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# Prospects for the use of growth stimulators based on nitrogen-containing heterocycles in plant propagation technologies

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**Abstract.** Nitrogen-containing heterocycles have attracted the attention of researchers as compounds widely represented in the structures of both natural and synthetic plant growth regulators. The relevance of using natural and synthetic growth regulators in plant propagation is extremely high, as they play a key role in regulating plant growth and development processes, including reproduction. Propagation technologies that employ growth regulators are a vital tool in modern horticulture, agriculture, and biotechnology, enabling the production of high-quality planting material and enhancing production efficiency. The aim of this study was to analyse current approaches to the use of both natural and synthetic growth stimulators based on nitrogen-containing heterocycles in plant propagation, and to further determine the prospects for their application. It has been established

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that nitrogen-containing natural and synthetic growth regulators are most effectively used for the rooting of cuttings, microclonal propagation (*in vitro* culture), seed pre-treatment, and the regulation of flowering and fruiting processes. Current strategies for the application of growth stimulators based on nitrogen-containing heterocycles have been systematised, and modern approaches to the development of new, highly efficient compounds using molecular modelling have been outlined. It was demonstrated that the integration of different pharmacophoric fragments within a single molecule can significantly enhance biological activity. Furthermore, the use of newly synthesised compounds, multicomponent formulations, methods for improving their efficiency, and controlled-release systems has shown high effectiveness. The practical significance of this work lays in its potential to guide the development and application of more effective growth stimulators, thereby improving plant propagation efficiency, increasing crop productivity, and optimising biotechnological processes in agriculture and plant science

**Keywords:** quinoline and succinate derivatives; hybrid molecules; vegetative propagation of plants; microclonal propagation; mixtures of growth stimulators; quinoline derivatives

## INTRODUCTION

The modern development of agriculture, biotechnology, and landscape gardening requires the implementation of efficient plant propagation technologies to ensure the production of high-quality planting material and to increase plant productivity and adaptability to changing environmental conditions. In this context, the use of plant growth regulators that specifically influence physiological processes, including rooting, organogenesis, flowering, and fruiting, is particularly important. Among a wide range of biologically active substances, nitrogen-containing heterocyclic compounds occupy a significant place due to their high biological activity, structural diversity, and the ability to modify their properties. Analysis of contemporary scientific studies indicates the active development of this research area. J. Cohen & L. Strader (2024) emphasise that indole compounds' ability to mimic natural phytohormones opens broad prospects for the development of new growth regulators. Auxins are key regulators of plant development, controlling cell division, differentiation, and organ formation processes. The balance between different auxin forms and their transport is critical for the normal functioning of the plant organism. G. Gomes & K. Scortecci (2021) and P. Sun *et al*. (2023) note that indole derivatives not only stimulate growth but also enhance plant resistance to biotic and abiotic stresses by activating protective metabolic pathways. This opens new opportunities for the application of such compounds under stress conditions. At the same time, the effectiveness of growth stimulants depends on both their concentration and the genetic characteristics of plants. An important research direction is the search for an individualised approach to the application of growth regulators for different plant species. Studies confirm the importance of using growth regulators in tissue culture, where they promote the induction of adventitious roots and the synthesis of secondary metabolites. Such approaches are promising for the biotechnological production of valuable compounds.

A number of studies by S.-H. Kim *et al*. (2021), D. Loconsole *et al*. (2023) and F. da Silva *et al*. (2025) demonstrate practical aspects of using growth regulators for biotechnological production and vegetative propagation of ornamental plants. The use of synthetic regulators yields more stable results than natural extracts. To stimulate rooting in difficult-to-root species and to preserve rare and endemic plants, new synthetic growth stimulants based on nitrogen-containing heterocycles are being actively investigated. Considerable interest is focused on studies of nanomaterials and novel biologically active compounds, particularly quinoline and pyrimidine derivatives, that enhance the efficiency of plant growth regulation and provide more controlled effects on physiological processes. At the same time, the development of environmentally safe preparations with high efficiency and low toxicity remains relevant.

The application of 6-benzylaminopurine (6-BAP) in *in vitro* culture stimulates shoot formation, increasing the efficiency of plant propagation. At the same time, different concentrations

of this growth regulator affect the accumulation of photosynthetic pigments (chlorophylls and carotenoids) in plants after acclimatisation. Optimal doses of 6-BAP promote both intensive shoot formation and improved plant physiological condition, as reflected in increased pigment content. The study by J. Seka *et al*. (2025) demonstrated that the addition of cytokinins – kinetin or thidiazuron (TDZ) – to the culture medium significantly improves shoot regeneration and overall *in vitro* culture efficiency. TDZ proved to be particularly effective, stimulating more intensive shoot formation in most of the studied varieties. These results indicate the potential to overcome cassava recalcitrance and are of great importance for the mass propagation of valuable agronomic varieties and for the development of agricultural biotechnology. Research by V. Tsygankova *et al*. (2024) and M. Zavhorodnii *et al*. (2024) demonstrated the perspective of the direction modification of the heterocycle and the residue of S-heterocyclic acids. In particular, residues of acetic and succinic acids influenced plant metabolic processes, stimulating growth and propagation.

Thus, the analysis of modern literature indicates significant scientific interest in the use of nitrogen-containing heterocyclic growth regulators in plant propagation technologies. At the same time, further research is needed to clarify their mechanisms of action, optimal concentrations, and the potential to develop new, effective compounds with targeted properties. The aim of this study was to conduct a systematic analysis of modern approaches to the use of natural and synthetic nitrogen-containing heterocycle-based growth stimulators in plant propagation technologies, and to identify prospects for their further application.

## MATERIALS AND METHODS

This study was conducted as a narrative review aimed at systematising and summarising current scientific data on the use of nitrogen-containing heterocycle-based natural and synthetic plant growth regulators in plant propagation technologies. The literature search was carried out during the period 2020-2025 using leading international scientific databases, including Scopus, Web of Science, PubMed, Google Scholar, as well as electronic libraries of specialised scientific journals. The search employed keywords in English and Ukrainian, including: plant growth regulators, nitrogen-containing heterocycles, auxins, micropropagation, plant propagation technologies, indole derivatives, quinoline derivatives, rhizogenesis, and their Ukrainian equivalents. The inclusion criteria were: publications in peer-reviewed scientific journals; relevance to the research topic (plant growth regulators, biologically active heterocyclic compounds, plant propagation technologies); timeliness of sources (preference given to studies with emphasis on 2023-2025); availability of experimental or review data on mechanisms of action, efficiency, or practical application of growth regulators. The exclusion criteria included: non-peer-reviewed publications; studies lacking sufficient information on mechanisms of action or application results; duplication of results or secondary sources without new data. In total, 35 scientific sources were analysed, including original studies, review articles, and experimental works on the synthesis, properties, and applications of growth regulators based on nitrogen-containing heterocycles. The literature analysis was performed using comparative, systemic, and structural-functional approaches. Particular attention was paid to studies examining the mechanisms of action of indole, quinoline, and pyrimidine derivatives, as well as their effects on root formation, organogenesis, seed germination, and plant adaptation to stress conditions.

To generalise the obtained information, qualitative analysis methods were used, including: systematisation of data by types of growth regulators; classification of compounds according to their chemical nature and mechanisms of action; comparison of the effectiveness of natural and synthetic stimulators; analysis of modern approaches to the development of new biologically active substances, including molecular modelling methods and the combination of pharmacophoric groups. Technological aspects of the application of growth regulators in plant production and biotechnology were also considered, including micropropagation (*in vitro*), cutting rooting, seed treatment, and the use of prolonged-release formulations. The analysis covers the current stage of scientific development (2020-2025), enabling identification of trends in the development and application of plant growth regulators. The main emphasis was on recent studies (2023-2025) demonstrating the potential of nitrogen-containing heterocyclic

compounds to enhance the efficiency of plant propagation technologies.

## RESULTS AND DISCUSSION

The modern development of plant science and biotechnology necessitates the search for effective means of regulating plant growth and development. Particular attention has been paid to compounds based on nitrogen-containing heterocycles, which are characterised by high biological activity and the ability to exert targeted effects on plant physiological processes. In this context, it is important to analyse current approaches to the development and application of such growth stimulators, as well as to determine their role in enhancing the efficiency of plant propagation. O. Nedukha (2015) and V. Tsygankova *et al*. (2024) believe that natural and synthetic growth stimulators based on nitrogen-containing heterocycles have attracted researchers' attention due to their high efficiency and potential for targeted influence on plant physiological processes. The development of modern growth regulators is proceeding in the following directions: creating safe, environmentally friendly growth stimulators; employing nanomaterials to enhance the delivery of active substances; and combining multiple active compounds to achieve synergistic effects. J. Cohen & L. Strader (2024) believe that indole compounds, with their unique capacity to mimic peptide structures and reversibly bind to enzymes, are of great importance in regulating plant growth. They stimulate the formation of roots and fruits while activating the plant's immune system against harmful biotic and abiotic factors. Analysing target recognition, receptor recognition, key activation sites, and the mechanism by which indoles activate processes in plants to improve crop growth or disease resistance is a crucial step in further designing such compounds as plant growth regulators and immunity inducers. Understanding the mechanisms of action of indoles is crucial in contemporary strategies for applying growth regulators to control plant growth and enhance their tolerance to biotic and abiotic stresses (Tsygankova *et al.*, 2024).

The paper by M. Faizan & S. Hayat (2024) presents the features of synthesis, potential applications, mechanisms of stress resistance formation, and aspects of stability for plant growth regulators. Strigolactones, karrikins, and heme-mediated regulation of plant biology are considered. Plant growth regulators act as biostimulants, enhancing plant tolerance to adverse conditions. Particular attention is paid to the fact that the application of these substances in low concentrations ensures significant improvement in plant vitality and contributes to increased crop yields. The publication by O. Nedukha (2015) indicates that among synthetic nitrogen-containing auxins, the most commonly used are 4-amino-3,5,6-trichloropyridine-2-carboxylic acid (picloram) (Fig. 1a) and 5,6-dichloroindole-3-acetic acid (Fig. 1b).

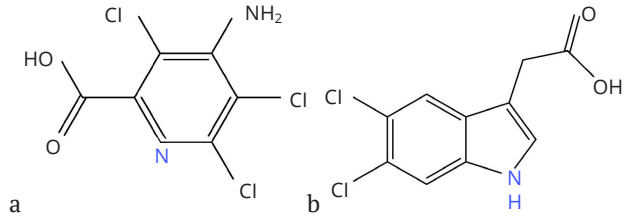


**Figure 1.** 4-Amino-3,5,6-trichloro-2-pyridinecarboxylic acid (a), 2-(5,6-dichloro-1H-indol-3-yl) acetic acid (b)
**Source:** developed by the authors based on O. Nedukha (2015)

Auxin is a key phytohormone regulating plant growth and development under various conditions. Even at low levels, it influences gene expression via specific transcription factors and signalling proteins (Sun *et al.*, 2023). Auxin is synthesised in actively dividing tissues and transported by specialised carrier proteins. Precise control of auxin levels, particularly of its primary form – indole-3-acetic acid (IAA), is crucial for organ formation and is regulated by converting IAA from conjugated forms and precursors (Gomes & Scortecci, 2021; Sosnowski *et al.*, 2023). One

such precursor is indole-3-butyric acid (IBA), which is converted to IAA via β-oxidation in peroxisomes. Disruptions in this conversion result in developmental defects, underscoring IBA's importance for maintaining auxin homeostasis (Roth *et al*., 2024). Like IAA, IBA can also be transported within plants, though many of its transporters remain unidentified. Auxin biosynthesis occurs through both tryptophan-dependent and tryptophan-independent pathways, involving indole intermediates and key enzymes such as YUC and TAA (Gomes & Scortecci, 2021). Crucially, indole compounds play a significant role in regulating plant growth and influencing resistance to biotic and abiotic stresses. They can enhance plant tolerance to stresses directly or indirectly through the salicylic acid, jasmonic acid, and malate dehydrogenase pathways, and by increasing the activity of related defence enzymes (Roth *et al*., 2024).

Studies by H. Li *et al*. (2024) have shown that triazole plant growth regulators are highly effective at preventing plant lodging and increasing crop yield. However, their prolonged persistence in soil may negatively affect subsequent crop development. Compounds of cyclohexanecarboxylic acid are characterised by moderate effectiveness and rapid soil degradation; however, prohexadione calcium requires caution due to the risk of soil toxicity. The use of B9 in succinic acid derivatives is limited by its elevated toxicity. Y. Zaytseva (2024) developed an effective system for regeneration of *Rhododendron yedoense* var. *poukhanense* (H. Lév.) Nakai from seedlings using TDZ as an inducer of meristem proliferation. Seedlings germinated *in vitro* were used as explants. The highest average number of shoots per explant was obtained after elongation under conditions of direct cultivation on AM medium supplemented with 1.0 μM TDZ, and after a pulse treatment with 30.0 μM TDZ (9.32 and 10.32, respectively). Rooting of plants (50%) was recorded after a 4-hour pulse treatment with indole-3-butyric acid with *in vitro* cultivation on hormone-free AM0 medium. M. Khanam *et al*. (2022) showed that growth regulators play a crucial role in ornamental nurseries, ensuring rapid production of well-developed seedlings. Prolonged growth in small pots leads to root deformation, hindering water and nutrient uptake and reducing plant stress tolerance. IBA often combined with 1-naphthaleneacetic acid, is commonly used in nurseries (Tsaktsira *et al*., 2021). A study on rhododendron propagation (*R. ponticum*, *R. luteum*, *R. ungernii*, and *R. caucasicum*) examined the effects of IBA dosage (0, 500, and 1,500 ppm) and propagation season (autumn/spring) on rooting. *R. caucasicum* and *R. ungernii* showed 100% rooting efficiency, while *R. ponticum* and *R. luteum* had lower rates. The highest root dry mass, volume, and diameter were observed in *R. caucasicum* (autumn, 1,500 ppm IBA), while the longest roots were found in *R. ungernii* (spring, 500 ppm IBA) (Altun, 2023).

Vegetative propagation is crucial for reproducing high-yielding trees (Elouaflin *et al*., 2023). In Ivorian cashew orchards, air-layering protocols were developed, testing various substrates, stem diameters, and IBA concentrations. Sawdust, rice husk, and coconut peat yielded rooting percentages of 88.09%, 79.36%, and 61.90%, respectively, while coffee husk yielded no roots. Larger diameter stems (8-12 mm) and 5 mg/L IBA resulted in the highest rooting (85.18%) and survival (89.41%), with over 80% survival after transplanting. Thus, 8-12 mm stems treated with 5 mg/L IBA in sawdust are optimal for cashew air-layering in Côte d'Ivoire. Vegetative propagation is also effective for species with complex seed germination requirements, such as red osier dogwood (*Cornus sericea* L.). Stem cuttings were used with varying IBA concentrations and cutting ages (previous-year shoots/PYS and current-year shoots/CYS). After four months, IBA improved survival, height, and biomass in PYS cuttings but not in CYS. IBA concentration and cutting age significantly affected root morphology; higher IBA increased root surface area and length, particularly in PYS cuttings, potentially enhancing resource uptake and growth (Inoue *et al*., 2023).

Another important avenue for using propagation technologies with growth regulators involves specific adaptations to challenging environmental conditions. Propagating plants for harsh environments requires tailoring them to specific stresses. A study on *Prunus* rootstocks showed that genotypes significantly affected auxin-induced root formation. This suggests that a plant's genetic makeup plays a key role in its ability to develop stress-resistant roots (Justamante *et al*., 2022). S.-H. Kim *et al*. (2021) showed that IBA is a common growth stimulator used in stem cuttings. Research on *V. dahurica* and *V. pusanensis* confirms that IBA is more effective than NAA in promoting

root growth. IBA at 1.5 mg/L significantly increased root number in both species and increased root length in *V. dahurica*. These findings highlight IBA's potential for vegetative propagation in these plants. The influence of mother plant age on adventitious root formation and IBA uptake was studied in *Prunus subhirtella* 'Autumnalis' leaf cuttings. IBA and IAA concentrations were measured over 24 hours in cuttings from mature (60 years), rejuvenated (16 years), and juvenile (*in vitro*) mother plants. Rooting success and root quality were then assessed. Semi-mature plants showed significantly higher rooting (95%) than mature plants (68%), with less callus formation. While IBA concentration in cuttings wasn't affected by mother plant age or time after cutting, the study highlights the impact of mother plant physiology on rooting success and root quality.

Traditional peach rootstock propagation relies on seeds because they are readily available and easy to handle. However, stem cuttings are crucial for propagating hybrids and maintaining genetic uniformity (Lesmes-Vesga *et al*., 2021). A study comparing K-IBA (potassium indole-3-butyric acid) concentrations (0-0.4%) on peach cuttings in aeroponics and rooting trays found that 0.2% K-IBA optimised rooting and survival, while 0.2% and 0.4% promoted the most adventitious roots. Rooting trays supported better root growth, but aeroponics proved equally effective for rooting with improved control and resource management. In floriculture, vegetative propagation is vital for preserving rose varieties. Research evaluating powdered and gel IBA on hybrid tea ('Mr. Lincolin') and floribunda ('Iceberg') roses, using cuttings of varying lengths (20-35 cm) and an anti-desiccant (Vapor Gard), found that 30 cm cuttings treated with Vapor Gard for three weeks yielded the highest rooting percentages (73-83%). Notably, gel IBA significantly outperformed the powdered form for floribunda roses, improving rooting (93%), root length (15.7 cm), root number (21), shoot number (4), shoot length (19.7 cm), leaf number (20), and leaf area (19.6 $cm^2$). While both forms were comparable in terms of hybrid tea rose leaf area, gel IBA was superior in all other aspects. This suggests that gel IBA with longer cuttings enhances rose rooting and may be applicable to other ornamentals (Mohammed *et al*., 2024).

This study evaluated the effect of different numbers of leaflets and concentrations of IBA on the rooting ability of leafy stem cuttings of *Hevea brasiliensis*. Rooting of *Hevea brasiliensis* leafy stem cuttings can be an effective tool for cultivation, conservation of genetic diversity, and restoration of this species in Peru, which has been decimated by decades of extractive practices (Gomes & Scortecci, 2021). Rubber tree cuttings (6-7 cm) with 2 or 5 leaflets were treated with 0-5,000 ppm IBA and rooted in sandy substrate under mist irrigation. After 29 days, cuttings with 5 leaflets and 2,000 ppm IBA showed the best results: 100% survival, 79% rooting, 4.1 roots, and 2.9 cm root length. This technique is a simple yet effective tool for conserving and commercialising rubber trees. A study by J. Seka *et al*. (2025) showed that the addition of exogenous plant growth regulators: KIN at concentrations of 0.12 and 0.24 μM and TDZ at concentrations of 5 and 10 nM, contributed to the optimisation of micropropagation *in vitro*. When reducing the concentration of mineral salts Murashige and Skoog (MS) by half, this was also effective, especially in combination with PGR. The authors of M. Seliem *et al*. (2025), investigated that although 1.0 mg L-1 TDZ produced the highest significant number of shoots, it did not promote rooting. The authors recommended using BAP at a concentration of 4.0 mg L-1. The separate effect of a single cytokinin, added to MS medium, on the *in vitro* propagation of A. sisalana was also studied.

One modern approach to the search for effective compounds is molecular modelling based on known natural and synthetic compounds. Research results from recent years by M. Zavhorodnii *et al*. (2024) show that the combination of a nitrogen-containing heterocycle and mercaptocarboxylic acids enhances biological activity or reveals new effects. An analysis of the lipophilicity, toxicity, and rhizogenesis effects of the studied compounds was conducted. The most toxic compounds had acetic and propanoic acid residues in the $4^{th}$ position. Among the triazoles, the compound containing bromine in the $4^{th}$ position of the anthraenedione ring was the most toxic. This is associated with increased bioavailability of more lipophilic compounds (Matada *et al*., 2021).

The studied compounds exhibited strong stimulatory activity for rhizogenesis *in vitro* in

explants of *Paulownia* clone 112 and *Rosa damascena* variety 'Lada'. Some of the studied compounds – (2-((7-chloroquinolin-4-yl)thio)acetic acid) and (3-((7-chloroquinolin-4-yl)thio) propanoic acid) – exceeded the reference drug – 2-(naphthalen-5-ol)acetate acid – by 10 to 20% (Shupeniuk *et al.*, 2023). The presence of L-cysteine and N-acetyl in the 4th position of the quinoline cycle reduced activity. The introduction of substituents into the anthraenedione ring did not significantly affect the activity of the triazoles. A number of effective compounds were obtained by combining a heterocycle and a succinic acid residue in a single molecule (Shupeniuk *et al.*, 2023) (Fig. 2).

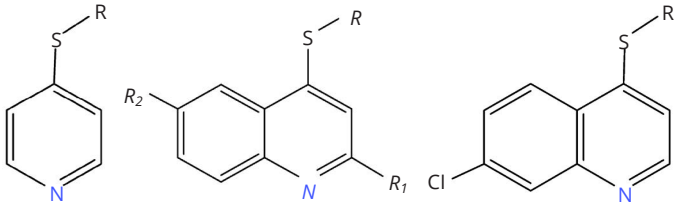


**Figure 2.** General structure of S-heteryl succinates
**Note:** R = CH(COOHCH$_2$-COOH); R$_1$ = H, CH$_3$; R$_2$ = H, -OCH$_3$, -OC$_2$H$_5$
**Source:** developed by the authors based on V. Shupeniuk *et al.* (2023)

The presented research results show that on a nutrient medium supplemented with the compounds: 2-((quinolin-4-yl)thio)succinic acid and 2-((7-chloroquinolin-4-yl)thio)succinic acid, cloned *Paulownia* plants form 4.22 ± 0.31 and 4.50 ± 0.71 roots ($p < 0.001$), respectively, and the rhizogenesis frequency reached 93%. Overall, *Paulownia* clone 112 on a hormone-free nutrient medium initiates the fewest roots and the shortest roots among all tested medium variants. On a nutrient medium containing the compounds with the addition of: 2-((quinolin-4-yl)thio)succinic acid and 2-((7-chloroquinolin-4-yl) thio)succinic acid, rose explants also had a significantly greater number of roots ($p < 0.001$) (Fig. 3).

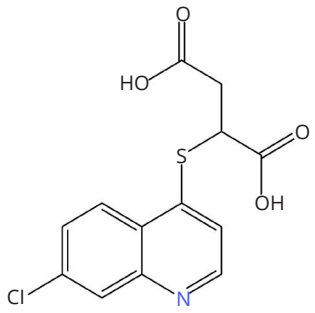


**Figure 3.** Structure of 2-((7-chloroquinolin-4-yl)thio)succinic acid
**Source:** developed by the authors based on M. Zavhorodnii *et al.* (2024)

The presented studies show that the compound 2-((7-chloroquinolin-4-yl)thio)succinic acid is a promising plant growth regulator (Zavhorodnii *et al.*, 2024). Thus, the creation of new compounds based on succinic acid, an important intermediate in the Krebs cycle and in plant energy metabolism, is a promising direction for the development of effective growth stimulators (Labenska, 2016). It is known that the main derivative of succinic acid used in growth stimulators is gibberellins. In addition to gibberellins, there are other growth stimulators that can be derived from succinic acid or have a similar structure. The triazoles obtained from anthracenedione derivatives showed a moderate stimulatory effect on rhizogenesis *in vitro* in explants of *Paulownia* clone 112 and *Rosa damascena* variety 'Lada'. The presence of a sulphur atom

contributes to both antiradical protection (OH) and inhibition of lipid peroxidation processes (ROOH) due to reducing properties with the formation of sulfoxide and six-membered complexes with metals of variable valency. New synthetic pyrimidine derivatives that have a regulatory effect similar to that of plant hormones on root and shoot growth are being actively researched as novel plant growth regulators, pesticides, and fungicides at concentrations of $10^{-5}$-$10^{-9}$ (Shupeniuk *et al*., 2023). A comparative assessment of the restorative activity of synthetic low-molecular-weight nitrogen-containing heterocyclic compounds was carried out, including derivatives of sodium and potassium salts of 6-methyl-2-mercapto-4-hydroxypyrimidine (Methyur, Kamethur), as well as new thioxopyrimidine derivatives. The most biologically active compounds were identified – Methyur, Kamethur and thioxopyrimidine derivatives (Tsygankova *et al*., 2025).

Research is exploring the use of natural extracts for plant propagation. A study on *Photinia* 'Red Robin' cuttings compared IBA and seaweed extracts. While seaweed extracts promoted early callus formation, IBA at 1% concentration ultimately yielded the best overall rooting. Seaweed extracts, despite increasing root number, inhibited root length and didn't improve biomass compared to the control, suggesting they aren't suitable for this species' propagation using this method (Loconsole *et al*., 2023). B. Altun (2023) conducted a study examining the effects of IBA dose and breeding season on rooting rate and several root parameters in rhododendron species: *R. ponticum* L., *R. luteum* Sweet, *R. ungernii* Trautv and *R. caucasicum* Pallas. The author noted that the highest rooting efficiency (100%) was obtained in *R. caucasicum* and *R. ungernii*.

Combining plant growth regulators, particularly auxins and cytokinins, shows promise, enhancing root regeneration, yield, and disease resistance, though some effects on plant chemistry are noted by D. Loconsole *et al*. (2023), J. Sosnowski *et al*. (2023) and V. Tsygankova *et al*. (2024). Direct organogenesis in mature *Pinus massoniana* was optimised using specific disinfection and PGR combinations (6-BA, IBA, NAA), establishing a regeneration system (Wan & Fan, 2024). Propagation of *Ilex aquifolium* benefited significantly from NAA application, with apical cuttings achieving 100% rooting (Tsaktsira *et al*., 2021). The paper by T. Thakur *et al*. (2025) demonstrates that plant growth retardants are widely used in ornamental horticulture to regulate plant morphology and quality, as well as flowering processes, to enhance ornamental value. Their action is associated with the inhibition of gibberellin biosynthesis. By limiting stem elongation, these substances promote the formation of more compact and bushier plants. It is well known that growth retardants can strengthen stems, increase plant stability, enhance stress tolerance, reduce the risk of lodging, and ensure more uniform flowering.

A. Pourkhaloee (2021) investigated the vegetative propagation of field elm (*Ulmus minor* Mill.) by softwood cuttings that were quickly immersed (8 s) in aqueous solutions of IBA (0, 1,500 and 3,000 mg/L) followed by foliar spraying with a commercial seaweed extract (Citoking – Anoca Chemistry, Spain) at concentrations of 0, 1.5 and 3 ml/L. The highest rooting percentage (78.9) was obtained with 1,500 mg/L IBA, which showed a significant difference compared to the control (20.9). The longest root and shoot lengths (18.0 cm and 55.8 mm, respectively) were observed with 1,500 mg/L IBA + 1.5 ml/L seaweed extract (SWE). The application of SWE had no significant effect on root diameter, leaf bud germination and number of new leaves. In contrast, all these traits improved with 1,500 mg L-1 IBA. Cutting survival during the rooting period was not affected by SWE. Increasing the IBA concentration from 0 to 3,000 mg L-1 decreased survival from 98.6% to 91.7%, respectively. Finally, adventitious root cultures provide a sustainable method for producing metabolites from medicinal plants, thereby addressing limitations in accessing wild plants (Khanam *et al*., 2022).

*Tetrastigma hemsleyanum*, a valuable medicinal liana, faces endangerment due to limited wild populations and low seed yield. A study developed protocols for shoot induction and organogenesis from leaves and petioles (Pang *et al*., 2024). A combination of IBA and thidiazuron induced callus and shoots, with optimal shoot induction on MS medium containing 1.0 mg/L IBA and 0.1 mg/L NAA, achieving a shoot proliferation coefficient (SPC) of 6.73. Increasing light intensity further improved SPC and chlorophyll content. Adventitious shoots readily formed roots (100%) on MS medium with NAA or IBA (0.1-2.0 mg/L). Plants exhibited high survival rates (>98%) after

transplanting. These protocols enable mass production of shoots for conservation and potential commercial propagation.

New vegetative propagation methods are being developed for industrially important plants like bamboo (Kumari *et al.*, 2024). A study investigated the effects of citrate- and CTAB-coated gold nanoparticles (AuNPs) on *Bambusa balcooa in vitro*. 400 µM citrate-AuNPs significantly improved shoot proliferation, photosynthetic pigment accumulation, and antioxidant activity. Conversely, 600 µM CTAB-AuNPs decreased growth. Transcriptome analysis identified differentially expressed genes and metabolic pathways associated with nanoelicitation and plant growth, including those involved in oxidative stress response and cell proliferation. This provides insights into the molecular mechanisms by which AuNPs modulate micropropagation.

Methods involving radical activation of plant growth regulators are also under development (Gil *et al.*, 2020). A study explored the effects of light treatment (blue, red, fluorescent) and NAA application on the rooting of single-node stem cuttings. Blue light combined with NAA effectively induced adventitious root formation in otherwise poorly rooting cuttings. Gene expression analysis revealed that cmLBD1 was upregulated by blue light after 5 days, initiating rooting, while other root formation genes were upregulated by fluorescent light after 14 days. This indicates that blue light and NAA are more effective for rapid rooting in single-node cuttings.

New approaches using mixtures of plant growth regulators are crucial for propagating endangered and endemic species. A study focused on *Hieracium lucidum* subsp. *lucidum*, a critically endangered Sicilian endemic (Gianguzzi *et al.*, 2024). Seed germination tests showed high germination rates (70-95%) across various temperatures, indicating no dormancy. Vegetative propagation via stem cuttings was enhanced by IBA treatment, with all treated cuttings rooting within two months compared to 50% rooting in untreated cuttings over a longer period. An efficient *in vitro* propagation protocol using leaf explants was also developed. The combination of meta-topolin (mT, 2 mg/L) and 2,4-D (1 mg/L) in MS medium maximised callus induction and shoot regeneration. Root regeneration was optimal on hormone-free MS and MS with IBA (1 mg/L). This research demonstrates that *H. lucidum* can be successfully propagated using various methods, depending on the available material.

## CONCLUSIONS

The use of natural and synthetic plant growth regulators based on nitrogen-containing heterocycles is a promising direction in modern plant propagation technologies. It has been shown that nitrogen-containing heterocyclic plant growth regulators are effective across various modern plant propagation technologies. A review of current research demonstrating the effectiveness of using different groups of growth stimulators for the propagation of plants with extremely complex propagation due to long stratification requirements and low seed germination, for the reproduction of potentially high-yielding plants, under conditions of specific plant adaptations to harsh environmental conditions, is presented. Plant propagation technologies involving plant growth regulators encompass a wide range of methods that stimulate and regulate propagation processes using natural and synthetic substances that affect plant growth and development. It has been shown that plant growth regulators based on nitrogen-containing heterocycles, both natural and synthetic, are effectively used in the main plant propagation technologies – rooting of cuttings, microclonal propagation (*in vitro* tissue culture), seed treatment, and regulation of flowering and fruiting. The review article analyses approaches to the design of new and effective compounds using molecular modelling. It has been shown that combining known pharmacophores into a single molecule increases the effect. Thus, the combination of a nitrogen-containing heterocycle and mercaptocarboxylic acids leads to an enhancement of biological activity or the appearance of new effects. The use of new synthetic preparations, mixtures of growth stimulators, various methods to enhance their effects, and slow-release strategies for growth stimulators has demonstrated their effectiveness. However, it is important to consider possible environmental risks and conduct further research to create safe and effective preparations. Future research should focus on elucidating the mechanisms of action, optimising molecular structure, and evaluating environmental safety and field-scale efficacy of growth stimulators based on nitrogen-containing heterocycles across diverse plant propagation systems.

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## CONFLICT OF INTEREST

The authors declare no competing interests relevant to this article.

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## Перспективи використання стимуляторів росту на основі азотовмісних гетероциклів у технологіях розмноження рослин

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**Анотація.** Азотовмісні гетероциклічні сполуки привертають увагу дослідників як речовини, широко представлені у структурах як природних, так і синтетичних регуляторів росту рослин. Актуальність використання природних і синтетичних регуляторів росту в розмноженні рослин є надзвичайно високою, оскільки вони відіграють ключову роль у регуляції процесів росту і розвитку рослин, включаючи розмноження. Технології розмноження із застосуванням регуляторів росту є важливим інструментом сучасного садівництва, сільського господарства та біотехнології, забезпечуючи отримання високоякісного посадкового матеріалу та підвищення ефективності виробництва. Метою цього дослідження було проаналізувати сучасні підходи

до використання як природних, так і синтетичних стимуляторів росту на основі азотовмісних гетероциклів, а також визначити перспективи їх подальшого застосування. Встановлено, що азотовмісні природні та синтетичні регулятори росту найефективніше застосовуються для укорінення живців, мікроклонального розмноження (*in vitro* культура), передпосівної обробки насіння, а також регулювання процесів цвітіння і плодоношення. Систематизовано сучасні стратегії застосування стимуляторів росту на основі азотовмісних гетероциклів та окреслено сучасні підходи до розробки нових високоефективних сполук із використанням молекулярного моделювання. Показано, що інтеграція різних фармакофорних фрагментів в одній молекулі може суттєво підвищувати біологічну активність. Крім того, використання новосинтезованих сполук, багатокомпонентних препаратів, методів підвищення їх ефективності та систем контрольованого вивільнення продемонструвало високу результативність. Практичне значення роботи полягає у можливості використання її результатів для розробки та впровадження більш ефективних стимуляторів росту, що сприятиме підвищенню ефективності розмноження рослин, зростанню врожайності та оптимізації біотехнологічних процесів у сільському господарстві та рослинництві

**Ключові слова:** похідні хіноліну та сукцинату; гібридні молекули; вегетативне розмноження рослин; мікроклональне розмноження; суміші стимуляторів росту; похідні хіноліну