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Review Article

Regulation of Potato Plant's Growth Functions

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ABSTRACT

Ontogenesis control is important for developing methods for modeling and yield forecasting potatoes. Knowledge of the mechanisms of phyto-regulation allows for a directed impact on plant ontogenesis. Phytohormone analogs are widely used both in culture *in vitro* and *in vivo*; under their influence, the processes of differentiation and callusogenesis take place, morphogenesis and tuberization are induced *in vitro*, a root formation is induced, seed dormancy is overcome, plant resistance to abiotic stress factors is increased, and protective properties against phytoinfections increases the content of valuable substances and yield. Currently, the list of drugs with pronounced regulatory activity has expanded significantly. Among chemical alternatives, preparations based on microorganisms are most widely used in practice as yield stimulants and resistance inducers. At the same time, there is a growing interest in herbal preparations containing a huge amount of valuable biologically active substances with a different spectrum of action. The growing role and importance of plant growth and development regulators necessitates a deep study of the action nature of these compounds using modern biochemical and molecular genetic methods. At the same time, the search for new strains and drugs that can positively influence plant health and growth under various growth conditions, especially under stress conditions, is relevant. Works

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in this direction should be intensified due to the constant climatic risks. Creating a science-based system of growth regulation can provide reliable, stable results for potatoes growing in any field conditions of future agriculture.

Keywords: Biological preparations, growth regulators, mechanisms of action, phytohormones, tuberization

INTRODUCTION

Throughout the development of plant breeding, the problems of growth and development control of plant organisms have attracted researchers in many countries. Quantitative levels of endogenous phytohormones and their antagonists underlie all correlations in the plant organism (Jing & Strader, 2019). With their changes, the growth centers move from one organ system to another (Zhao et al., 2022). For example, a high concentration of auxin leads to the formation of nutrients' attraction centers. As a result, growth processes in some organs are delayed, and in others, they are activated (Kurepa & Smalle, 2022). Over two centuries, great success has been made in studying growth regulators, their influence on individual development, and the periodicity of plant growth. The molecular and genetic basis of regulation of plant development processes in ontogeny and phylogeny have been revealed.

Now, a general schematic diagram of the formation of phytohormones, the implementation of their regulatory action, including the biosynthesis of a precursor, binding to a hormone-specific protein receptor with the formation of an active hormone-receptor complex, and the effect of this complex on the plant genome and the activity of enzyme systems have been identified. At the same time, the analysis of the study of the issues showed that the main studies were aimed at studying the effect of phytohormones and their chemical analogs on the growth and yield characteristics of the plants, and this is understandable because chemical growth regulators are now a day a mandatory element of successful agricultural production (Amoanimaa-Dede et al., 2022). It has been reliably established that they not only affect growth and development but also activation of the plants' internal potential, contribute to the activation of internal reserves of the plant organism, the process of photosynthesis, and growth of leaf mass, increase the supply of nutrients from the soil (Ahmed et al., 2021; Mitrofanov & Novikov, 2020).

Modern Approaches to Plant Growth Regulation

The number of compounds with hormonal activity in plants has expanded. In addition to the long-known auxins, cytokinins, gibberellins, abscisic acid, and ethylene, many new physiologically active compounds have been added, i.e., brassinosteroids, jasmonic acid, salicylic acid, and fusicoccin. All these phytohormones and their analogs have common properties, i.e., they are formed in plants in small quantities, easily move from one part to another, and cause significant metabolic and morphogenesis effects (Vural et al., 2018). Modern biochemical and molecular genetic methods are being used to identify the specific role of phytohormones in tuber formation. Representation of great interest is the study of directed changes in the endogenous content of hormones in potato plants using a transgenic approach. Genetic engineering methods have created chimeric gene structures that include effective regulatory and promoter regions and carry marker and coding genes.

Obtaining transgenic plants with the help of such chimeric genes made it possible to elucidate the features of regulating the activity of poetin genes and study the functions performed by these storage proteins. Thus, it was found that the inclusion of markers, for example, the luciferase gene, in the chimeric gene, constructs carrying poetin genes, makes it possible to detect by using a luminometer, the inclusion, and exclusion of the genes of these proteins in connection with the control of tuberi formation both *in vitro* and *in vivo* plants (Hannapel et al., 2017). Great interest in studying plant growth regulation and development is associated with this area's important theoretical and practical significance. Growth regulators are currently an integral element of modern crop production, which allows for solving many problems, as well as an effective and affordable tool for increasing the profitability of agricultural crop production (Marenych et al., 2019). The studies of Mani and his co-authors showed the effectiveness of pre-plant treatment of tubers with thiourea to stop the dormant period and the germination of potatoes. Under the action of thiourea, the activity of catalase was suppressed, and the concentration of hydrogen peroxide increased, which caused an interruption of dormancy of tubers. Other researchers have shown a positive effect of thiourea on the formation and height of potato stems and tuber yield (Mani et al., 2013).

Using Phytohormones

The works of Murashev and his associates showed a positive effect of potato treatments with growth regulators based on amino acids on productivity, which increased by 20–30%. At the same time, a reduction in the interphase period of development by 20% and a reduction in the growing season by 5–10 days were noted (Murashev et al., 2020). Preparations of the retardants group are most often used in agricultural crop production (Singh & Jambukiya, 2020). In potato seed production, these preparations are used to increase the reproduction rate; one of the characteristic manifestations of their action is the inhibition of growth, which increases the mechanical strength of stem tissues, which positively affects the survival rate of meristem potato seedlings (Anikina et al., 2015). Several researchers found that spraying potato plants with chlorcholine chloride inhibited stem growth by reducing the length and number of internodes, increasing the number of leaves and their size, reducing the length of stolons, and accelerating tuber maturation (Hossain et al., 2019). It has been shown that as a result of leaf treatment of potato plants with chlorcholine chloride at a dose of 2.0 g/L, the content of indoleacetic-3-acid (IAA) and zeatin (Z) increased in the leaves, while the content of abscisic acid decreased. It was determined that this preparation has a significant regulatory role in plant photosynthesis; stomatal conductance, net photosynthesis rate, and transpiration rate increased under its influence. Consequently, the yield and quality of tubers increased (Wang & Xiao, 2008). The use of cytokinins to improve the growth of agricultural plants under conditions of increased salinity and waterlogged soil is well understood (Li et al., 2020).

Growth regulators are of great importance for the reproduction of potatoes *in vitro*. Two groups of growth regulators, i.e., auxins and cytokinins, control the processes of differentiation and callusogenesis. In addition, they affect the processes of morphogenesis and tuberization *in vitro*. Tuberization is a multifaceted, specific process caused by a combination of external and internal stimuli and is associated with changes in the synthesis and transport of substances. Phytohormones act as internal stimuli; among them, auxins, cytokinins, and gibberellins also play a special role in tuber ontogenesis. Other hormones are also involved, but to a lesser extent (Vural et al., 2018; Wróbel et al., 2017). In the case of auxins, it was found that the introduction of indole acetic acid (IAA) in potato cultivation medium increased the number and accelerated the growth of tubers (Aksenova et al., 1999), and larger tubers grown in the soil contained more IAA than smaller ones. In addition, it was found that the auxins concentration in the stolon tips increases several times immediately before tuber initiation (Kolachevskaya et al., 2019), pointing out the essential role of auxins in tuber initiation and growth. In this regard, interest arose to study the effects of directed changes in the endogenous content of auxins in potato plants by using a transgenic approach (Kolachevskaya et al., 2019).

There are many publications on the influence of kinetin on the induction of *in vitro* tuberization (Kolachevskaya et al., 2021). Confirming data on the role of cytokinins in the formation of tubers were obtained from the study of transgenic plants with the expression of the isopentenyl transferase gene (iptTi plasmids of *Agrobacterium tumefaciens*) (Guivarc'h et al., 2002). Subsequently, a great deal of research has been done in this direction (Kumlay et al., 2021; Meenakshi, 2021; Vural et al., 2018).

The important role of gibberellins in the process of tuberization has been proved. Treatments with gibberellins enhanced the length of plant stem organs, stimulated the initiation, growth, and branching of stolons in potatoes (Külen et al., 2011), and prevented the formation of tubers *in vitro*. There is evidence of gibberellic acid's effect on the expression of potato genes associated with carbohydrates and protein metabolism in leaves and the genes associated with photoperiodic regulation of tuberization. Data have been obtained on the participation of recently recognized phytohormones in tuber formation *in vitro*. In studies by Vural and his co-authors, a jasmonic acid compound called methyl jasmonate at 1.0 ppm in Nitsch and Nitsch medium stimulated the formation of micro-tubers (Vural et al., 2018). According to Z. J. Zhang et al. (2006), while using jasmonic acid in Murashige and Skoog medium at a concentration of 0.2-2 mg/dm^3, the shoot and root formation was significantly increased when cultivating regenerated potatoes of Favorita and Helanwuhua varieties. When studying the joint effect of jasmonic acid compounds and benzyladenine cytokinin on potato tuberization (*Solanum tuberosum* L.) *in vitro*, it was observed that benzyladenine suppressed the action of jasmonates and inhibited root growth and tuberization (Sarkar et al., 2006). The *in vitro* method of potato propagation opened a new milestone in potato breeding. Using virus-free starting material has become the basis of modern potato seed production. Growth regulators are actively used at every stage of seed multiplication, starting from the meristem crop (Anikina et al., 2015; Kolachevskaya et al., 2021; Kumlay et al., 2022).

Hormones play a key role in the formation and growth of potato tubers. It was found that the same chemicals, i.e., gibberellic acid, indole butyric acid, and kinetin, which are involved in tuber formation *in vitro*, showed a positive result on tuber formation *in vivo* when they treated potato foliage during the phase of budding flowering (Prasad, 2022; Zhao et al., 2022).

Ali and employees confirmed that the gibberellic acid (GA_3) significantly impacted the morphogenesis of the *in vitro* potatoes and was effective in acclimatizing plantlets of potatoes in the field (Ali et al., 2018). The property of growth regulators to increase the adaptive functions of the plant organism is of great importance in crop reproduction. Kanmani et al. (2017) found that the growth regulator brassinolide under saline conditions increased the rate of photosynthesis and chlorophyll fluorescence in plants, as well as showed that the plant growth regulators based on gibberellic acids and kinetin can be used to improve the physiological performance of plants under stress conditions.

Recently, there has been increased interest in the preparations of natural origin, which are derived from plant or microbial raw materials, and they are not inferior in their effect to synthetic hormonal preparations. Therefore, Dahshan et al. (2018) found a positive effect of treatments with both traditional phytohormones, i.e., gibberellic acid (GA_3), indole butyric acid (IBA), and solutions of natural preparations, i.e., garlic extract, yeast extract, and green tea extract on potato yield.

Use of Microorganisms

The use of biopreparations has become a biosafety alternative to reduce the use of agrochemicals (Pirttilä et al., 2021). Among biopreparations, microorganism-based preparations are the most widespread in practice. Efforts of many scientists have laid the scientific basis for clarifying the role of microorganisms as yield stimulators and resistance inducers (Dasgupta et al., 2023; Khan et al., 2020; Meena et al., 2020). The use of mycorrhiza in crop production is particularly interesting in this area. Mycorrhizae, or mycorrhiza, is a symbiotic association between fungus and plant roots. As a result of this interaction, plants' uptake of water and nutrients is improved, and plant growth is accelerated (Chifetete & Dames, 2020; Jansa et al., 2020; Shuab et al., 2017). Mycorrhizae continue to influence plant growth even after the fungi die, as fungal neuromas have been shown to stimulate crop biomass (Jansa et al., 2020). Lone et al. (2015) found that inoculation with mycorrhiza had a stimulating effect not only on the morphogenic parameters of potato plants but also caused an increase in chlorophyll content. Wu and his co-workers showed that mycorrhizal plants have significantly greater root length, projection area, surface area, and volume than non-mycorrhizal plants (Wu et al., 2016). The stimulating effect of mycorrhiza on potato tuber formation has long been proven. Lone concluded that tuber initiation by mycorrhiza action is hormonally mediated (Lone et al., 2015).

The ability of bacteria to mobilize nutrients from difficult-to-dissolve soil components has led to the widespread use of commercial bacterial preparations in agricultural crop production, which are erroneously called bacterial fertilizers, although their functions are not limited to this property (Htwe et al., 2018; Kudoyarova et al., 2019). Various studies revealed that plant inoculation with consortia of symbiotic bacteria has a synergistic effect on plant growth and helps in alleviating abiotic and biotic stresses by producing various defense compounds (Bulgarelli et al., 2013; Hakim et al., 2021). In addition, bacteria can release substances of hormonal nature and biofungicides, which improve plant growth and increase their resistance against various biotic and abiotic stresses (Table 1).

Table 1
The results of the influence of rhisobacteria on plant development

Influence on plants	Source
Stimulation of root system development	Hong et al. (1991); Llorente et al. (2016); Mantelin and Touraine (2004); Rahman et al. (2018); Vicente and Plasencia (2011)
Improving the water budget of plants	Chifetete and Dames (2020); Jansa et al. (2020); Kaushal and Wani (2016); Khan and Bano (2016); Marulanda et al. (2010); Shuab et al. (2017)
Stimulation of photosynthesis	Khan et al. (2020); Marulanda et al. (2010); R. Zhang et al. (2017); Shi et al. (2010)
Induction of hormone synthesis	Jha and Saraf (2015); Lone et al. (2015); Ruzzi and Aroca (2015); Spaepen et al. (2014); Tsukanova et al. (2017); Vacheron et al. (2013)
Increasing the content of organic matter	Chifetete and Dames (2020); Fan et al. (2017); Naseri et al. (2013); Shuab et al. (2017); Ul Hassan and Bano (2015)
Stimulation of protective functions against phytopathogens	Bulgarelli et al. (2013); Chen et al. (2020); Hakim et al. (2021); Mącik et al. (2020); Polyksenova (2009); Puopolo et al. (2011); Rahman et al. (2018)
Stimulation of resistance to abiotic factors	Han et al. (2014); Harb et al. (2015); Kasim et al. (2016); Khan and Bano (2016, 2019); Khan et al. (2018); Mahmood et al. (2016); Nadeem et al. (2014); Shahzad et al. (2017); Subramanian et al. (2016); Xun et al. (2015)

It should be noted that microbial preparations of different origins positively affect plants. It was found that secondary metabolites of microorganisms can stimulate growth and increase plant resistance (bacteria *Bacillus*, *Fusarium* fungi, symbiotrophic endophyte fungi, and trout fungi). In addition, the positive role preparation of yeast-based treatments that contain many valuable plant substances, *viz*. cytokinins, carbohydrates, amino acids, enzymes, and vitamins B_1, B_2, and B_3, on potato development and productivity has been proved (Dahshan et al., 2018).

The role of rhizosphere bacteria in the stimulation of plant growth and synthesis of various types of bacteriocins and exo-toxin proteins, which are biologically active peptide fragments with fungicidal action has been most studied, e.g., *Azospirillum brasilense*, *Agrobacterium* spp., *Bradyrihizobium* spp., *Enterobacter* spp., and *Rhizobium legominosarum*, can produce indole-3-acetic acid (IAA), an auxin that promotes plant growth (Oleńska et al., 2020). Other mechanisms include synergistic relationships, root growth stimulation, and biocontrol (Dahshan et al., 2018; Hakim et al., 2021; Karthika et al., 2020). Studies reported the antifungal and chitinolytic actions of *Serratia marcescens* to inhibit pathogenic fungi such as *Fusarium oxysporum* and *Rhizoctonia solani* (Karthika et al., 2020). The great interest in plant growth-promoting rhizobacteria (PGPR) has contributed to the development of numerous commercial microbial preparations, which contribute to the efficiency of crop production. The use of beneficial PGPRs such as *Azotobacter*, *Pseudomonas*, *Bacillus*, and *Azospirillum* in the form of biofertilizers can be an alternative to conventional chemical fertilizers (Htwe et al., 2018). They promote plant growth by affecting plant hormone production, iron binding by siderophore, stress management by key enzymes, such as 1-aminocyclopropane-1-carboxylate, and soil organic matter decomposition.

Bacteria can interact closely with the host plant. Thus, they can be effective biocontrol agents in sustainable agricultural production (Hakim et al., 2021). Soil bacteria exhibit antifungal properties through the production of various enzymes that are part of their lytic system and allow the uptake of hyphae as a nutrient substrate (Chen et al., 2020).

Using Plant-based Preparations

At the same time, there is increasing interest in biologically active substances of plants, which also show positive results in increasing productivity and adaptive properties and as inducers of resistance to phytopathogens. Plants are available raw materials containing a huge number of valuable biologically active substances of different spectrum of action, which have been used since ancient times, including plant breeding (Abbas & Hussain, 2020; Abd-El-Khair & Haggag, 2007; Anikina & Issayeva, 2023).

Davidyants (2011) generalized the results of numerous studies and suggested that triterpene glycosides are involved in the regulation of physiological and biochemical processes underlying the growth, development, and stress resistance of plants. According to her research, plants containing this class of biologically active compounds can act as raw materials for plant growth stimulants. Efforts of many scientists have proven the role of plant biologically active substances (BAS: epibrassinolide, flavonoids, steroid glycosides, triterpene, and hydroxycinnamic acids) in the regulation of growth processes and increasing the yield and resistance to stress and pathogens (Gorbyleva & Borovskii, 2018). Many researchers noted the positive effect of using biopreparations based on steroid glycosides (secondary plant metabolites), including potato crops. When using the preparations pavstim, moldstim, and emistim in the tomato crop in protected ground, the yield increase was more than 30%, while the quality of fruits was improved, and the infectious potential of soil was reduced (Godlewska et al., 2021). Steroid glycosides have a particularly significant immunoregulatory result under biotic and abiotic stresses. These statements are confirmed by the results of Anikina, who conducted an experiment under the conditions of Northeast Kazakhstan and obtained data indicating a significant stimulating effect of black nightshade infusion, which contains steroid glycosides, steroid alkaloids, and steroid oligoglycosides on potato productivity. The increase in total weight of tubers of one bush after treatment with the preparation averaged 34%. The increase in the food fraction of tubers was 46% (Anikina & Issayeva, 2023).

Regulating activity of extracts isolated from Siberian fir (*Abies sibirica* Ledeb.) was established, and the number of preparations was developed on their basis, i.e., Silk, Biosil, and Novosil, which are widely used in the cultivation of crops. Such preparations have a wide range of favorable properties, having a growth-regulating and fungicidal effect on the plant. Application of these preparations increases plant resistance against various diseases, while the activity of stress resistance genes increases (Gorbyleva & Borovskii, 2018).

Thus, Zaitseva (2017) proposed to use medicinal plants of Yakutia as raw material for stimulating preparations that increase seed germination of cultivated plants and resistance against stressful environmental factors. As raw materials for stimulating drugs, she proposed to use such plants as *Melilotus officinalis* (L.) Pall., *Melilotus albus* Medikus, *Oberna behen* (L.) Ikonn., *Sanguisorba officinalis* L, *Plantago major* L., *Ribes fragrans* Pall., *Ledum palustre* L., *Artemisia lagocefala* (Bess.), *Chamaenerion angustifolium* (L.) Scop., *Trifolium pratense* L., *Tanacetum vulgare* L., *Rubus idaeus* L., *Artemisia vulgaris* L., *Equisetum arvense* L., *Artemisia integrifolia* L., and *Galium album* Mill. In these studies, it was found that treatment with plant extracts not only increased seed germination but also significantly increased the stress tolerance of treated plants. Table 2 presents the generalized results of different researchers by type of plant growth regulators.

Table 2
Results of different researchers by type of plant growth regulators

Type of the drug	Reference
Microorganism-based biopreparations	Bulgarelli et al. (2013); Chen et al. (2020); Dahshan et al. (2018); Hakim et al. (2021); Htwe et al. (2018); Jansa et al. (2020); Karthika et al. (2020); Khan and Bano (2019); Khan et al. (2020); Mitrofanov and Novikov (2020); Oleńska et al. (2020); Polyksenova (2009); Shainidze et al. (2022); Vissey (2003)
Influence of mycoriza	Chifetete and Dames (2020); Lone et al. (2015); Shuab et al. (2017); Xu and Tong (2018)
Analogs of phytohormones	Ahmed et al. (2021); Aksenova et al. (1999); Ali et al. (2018); Amoanimaa-Dede et al. (2022); Anikina et al. (2015); Dasgupta et al. (2023); Guivarc'h et al. (2002); Hossain et al. (2019); Jing and Strader (2019); Kanmani et al. (2017); Kolachevskaya et al. (2019); Külen et al. (2011); Kumlay et al. (2021); Kurepa and Smalle (2022); Meena et al. (2020); Meenakshi (2021); Pavlista (2011); Sarkar et al. (2006); Singh and Jambukiya (2020); Vural et al. (2018); Wróbel et al. (2017); Z. J. Zhang et al. (2006); Zhao et al. (2022)
Plants-based biopreparations	Abbas and Hussain (2020); Abd-El-Khair and Haggag (2007); Anikina and Issayeva (2023); Dahshan et al. (2018); Davidyants (2011); Godlewska et al. (2021); Gorbyleva and Borovskii (2018); Polyksenova (2009); Zaitseva (2017)

CONCLUSION

The increasing role and importance of plant growth and development regulators cause the need for an in-depth study of the nature of the action of these compounds. At present, certain success has been achieved in studies of growth regulators' influence on the process of vegetation and establishing their correlation links with abiotic and biotic factors of crop yield formation. Understanding and using the mechanisms of growth regulation based on the control of ontogenesis in each case will optimize the processes of modeling and forecasting potato yield, as well as obtaining certain fractions of tubers, which is important for seed production.

It is known that the biosynthesis of phytohormones and inhibitors, their inactivation, and functioning are under direct control of the cell nucleus. In turn, phytohormones influence the functioning of the nucleus and other genetic structures in the cell through cytoplasmic inducers and inhibitors. With a better understanding of the signals controlling tuber formation, a molecular approach to improve yield may soon become available.

At the same time, the search for new strains and drugs that can positively influence plant health and growth under various growth conditions, especially under stress conditions, is relevant. Works in this direction should be intensified due to the constant climatic risks. Creating a science-based system of growth regulation can provide reliable, stable results for potatoes growing in any field conditions of future agriculture.

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