне баса назар аударады.

Түйін сөздер: өсімдіктер, өсу реттегіштер, фитогормондар, гуминдік заттар.

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Значение рост регуляторов и их применение

Регуляторы роста растений (PGR) – это природные или синтетические соединения, которые модулируют рост, развитие растений и реакцию на стресс, регулируя концентрацию эндогенных гормонов и влияя на сигнальные пути. В этом обзоре рассматривается роль ключевых фитогормонов – абсцизовой кислоты, ауксинов, цитокининов, гиббереллинов и жасмонатов – в регуляции процессов роста растений и обеспечении устойчивости к абиотическим стрессам, включая засуху, засоление, экстремальные температуры и загрязнение тяжелыми металлами. Абсцизовая кислота выступает в качестве основного гормона, реагирующего на стресс, регулирующего закрытие устьиц, поддержание водного баланса и осмотическую регуляцию в неблагоприятных условиях. Ауксины регулируют удлинение клеток, дифференцировку сосудов и архитектуру корней, при этом их гомеостаз значительно изменяется в условиях воздействия окружающей среды. Цитокинины повышают эффективность фотосинтеза, замедляют старение, гиббереллины контролируют удлинение стебля, прорастание семян, индукцию цветения. Жасмонаты способствуют защите как от биотического, так и от абиотического стресса за счет активации антиоксидантных систем и устьичной регуляции. В обзоре также рассматривается роль гуминовых веществ как природных биостимуляторов, способных повышать устойчивость растений к стрессу за счет улучшения усвоения питательных веществ, активации антиоксидантных ферментов и модуляции ауксиноподобных сигнальных путей. Гуминовые кислоты взаимодействуют с клетками корней, влияют на поглощение ионов и смягчают окислительные повреждения, вызванные активными формами кислорода в условиях стресса. Обсуждается практическое применение PGR в сельском хозяйстве, включая их использование для стимулирования цветения, развития плодов, вегетативного размножения и повышения урожайности. Интеграция PGR с биостимуляторами и микробиологическими инокулянтами представляет собой многообещающую стратегию устойчивого растениеводства во все более сложных условиях окружающей среды. В будущих направлениях исследований особое внимание уделяется молекулярным подходам к оптимизации гормональных манипуляций и выведению устойчивых к стрессам сортов сельскохозяйственных культур.

Ключевые слова: растения, рост регуляторы, фитогормоны, гуминовые вещества.

Introduction

Plant growth regulators (PGRs) are synthetic substances widely used in agriculture to protect against diseases, stimulate growth, and increase crop yields. Despite their diversity, their action is based on a common principle: they regulate the levels of natural plant hormones by influencing various signaling pathways. GRs are applied in agriculture to support growth under unfavorable conditions, boost productivity, and alter plant development (Peleg et al., 2011; Small, Degenhardt, 2018).

PGRs are agents capable of modifying the processes governing plant growth and maturation. Endogenous PGRs are synthesized naturally within plants in trace amounts. Growth stimulating phytohormones (auxins, cytokinins, gibberellins, brassinsteroids) promote cellular elongation and proliferation, ethylene and abscisic acid serve as suppressors of these activities. They are small diffusing molecules, and brassinosteroids, jasmonic acid, and salicylic acid are distinguished among the newer classes, which also play an important role in regulating growth and development (Choudhary, A. Kumari. 2021).

Auxins are the main hormones responsible for stretching cells during during tropisms (photo- and gravitropism), while also regulating differentiation of meristem. They play an important role in cell expansion, formation of vascular tissue and lateral roots, and also the maintenance of apical dominance.

Cytokinins were first identified by their ability to stimulate cytokinesis, promote cellular division, bud initiation, the expansion of lateral shoot buds. Gibberellins promote the release from dormancy across diverse plant species, accelerate seed germination, drive stem elongation, and induce flowering. Gibberellins trigger germination in certain seeds, promote the development of parthenocarpic fruits,

Synthetic counterparts of naturally occurring growth regulators hold the greatest value for practical applications. These include artificial versions of auxins and cytokinins, engineered brassinolides, and compounds that exert a retarding influence on development. Most commercial plant growth regulators are compounds that reduce the longitudinal growth of shoots (retardants). Growth retardation can be caused by ethephone, a compound that releases ethylene, as well as compounds such as chlorometachloride and mepiquate chloride, which block the early stages of gibberellin biosynthesis (Rademacher, 2000). New structurally related compounds are constantly being synthesized, as well as chemically unrelated compounds with similar hormone-like activity, including substances that inhibit the synthesis, transport, and action of hormones.

The practical application of growth regulators enables researchers and farmers to induce metabolic changes comparable to those triggered by specific environmental factors (such as photoperiod duration and temperature). Ethey can hasten the development of reproductive structures or either enhance or suppress vegetative growth. Growth regulators (stimulators) contribute to boosting crop productivity and enhancing product quality to a degree comparable with the effects of fertilizer application or crop protection measures. This outcome is made possible by their capacity to direct plant growth and developmental processes toward the full expression of a plant's biological potential (Peleg et al., 2011). Growth regulators and biostimulators have significant potential to increase crop yields, allowing farmers to increase productivity and profitability. Their use helps to reduce dependence on synthetic fertilizers and pesticides, increasing nutrient absorption and improving soil quality (Gupta, 2023).

1. Endogenous hormones and related bioactive compounds

Abscisic acid (ABA) is a key plant hormone that regulates growth and development. Initially identified as two separate compounds (dormin and abscisin II), it was later recognized as a single molecule and named ABA. It is mainly produced in leaf chloroplasts, especially under stress conditions (Bhattacharya, 2019).

ABA plays a central role in helping plants tolerate abiotic stresses such as drought, extreme temperatures, and salinity. Under these conditions, its levels increase, activating protective responses. It is also involved in normal plant development. Studies show that ABA accumulation rises in many crops during drought and cold stress, and many ABA-regulated genes are linked to stress responses, particularly to drought and salinity (Sah et al., 2019).

In rice, stress-responsive genes were characterized, with 43 of them being ABA-inducible. These findings point to a substantial degree of interaction between ABA-mediated signaling and abiotic stress response pathways, particularly under conditions of moisture deficit and elevated salinity. ABA facilitates water movement and ion transport through root tissues, suggesting that it plays a role in turgor regulation by decreasing transpiration rates while simultaneously enhancing water uptake by the root system. When ABA is present under low water potential conditions, root growth is proportionally greater relative to shoot growth compared to situations where ABA is absent. Research has demonstrated that under reduced water potential, ABA accumulation sustains primary root elongation in maize by limiting ethylene biosynthesis, and it has been shown that ethylene serves as a major inhibitor of root extension (Sah et al., 2019).

Studies have shown that heavy metals increase ABA levels in plants (Vishwakarma et al., 2017).

Abscisic acid (ABA) regulates many plant processes, including seed maturation and dormancy, the transition to flowering, stomatal control, and stress responses. Under unfavorable conditions ABA levels increase to enhance plant tolerance (Pompeu et al., 2019).

In this way, ABA serves a critical function in plants exposed to adverse environmental conditions by decelerating growth rates and reducing metabolic activity. Furthermore, under water-deficit conditions, ABA helps sustain internal water equilibrium, enabling the plant to withstand temperature extremes.

Auxin is a phytohormone responsible for modulating plant growth and development, as well as governing bud formation and the initiation of root systems (Kazan, 2023). Auxins fulfill a central regulatory function in plant growth, regulating cell elongation, vascular differentiation, and apical dominance, while also guiding development under stress conditions. They are involved in responses to salinity, with clear links between auxin signaling and salt stress. (Fahad et al., 2013; Bhattacharya, 2019).

Auxins promote cellular elongation by altering the plasticity of the cell wall structure. They stimulate the division of cambial cells and induce the differentiation of secondary xylem within stem tissues.

Auxin redistribution in response to light or gravity causes uneven growth in plant tissues and shapes overall plant morphology; at certain levels, it can also inhibit growth. Auxin metabolism, transport, and signaling are closely linked to stress responses, and disruptions in auxin balance can lead to developmental abnormalities. Environmental stresses can alter auxin homeostasis, while controlled changes in auxin levels, especially in genetically modified plants–have been shown to improve stress tolerance, including drought resistance. Overall, auxin regulation is strongly connected to how plants adapt to adverse conditions (Derfling et al., 1985; Park et al., 2007; Tognetti et al., 2010; Remy et al., 2013; Bhattacharya, 2019).

Cytokinins are hormones that promote cell division, shoot formation, delay aging, and regulate leaf growth and internode length. They interact with auxins by reducing apical dominance and, together with ethylene, contribute to organ abscission.

Higher cytokinin levels can enhance photosynthesis and metabolism under drought or salinity, though their effects depend on regulation and localization. Under heat stress, cytokinin levels often rise temporarily, supporting stress responses such as antioxidant activity and heat shock protein accumulation, indicating their role in temperature adaptation (Du et al., 2007; Bhattacharya, 2016; Vojta et al., 2016; Pavlů et al., 2018).

Gibberellins (GAs) constitute a large family of tetracyclic diterpenoid phytohormones that play a multifaceted role in regulating nearly every stage of the plant life cycle. Among more than 130 identified gibberellin forms, only a few – most notably GA_1, GA_3, GA_4, and GA_7 – are biologically active and directly participate in growth regulation. One of the most well-characterized functions of gibberellins is the promotion of stem and internode elongation through the stimulation of both cell division and cell expansion. Gibberellins are indispensable for the process of seed germination. During this stage, GAs stimulate the synthesis of hydrolytic enzymes, particularly α-amylase, in the aleurone layer of cereal grains. These enzymes mobilize stored starch reserves in the endosperm, providing the developing embryo with the energy and nutrients required for successful seedling emergence Beyond germination, gibberellins play a pivotal role in the transition from vegetative to reproductive development. They promote flowering, particularly in long-day and rosette-forming plants, by activating floral meristem identity genes. Gibberellins also contribute to the development of parthenocarpic (seedless) fruits and are essential for normal pollen maturation and fertility (Bhattacharya et al., 2019)..

Gibberellic acid (GA) is involved in plant growth as well as responses to abiotic stress. While GA alone does not significantly affect root elongation, it can promote root growth under cadmium stress by reducing Cd accumulation in tissues. It also lowers cadmium-induced nitric oxide (NO) levels, helping to mitigate toxicity (Zhu et al., 2016).

Jasmonates (JAs) are a class of lipid-derived phytohormones that originate from the oxidative metabolism of polyunsaturated fatty acids, primarily α-linolenic acid, through the octadecanoid biosynthetic pathway. The most prominent members of this group include jasmonic acid (JA), its methyl ester methyl jasmonate (MeJA), and the biologically active conjugate jasmonoyl-isoleucine (JA-Ile). Initially identified as fragrant components of jasmine oil (*Jasminum grandiflorum*), jasmonates have since been recognized as critical signaling molecules governing a wide spectrum of physiological and developmental processes in plants (Bhattacharya et al., 2019).

Jasmonic acid (JA) involved in plant defense against abiotic stress. It activates physiological and molecular responses, including antioxidant enzymes, accumulation of amino acids and sugars, and regulation of stomatal movement. JA also helps reduce water loss by controlling stomatal closure (Acharya et al., 2009; Wasternack et al., 2014).

Jasmonates play a significant role in plant responses to abiotic stresses such as drought, salinity, heavy metal contamination, and extreme temperatures. Under drought conditions, endogenous JA concentrations rise rapidly, activating downstream signaling pathways that promote the accumulation of osmoprotectants, enhance antioxidant enzyme activity, and regulate stomatal closure to minimize water loss. In *Arabidopsis thaliana*, exogenous application of JA has been shown to modulate stomatal aperture, thereby reducing transpiration rates under water-deficit conditions. Furthermore, jasmonates facilitate plant adaptation to heavy metal toxicity by upregulating genes involved in detoxification and metal chelation processes. It was compared cadmium-induced stress responses between wild-type tomato plants and spr2 JA-deficient mutants and found that Cd concentrations in both roots and leaves increased more substantially at higher $CdCl_2$ doses. The findings indicated that the absence of endogenous JA can heighten the susceptibility of tomato seedlings to Cd toxicity (Savchenko et al., 2014; Zhao et al., 2016;Fu et al., 2017).

2. Humic compounds and their role in mitigating abiotic stress

Humic substances (HS) make up about 60% of soil organic matter and consist of complex molecular assemblies that drive many soil chemical processes. They include humic and fulvic acids, differ in solubility, and form stable complexes with metals and pollutants, which can reduce toxicity and influence their movement in soil (Bollag et al., 2019).

Humic acids (HA) are resistant to decomposition and can promote plant growth by improving nutrient uptake, membrane permeability, and metabolic activity. Their structure is highly complex and still debated, but they are considered multifunctional compounds with potential signaling roles in plant–soil systems. HA can enhance root and shoot growth, biomass, and germination, although effects depend on concentration, plant species, and environmental conditions. They also influence respiration, protein synthesis, enzyme activity, and mineral uptake–particularly improving availability of nutrients like nitrogen, phosphorus, and iron(Thomas et al., 1978; Nardi et al., 2002; Alvarez-Puebla et al., 2005 Bollag et al., 2019).

Application of various HAs to *Arabidopsis* and wild-type tomato seedlings prompted the researchers to propose that these organic substances contain compounds exhibiting auxin-like properties. Nevertheless, these same substances proved unable to trigger lateral root development in a tomato mutant harboring a dysfunctional auxin signaling gene. Based on these observations, the investigators suggested that HA most likely function as a "buffering system," capable of sequestering or liberating signaling molecules in accordance with shifts in the rhizosphere environment, such as acidification driven by plasma membrane activity, thus serving as a modulator of hormonal equilibrium with respect to lateral root initiation (Dobbss et al., 2007).

Owing to the inherently complex and heterogeneous character of HA, the question of whether they possess genuine auxin-like biological activity continues to be a matter of scientific discussion. The hormonal responses observed in experimental settings did not consistently correlate with the actual concentrations of IAA identified within HA preparations, leaving open the possibility that other members of the auxin family or structurally related molecules may be present that either replicate auxin function or activate the endogenous auxin biosynthetic machinery in plants. Approaches rooted in functional genomics, transcriptomic profiling, and proteomic analyses could serve as promising strategies for clarifying the mechanisms underlying the biological effects of HAs (Trevisan et al., 2010).

Alleviating the adverse impacts of abiotic stresses on plant growth throughout ontogenetic development can substantially enhance the productivity of cultivated crops (Van et al., 2017; Zhang et al., 2008). Various studies demonstrate that HA possess the capacity to strengthen plant tolerance to environmental stress. Application of HA to bent grass and tall fescue resulted in improved leaf water retention, greater antioxidant potential, and enhanced growth of both roots and shoots under water-limited conditions. The simultaneous use of HA together with seaweed extract bolstered resistance to water deficit and raised the levels of endogenous cytokinins. In bell pepper, HA treatment led to elevated concentrations of vital mineral elements in root and shoot tissues, pointing to a protective role against salt-induced damage.

Humic acids (HA) improve plant tolerance to salinity by increasing proline levels while reducing membrane damage and reactive oxygen species (ROS). They also enhance antioxidant enzyme activity, especially when applied via vermicompost, helping plants cope with drought and salt stress. HA influence membrane proton pumps, improving nutrient uptake and root development, likely through auxin-related pathways. They can also reduce the toxicity of heavy metals by limiting ROS damage and supporting protective systems such as glutathione production. Additionally, HA help maintain redox balance, boost antioxidant defenses, and improve plant recovery under stress conditions like drought and osmotic stress (García et al., 2012; Guridi-Izquierdo et al., 2017; Van et al., 2017; Aguiar et al., 2018; Shah et al., 2018; Zandonadi et al., 2018).

I was showed enhanced peroxidase function, lower hydrogen peroxide levels, and heightened proline accumulation in cells, collectively resulting in diminished ROS production and the re-establishment of redox balance in the cytosol (García et al., 2018; García et al., 2016). Seedlings that received prior HA treatment exhibited greater resilience when subjected to osmotic stress induced by polyethylene glycol (PEG 6000) (Guridi-Izquierdo et al., 2017). In a comparable manner, sugar cane plants previously exposed to HA displayed superior recovery following water-deficit conditions, characterized by an upregulation of key antioxidant enzymes (Aguiar et al., 2018).

3. The practical use of plant growth-regulating compounds

Plant growth regulators (PGRs) play a central role in coordinating these processes, including both classical hormones and other bioactive compounds (Peleg et al., 2011).

Contemporary research has revealed that phytohormones participate in a multitude of biological processes. The interplay among different plant hormones gives rise to synergistic or antagonistic interactions that serve an essential function in mediating plant responses to abiotic stress. The targeted manipulation of molecular mechanisms governing hormone biosynthesis, intracellular signal transduction, and downstream hormonal actions facilitates the engineering of hormone biosynthetic pathways, enabling the development of transgenic crop varieties exhibiting superior abiotic stress tolerance under field conditions (Sajid et al., 2009; Alcázar et al., 2010).

The commercial application of auxins aimed to prevent premature leaf and fruit drop, promote flowering, thin fruits, induce seedless fruit formation, and stimulate rooting in cuttings. Growth regulators are applied throughout plant development -from flowering to post-harvest–to improve yield and quality, including in crops like lilies. In the case of the tropical evergreen mango tree, low temperature is the sole recognized factor capable of triggering the flowering process; however, it does not ensure that floral initiation will take place, as complex interactions involving phytohormones associated with vegetative growth also play a determining role (Dias et al., 2019).

Forthcoming investigations in rhizosphere biology will depend on advances in molecular and biotechnological methodologies to deepen our understanding of rhizosphere processes, microbial diversity, and the multifunctional properties that underpin sustainable agricultural practices, as well as to achieve integrated management of soil microbial communities.

New approaches to using bioinoculants in high-value crops–such as vegetables, fruits, and ornamentals–should be further developed. Combining multiple stress-tolerant bacterial strains may be more effective than single-strain inoculation in reducing stress effects on plants. Future research should focus on optimizing growth conditions and developing safe, resilient plant growth-promoting rhizobacteria (PGPR) to enable affordable and efficient agricultural applications (Davies et al., 2010).

Conclusion

The comprehensive analysis presented in this review underscores the indispensable role of plant growth regulators in governing fundamental physiological processes and conferring tolerance to abiotic stress factors in cultivated crops. The evidence clearly demonstrates that phytohormones do not function in isolation but rather operate through an intricate network of synergistic and antagonistic interactions that collectively determine plant adaptive capacity under adverse environmental conditions. Abscisic acid, auxins, cytokinins, gibberellins, and jasmonates each contribute distinct yet interconnected regulatory functions, ranging from stomatal control and osmotic adjustment to antioxidant defense activation and root architecture modification.

The role of humic substances as natural mediators of stress tolerance represents a particularly promising area of agricultural biotechnology. Their capacity to enhance nutrient bioavailability, stimulate antioxidant enzyme systems, modulate auxin-like signaling, and buffer rhizosphere conditions positions humic acids as valuable complementary tools alongside conventional plant growth regulators. The documented ability of humic acids to reduce the genotoxic effects of heavy metals and restore cellular redox homeostasis further highlights their potential in remediating contaminated agricultural soils.

From a practical standpoint, the strategic application of growth regulators – both synthetic and natural – offers farmers effective means to optimize crop productivity and quality while reducing dependence on chemical fertilizers and pesticides. The development of transgenic crop varieties with modified hormonal pathways and enhanced stress tolerance continues to expand the possibilities for sustainable agriculture.

Future research should prioritize the integration of functional genomics, transcriptomics, and proteomics to elucidate the precise molecular mechanisms underlying PGR-mediated stress responses. Additionally, the exploration of multi-stress bacterial consortia combined with humic biostimulants may yield innovative, cost-effective solutions for maintaining agricultural productivity under the increasingly unpredictable environmental conditions driven by global climate change.

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