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Efficacy of plant growth regulator (PGR) in lieu of root growth and dynamics: A review

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Abstract

Plant Growth Regulators (PGRs) have emerged as crucial supplements for optimizing root growth and dynamics in plants, thereby significantly influencing overall plant health and productivity. This study explores the pivotal role of PGRs in regulating root architecture, enhancing nutrient and water uptake efficiency, and fortifying plants against environmental stresses. It discusses the diverse mechanisms through which PGRs modulate gene expression, signal transduction pathways, and hormonal interactions to orchestrate root development. Furthermore, the abstract highlights the practical applications of PGRs in agricultural and horticultural practices, including their use in various application methods, dosage considerations, and timing strategies. By providing insights into the significance of PGRs as supplements for root growth enhancement, this abstract underscores their importance in promoting sustainable agriculture and ensuring global food security.

Keywords: Growth promotors, root growth modulation, root dynamics, crop efficacy

Introduction

Root growth dynamics encompass the intricate processes by which roots develop, elongate, branch, and interact with their environment. Understanding these dynamics is crucial for comprehending how roots acquire water and nutrients, anchor the plant, and respond to various environmental stresses. Additionally, the health and vigor of roots directly impact overall plant health, productivity, and stress tolerance. Root growth typically occurs in distinct phases: primary root growth, lateral root initiation and emergence, and secondary root growth. Primary root growth involves the elongation of the radicle, the embryonic root, and the establishment of the primary root system. This phase is critical as it sets the foundation for the plant's root architecture. The primary root penetrates the soil, creating pathways for water and nutrient uptake. As the primary root extends, it differentiates into various cell types, including those responsible for absorption and conduction [1].

Lateral root initiation and emergence occur as lateral root primordia are formed, and new roots emerge from the primary root. This phase significantly enhances the root system's ability to explore the soil environment. Lateral roots increase the surface area available for nutrient and water absorption and allow the plant to exploit soil resources more effectively. The emergence of lateral roots is a complex process regulated by hormonal signals, environmental cues, and genetic factors [2].

Secondary root growth involves the elongation and branching of existing roots, contributing to the expansion of the root system. This phase includes both the growth of lateral roots and the further development of the primary root. Secondary root growth allows plants to adapt to changing environmental conditions by modifying root architecture to optimize resource acquisition. This phase is essential for maintaining plant health and supporting the plant's increasing demands for water and nutrients as it grows [2].

Root architecture refers to the spatial arrangement and morphology of roots within the soil. It includes parameters such as root length, depth, angle of growth, and branching patterns. Root architecture is highly plastic and influenced by both genetic and environmental factors. An optimal root architecture facilitates efficient resource acquisition, water uptake, and nutrient exploration, thereby enhancing plant growth and productivity. For example, deep-rooted plants can access water from deeper soil layers during drought conditions, while shallow-rooted plants can quickly absorb nutrients from the soil surface [2].

Roots interact dynamically with the soil environment, forming symbiotic relationships with soil microorganisms, exchanging nutrients, and modifying soil structure. Root hairs and mycorrhizal associations increase the surface area for nutrient absorption and facilitate nutrient uptake from the soil. Mycorrhizal fungi, in particular, form extensive networks that connect roots with distant soil resources, effectively extending the root system's reach. Root exudates, which are organic compounds released by roots, play a crucial role in mediating interactions with soil microbes. These exudates can stimulate microbial activity, promote nutrient cycling, and enhance soil fertility. Additionally, roots can alter the soil's physical properties by creating channels and aggregating soil particles, which improve soil structure and porosity [3].

Root health is fundamental to overall plant health and productivity. Healthy roots provide structural support, anchor the plant in the soil, and ensure efficient water and nutrient uptake. Well-developed root systems enhance plant vigour, tolerance to environmental stresses, and resistance to pests and diseases. Conversely, root diseases, soil compaction, or nutrient deficiencies can impair root function, leading to stunted growth, reduced yield, and susceptibility to stress. For instance, root rot caused by pathogenic fungi can severely damage root tissues, hindering the plant's ability to absorb water and nutrients. Soil compaction, often resulting from heavy machinery or foot traffic, restricts root growth and reduces soil aeration, further compromising root function. Nutrient deficiencies, such as a lack of nitrogen or phosphorus, can limit root development and reduce the plant's overall growth and productivity [4].

Overview of Root Growth Dynamics and Importance in Plant Health: Plant growth regulators (PGRs) are “key molecules involved in regulating various aspects of plant growth and development, including the development of root systems. Roots are essential plant organs responsible for anchorage, water and nutrient uptake, and interactions with the soil microbiome.”

PGRs exert their effects on root development through complex signaling pathways and interactions with other hormones. Among the major classes of, “PGRs, auxins, cytokinins, gibberellins, abscisic acid, ethylene, and brassinosteroids” play pivotal roles in regulating root growth and architecture.

Auxins

Auxins are a class of plant hormones that play crucial roles in the growth and development of plants. They are primarily responsible for regulating various processes such as cell elongation, cell division, root initiation, and fruit development. Auxins are synthesized primarily in the apical meristems of the shoot tips and young leaves, but they can also be found in other parts of the plant, including the roots. Auxins exert their effects by regulating gene expression and by influencing various physiological processes. They can promote cell elongation by loosening the cell wall, allowing for increased water uptake and expansion. Additionally, auxins can stimulate cell division, particularly in the cambium and lateral meristems, leading to growth in thickness. (Fig.1)

Auxins, particularly indole-3-acetic acid (IAA), are known as primary regulators of root development. They promote cell elongation, root initiation, and the establishment of root apical meristem (RAM). Auxin gradients within the root tip regulate root gravitropism, guiding the growth direction of roots towards water and nutrient sources [5-6].

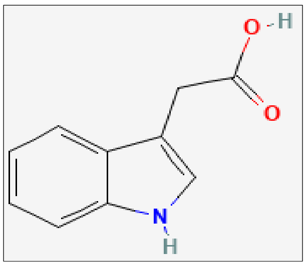

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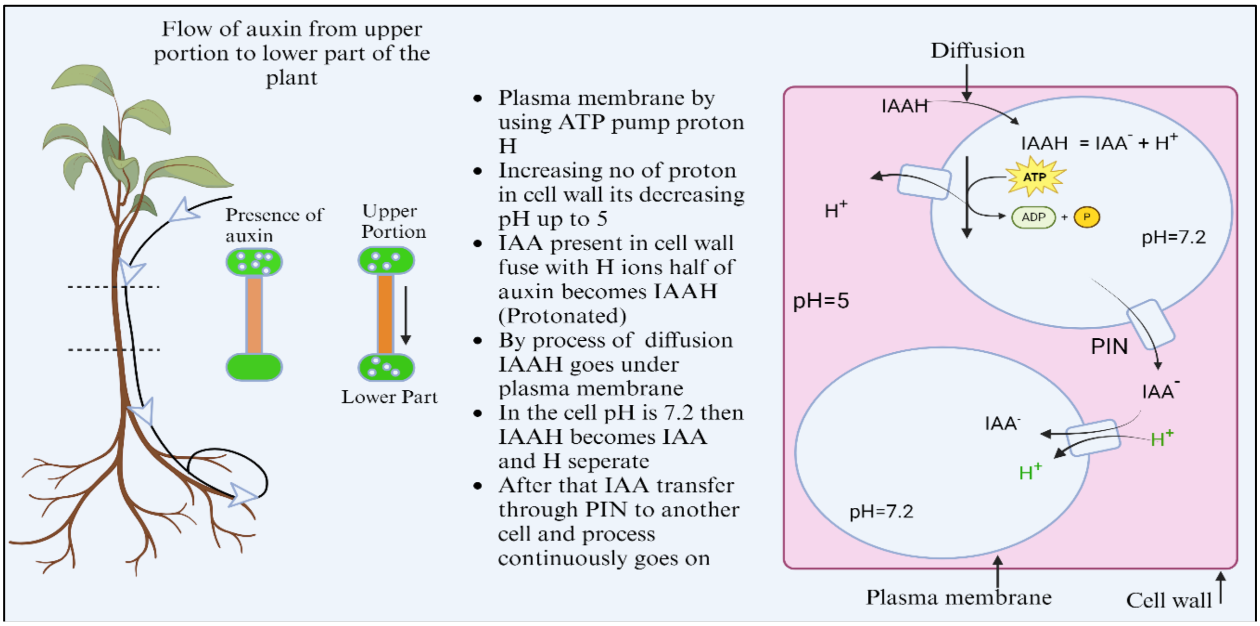
Fig 1: Structure of Auxin.

Mechanism action of auxin



- Plasma membrane by using ATP pump proton H
- Increasing no of proton in cell wall its decreasing pH up to 5
- IAA present in cell wall fuse with H ions half of auxin becomes IAAH (Protonated)
- By process of diffusion IAAH goes under plasma membrane
- In the cell pH is 7.2 then IAAH becomes IAA and H seperate
- After that IAA transfer through PIN to another cell and process continuously goes on

Fig 2: Mechanism action of auxin.

Auxin formation was done in upper portion of plant and it transfer from upper portion to lower portion of the plant and it helps to cell elongation in rootzone area. Auxin IIA^- directly enters into the cell with H^+ ion (proton) by diffusion, otherwise another method should be followed. Inside plasma membrane H ion transfer into cell wall by energy formation. Transfer of H^+ ion into cell wall causes decrease in pH (pH=5) and H^+ ion fuses with IAA^- it becomes IIAH and enters into plasma membrane. Auxin present in plasma membrane goes deprotonated form and becomes separate IAA^- and H^+. IAA^- is transfer through PIN efflux in cell wall and move in cell membrane and forward to next cell by symporters and H^+ ion which is present inside cell wall. H^+ ion concentration is higher in cell wall so its goes in plasma membrane with IAA^-.

Cytokinin's

Cytokinin's are a class of plant hormones that play vital roles in regulating various aspects of plant growth and development. They are known for their ability to promote cell division, delay senescence (aging), and regulate various physiological processes such as shoot and root growth, nutrient mobilization, and stress responses. Cytokinin's are primarily synthesized in actively growing tissues, such as roots, developing seeds, and fruits, and are transported to other parts of the plant where they exert their effects. They work in concert with other plant hormones, such as auxins, to maintain proper growth and development. (Fig.3)

Cytokinin's are known to, "promote cell division and differentiation in plant tissues. In roots, cytokinin's regulate the activity of the root apical meristem (RAM) and promote lateral root initiation and development. By balancing the auxin-cytokinin ratio, cytokinin's influence root growth and branching patterns, ultimately shaping the architecture of the root system [7-8]."

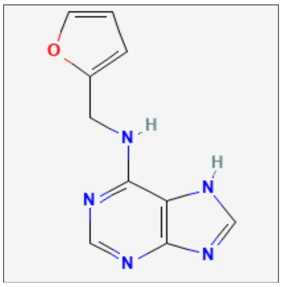


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Fig 3: Structure of Cytokinin.

Mechanism action of cytokinin

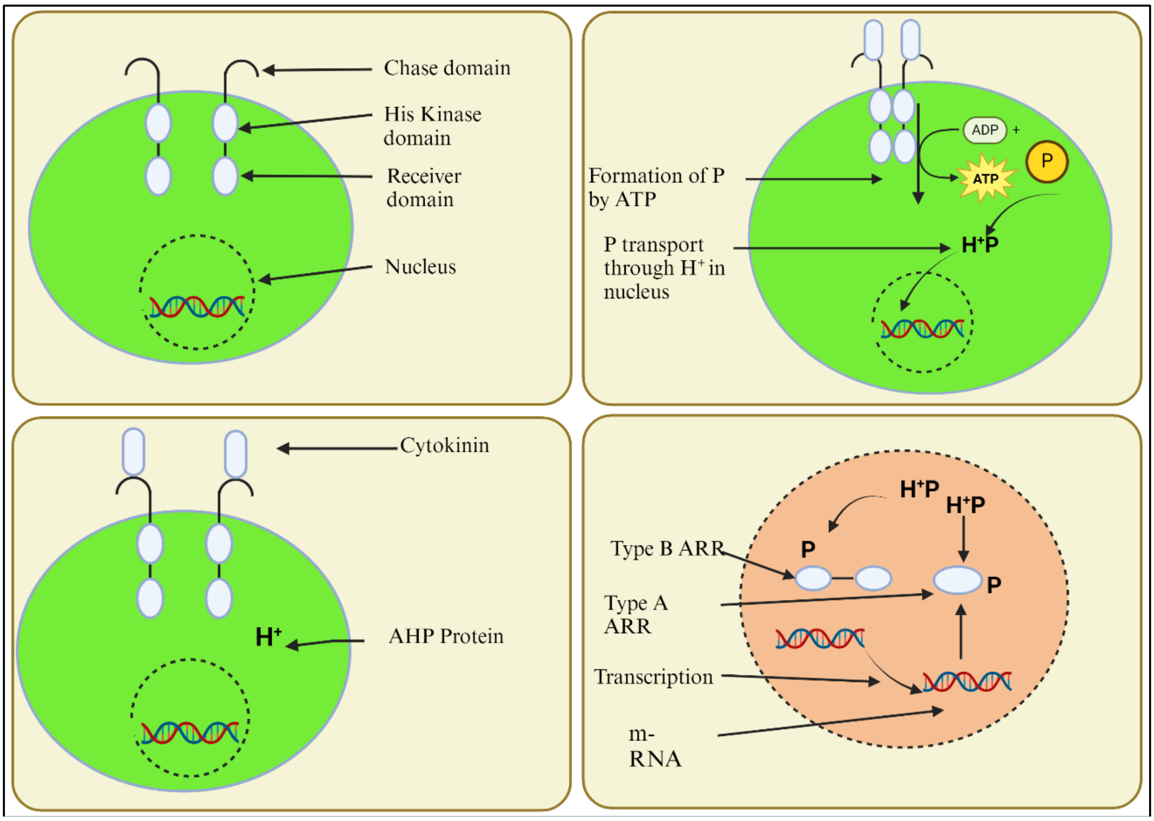

Fig 4: Mechanism action of cytokinin.

For transfer of cytokinin receptors are CRE-1 i.e., cytokinin response 1(Chase domain) and AHK-2 i.e., Arabidopsis his kinase present on cell membrane. We can see extracellular domain of receptor is the chase domain also have his kinase domain and receiver domain. Cytokinin attached to case domain this ligand binding induces the dimerization of CRE-1 and AHK-2 receptor this causes his kinase activated, this active his kinase acts on ATP and get the phosphate from it and this phosphate on his kinase transferred to the aspartate residue on receiver domain as shown in the fig. We got the fully activated cytokinin receptor. We have the inactive AHP protein into the cytoplasm this protein is acted upon by postulated active receiver domain of cytokinin receptor. Phosphate from the receiver domain of receptor is transport to AHP protein this phosphate is receive by conserve histidine present on the AHP protein. Due to phosphorylation AHP protein move into nucleus. AHP transpose the phosphate to an aspartate residue located within the receiver domain of type B ARR and it get active and start regulating DNA and we get type A ARR and from this we get mRNA on this we get type A ARR protein which also got receiver domain and it's also get phosphorylated by AHP and ARR protein which actually regulates the cytokinin response to genes.

Gibberellins

Gibberellins are a class of plant hormones that play essential roles in regulating various aspects of plant growth and development. They are involved in processes such as seed germination, stem elongation, leaf expansion, flowering, and fruit development. Gibberellins were first discovered in Japan in the 1920s when researchers observed that a fungus (Gibberella fujikuroi) caused abnormal elongation of rice plants. Further study revealed that the active compounds produced by the fungus were gibberellins, which were later found to be produced naturally in plants as well. (Fig.5)
Gibberellins are involved in promoting cell elongation and expansion in various plant organs, including roots. In root development, gibberellins influence root elongation rates and the size of the root meristem zone. They regulate cell division and expansion in the elongation zone, contributing to overall root growth [9-10].

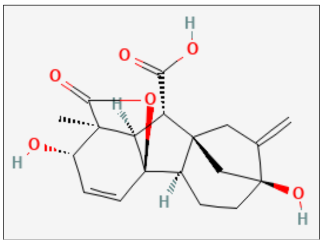

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Fig 5: Structure of Gibberellins.

Mechanism action of gibberellins

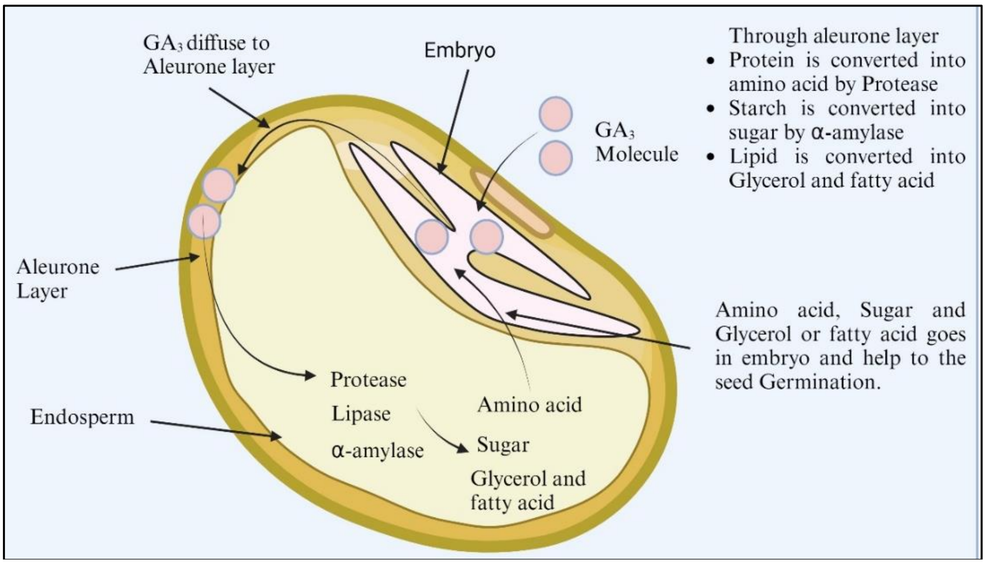

Fig 6: Mechanism action of gibberellins.

Applying H_2O treatment to breaking seed coat and water molecule goes inside the endosperm (imbibition). O_2 present outside of the seed its also uptake by the seed and synthesis of ATP this process is crucial as activate synthesis of an important hormone Gibberellic acid. Gibberellic acid is important factor which germinate seed. It goes through embryo inside the seed, it diffuses and goes in Aleurone layer which is outer layer of endosperm and activate aleurone layer to synthesis the enzyme such as protease, lipase and α-amylase those enzymes are important to digest storage food in the endosperm here it is in monocotyledon seed in dicotyledon seed GA is travelled through cotyledon to active enzymes. In endosperm protease digest protein into amino acid, α-amylase digest the starch into sugar and lipase digest the lipid into glycerol or fatty acids. Such digested nutrients amino acid sugar and fatty acid they are transfer to embryo and leading to the germination of the seed.

Abscisic Acid (ABA)

Abscisic acid (ABA) is a plant hormone that plays crucial roles in various physiological processes, particularly in response to environmental stresses and in regulating growth and development. It is involved in mediating plant responses to factors such as drought, salinity, cold, heat, and pathogen attack. (Fig.7)
In root development, ABA influences root growth inhibition under water deficit conditions, regulating stomatal closure and water uptake to maintain plant water balance [11-12].

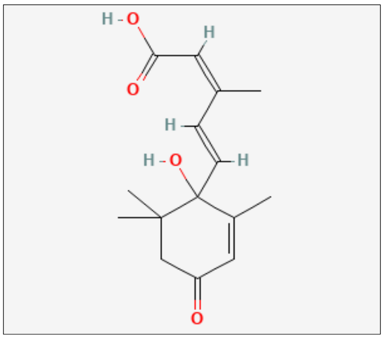

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Fig 7: Structure of Abscisic acid.

Mechanism action of Abscisic acid

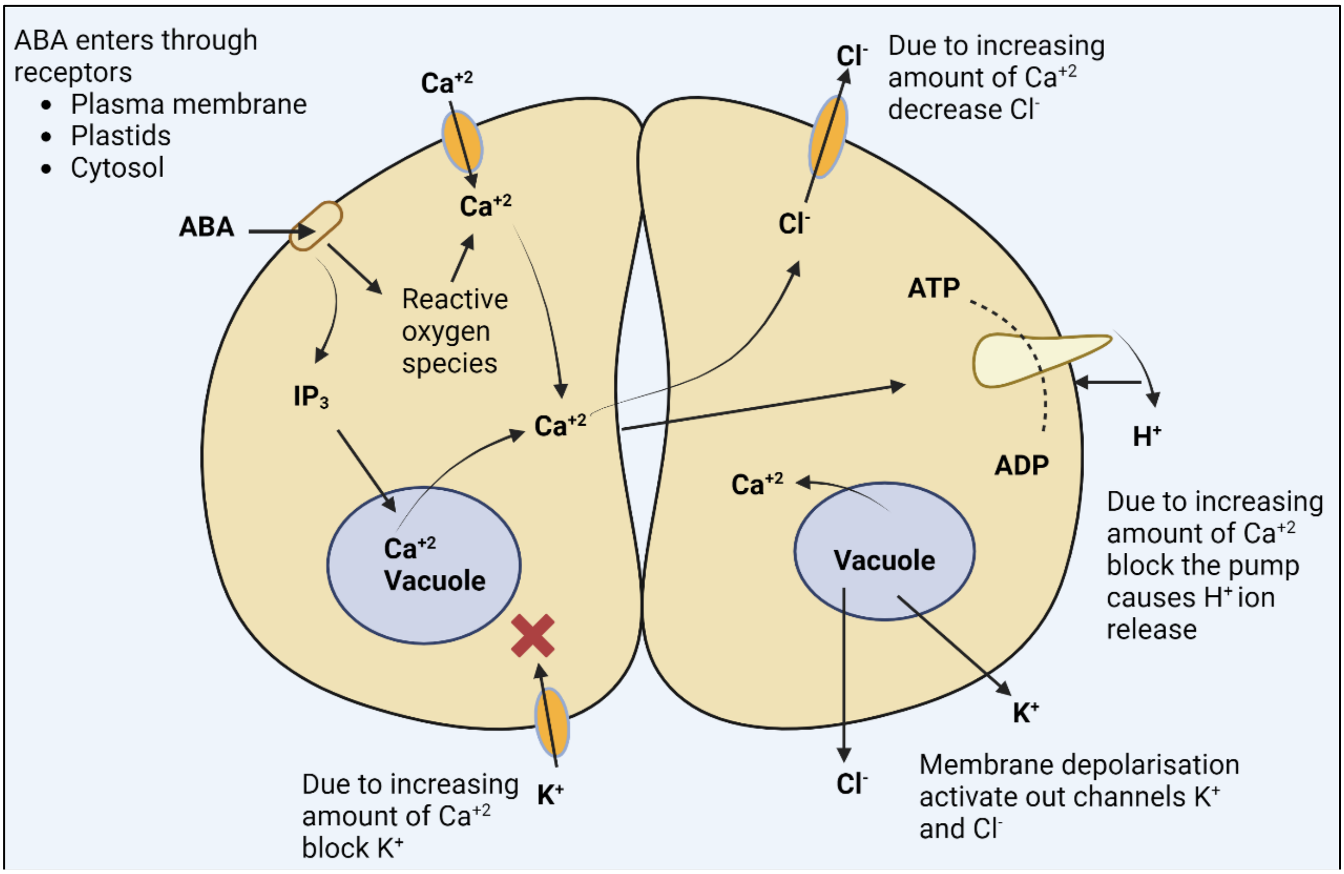

Fig 8: Mechanism action of Abscisic acid

Receptors are present in the cell membrane they are of three types they are on plasma membrane, on plastids and on cytosol. They are guard cell and at centre stomatal opening as we provide ABA, receptors are catch them. ABA binds induced the reactive oxygen species and active them causes intake of calcium Ca^{+2}. ABA increases the level of cyclic ADP ribose and IP3 which activate additional calcium channel on tonoplast of the vacuole increasing intracellular Ca blocks potassium channel. Rise in intracellular Ca the opening of cl anions depolarisation of membrane and also inhibit proton pump and increase pH and H ion goes outside. Potassium and chloride ions release across the membrane or cytosol. This causes water potential of cytosol becomes less negative. Due loss of water turgor pressure becomes low and shrink the stomata this we can protect the plant in stress condition by supplying ABA.

Ethylene

Ethylene is a simple gaseous plant hormone that plays fundamental roles in regulating various aspects of plant growth, development, and responses to environmental stimuli. It is involved in processes such as fruit ripening, senescence, abscission (shedding of leaves and fruits), and response to biotic and abiotic stresses. In roots, ethylene regulates root hair development, root elongation, and responses to mechanical stress and flooding [13-14]. (Fig.9).

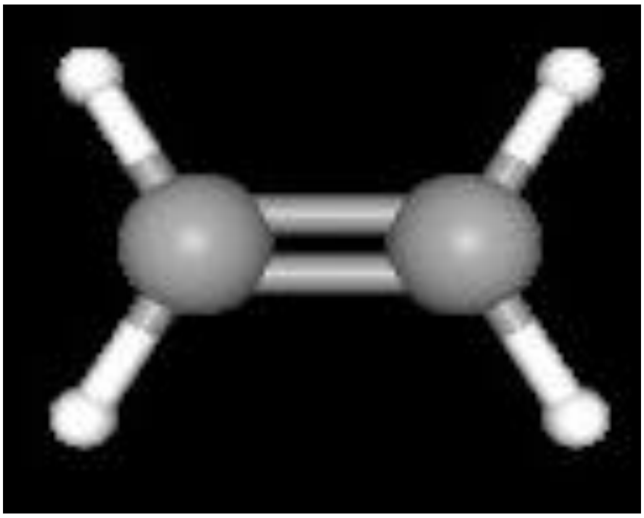

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Fig 9: Structure of Ethylene.

Mechanism action of ethylene

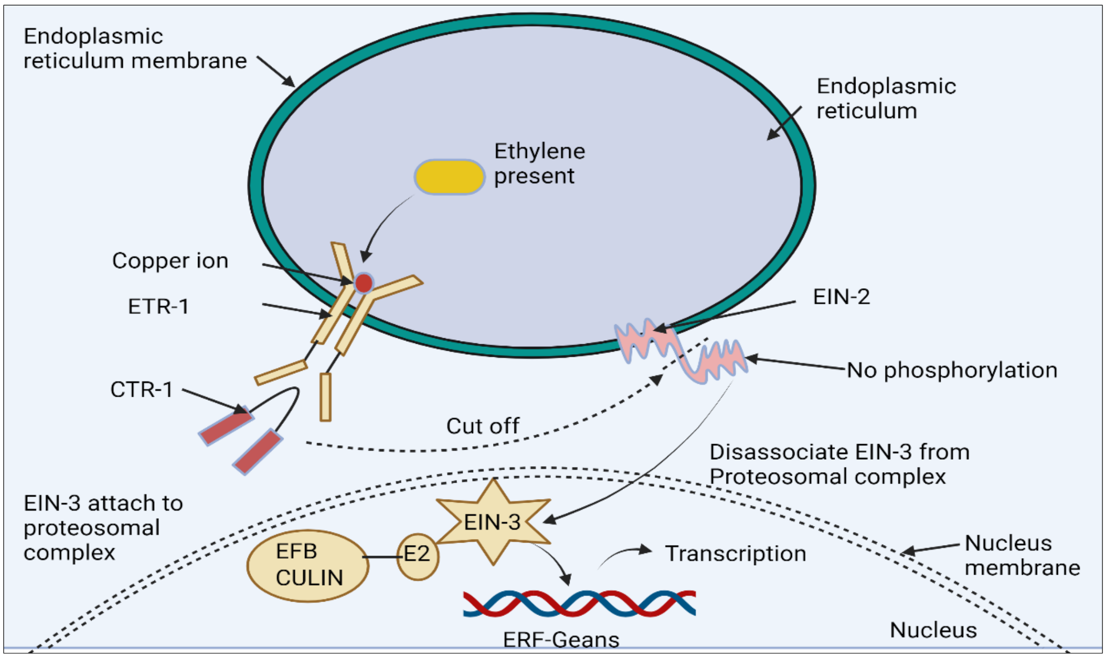

Fig 10: Mechanism action of ethylene.

Because ethylene is a negative regulator, it binds to the ETR-1 receptor in the presence of the molecule and inhibits it. The CTR-1 molecule, which was hypothesized in the absence of ethylene, is now dephosphorylated in the presence of ethylene as a result of the ATR-1 dephosphorylation. In (Fig.10) illustrates how this dephosphorylation facilitates the cleavage of EIN-2. The EIN-2 disk left it off and it moved to the nucleus, where it found an ENT-3 attached to a proteasomal complex. However, as soon as EIN-2 reached the nucleus, it stabilized the EIN-3 molecule and released it from the degradation complex. Thus, we can observe that EIN-2 protects this EIN-3 from degradation when ethylene is present. When the EIN binds to ERF genes, it initiates transcription.

Defining PGRs: Types and Functions

Plant Growth Regulators (PGRs), “also known as plant hormones or phytohormones, are chemical compounds that regulate various physiological processes in plants, including growth, development, and responses to environmental stimuli. PGRs exert their effects at very low concentrations and play crucial roles in controlling cell division, elongation, differentiation, and other aspects of plant growth. There are several types of PGRs, each with distinct functions and mechanisms of action.”

Table 1: Natural plant growth regulators (PGRs), their origins, and roles in plant growth and development

Natural PGR	Origin	Roles	References
Auxins	Shoot apex, young leaves	Stimulate cell elongation, lateral root formation.	Woodward *et al*., (2005) [15]
Cytokinins	Root tips, developing fruits	Promote cell division, delay senescence, regulate shoot meristem activity, influence leaf expansion	The Arabidopsis Book [16]
Gibberellins	Young tissues, developing seeds	Regulate stem elongation, seed germination, flower and fruit development, leaf expansion	Yamaguchi *et al*., (2008) [17]
Abscisic Acid (ABA)	Leaves, roots, seeds	Induce seed dormancy, promote stomatal closure, regulate responses to environmental stresses	Vishwakarma *et al*. (2017) [18]
Ethylene	Ripening fruits, senescing leaves	Mediate fruit ripening, leaf abscission, flower senescence, promote root hair development, adventitious root formation	Wilkinson *et al*.,(2010) [19]
Brassinosteroids	Various tissues	Promote cell elongation, leaf expansion, pollen tube growth, seed germination	Clouse *et al*.,(1998) [20]
Jasmonates	Wounded tissues, developing seeds	Mediate responses to biotic and abiotic stresses, regulate growth, development, and defense mechanisms	Wasternack *et al*.,(2013) [21]
Salicylic Acid	Various tissues	Induce systemic acquired resistance (SAR) against pathogens, regulate plant defense responses	Vlot *et al*.,(2009) [22]
Polyamines	Various tissues	Regulate cell division, differentiation, flower development, and stress responses	Hussain *et al*.,(2011) [23]
Strigolactones	Roots, young leaves	Suppress shoot branching, stimulate secondary root development, promote symbiotic interactions with fungi	Brewer *et al*.,(2016) [24]

Table 2: Synthetic plant growth regulators (PGRs) along with their development and applications

Synthetic PGR	Development	Applications	References
1. 2,4-D	Developed in the 1940s	Herbicide for weed control in agriculture and forestry, promotes root initiation in tissue culture	Hayes *et al*.,(1991) [25]
2. NAA (1-Naphthaleneacetic acid)	Synthesized in the mid-20th century	Rooting hormone for vegetative propagation, promotes lateral root formation, controls fruit drop	Davies *et al*.,(2010) [26]
3. Paclobutrazol	Developed in the 1980s	Growth retardant for controlling plant height in ornamental crops, induces flowering and fruiting in some species	MacMillan *et al*.,(1987) [27]
4. Glyphosate	Developed in the 1970s	Broad-spectrum herbicide for weed control in agriculture, inhibits amino acid synthesis in plants	Duke *et al*.,(2008) [28]
5. ABA (Abscisic Acid)	Synthesized in the 1960s	Used as a plant growth regulator in agriculture to induce dormancy, regulate stomatal closure	Davies *et al*.,(2010) [29]
6. Daminozide	Developed in the 1960s	Growth regulator for controlling plant growth and improving flowering in ornamental crops	Jacobs *et al*.,(1960) [30]
7. Ethephon	Developed in the 1960s	Induces fruit ripening, promotes flower and fruit abscission, enhances latex yield in rubber trees	Kende *et al*.,(1993) [31]
8. Chlormequat	Developed in the 1960s	Plant growth regulator for controlling stem elongation in cereals, turfgrass, and ornamental crops	Rademacher *et al*.,(2000) [32]
9. Thidiazuron	Developed in the 1970s	Cytokinin-like activity, used for shoot regeneration in tissue culture, promotes flowering and fruiting	Mok *et al*.,(2001) [33]
10. Trinexapac-ethyl	Developed in the 1990s	Growth regulator for controlling grass growth in turf management, enhances stress tolerance in grasses	Beard *et al*.,(1994) [34]

Mechanisms of PGR Action in Root Growth

Mechanisms of PGR Action in Root Growth involve intricate processes that regulate gene expression, signal transduction pathways, and interactions with hormonal signaling networks. These mechanisms play crucial roles in orchestrating root development and architecture in response to various internal and external cues [35].

Regulation of Gene Expression and Signal Transduction Pathways

Plant growth regulators (PGRs) exert their effects on root growth by modulating gene expression patterns and signal transduction cascades within plant cells. For example, “auxins regulate the expression of specific genes involved in cell elongation, root initiation, and lateral root formation. Through receptor-mediated signaling pathways, auxins activate transcription factors and other regulatory proteins that control downstream gene expression related to root development [36-37].”

Similarly, “other PGRs such as cytokinins, gibberellins, abscisic acid, and ethylene, regulate the expression of target genes involved in root growth and development.” These PGRs often act in concert or antagonistically to fine-tune gene expression patterns and coordinate various aspects of root physiology. The modulation of gene expression by PGRs ultimately leads to changes in cell division, elongation, differentiation, and other processes essential for root growth and architecture [38-39].

Interactions with Hormonal Signalling Networks

PGRs interact extensively with other hormonal signalling networks to coordinate root growth and development. Cross-talk between different hormone pathways allows plants to integrate multiple signals and fine-tune their responses to environmental cues. For example, auxins and cytokinin’s often act synergistically to regulate root meristem activity and lateral root formation. Auxin-cytokinin interactions control the balance between cell division and differentiation, influencing root architecture [40-41].

Additionally, hormonal interactions between gibberellins, abscisic acid, and ethylene play crucial roles in mediating responses to various stresses and developmental processes in roots. Ethylene, for instance, can modulate auxin biosynthesis and transport, influencing root growth and tropic responses. These intricate interactions between PGRs and other hormones enable plants to dynamically adjust their root growth strategies in response to changing environmental conditions [42-43].

Enhancing Root Dynamics with PGRs

Enhancing Root Dynamics with PGRs involves utilizing plant growth regulators to optimize root architecture, improve resource acquisition, and enhance root resilience to various environmental challenges. This multifaceted approach aims to maximize root efficiency in water and nutrient uptake, overcome soil constraints, and improve plant performance under adverse conditions.

1. **Optimizing Root Architecture for Enhanced Resource Acquisition:** PGRs can influence root system morphology and branching patterns to optimize root architecture for improved resource acquisition. By promoting lateral root formation and enhancing root branching, PGRs increase the surface area for nutrient and water absorption, leading to enhanced plant growth and productivity [44].
2. **Strategies for Maximizing Root Efficiency in Water and Nutrient Uptake:** PGRs play a crucial role in maximizing root efficiency in water and nutrient uptake by regulating root growth and development. For example, auxins and cytokinin’s can stimulate root elongation and proliferation, facilitating deeper root penetration into the soil and enhancing nutrient uptake efficiency [46].
3. **Improving Root Adaptation to Environmental Challenges:** By modulating stress-responsive pathways and promoting the accumulation of osmoprotectants, PGRs enhance root resilience to adverse environmental conditions, thereby improving plant survival and productivity [47].
4. **Facilitating Root Growth in Challenging Soil Conditions:** PGRs help facilitate root growth in challenging soil conditions by overcoming soil compaction, poor drainage, and low-nutrient availability. By promoting root elongation and

penetration, PGRs improve soil exploration and nutrient uptake, enabling plants to thrive in suboptimal soil environments [48].

5. **Overcoming Soil Compaction and Poor Drainage through PGR Applications:** PGRs can mitigate soil compaction and poor drainage issues by promoting root growth and development. By enhancing root penetration and soil structure, PGRs improve soil aeration, water infiltration, and nutrient availability, thereby mitigating the adverse effects of soil compaction and waterlogging [49].
6. **Enhancing Root Penetration in Hardened or Low-Nutrient Soils:** PGRs enhance root penetration in hardened or low-nutrient soils by stimulating root elongation and proliferation. By increasing root biomass and surface area, PGRs improve soil exploration and nutrient acquisition, enabling plants to access essential nutrients and water resources more effectively [50].

Practical Applications and Considerations

Implementing PGRs in Agricultural and Horticultural Practices involves careful consideration of application methods, timing, dosage, formulation, and crop-specific factors to achieve optimal results. Here's an explanation of each aspect:

- **Implementing PGRs in Agricultural and Horticultural Practices:** PGRs serve as valuable tools in agricultural and horticultural systems to manipulate plant growth and development. Studies have demonstrated the effectiveness of PGRs in managing plant height, promoting flowering, enhancing fruit set, and mitigating stress responses [51].
- **Application Methods: Foliar Sprays, Soil Drenches, Seed Treatments:** Different application methods offer unique advantages depending on the desired outcome and crop species. Research has shown that foliar sprays provide quick uptake and localized effects, while soil drenches offer systemic action and long-lasting effects [52]. Seed treatments, on the other hand, enhance germination, seedling vigor, and early root development [53].
- **Timing and Frequency of PGR Application for Optimal Results:** The timing and frequency of PGR application play critical roles in achieving desired outcomes. Studies have highlighted the importance of timing applications based on crop growth stages and environmental conditions to maximize efficacy and minimize potential negative effects [54].
- **Dosage Optimization and Formulation Considerations:** Optimizing PGR dosage and formulation is essential to avoid phytotoxicity and ensure effectiveness. Research suggests that dosage optimization should consider factors such as crop sensitivity, soil characteristics, and target growth responses [55]. Additionally, selecting appropriate formulations and adjuvants influences efficacy and application convenience [56].
- **Determining Appropriate Concentrations for Desired Effects:** Effective PGR application requires determining suitable concentrations to achieve desired growth responses. Studies have demonstrated the importance of conducting dose-response trials to identify optimal concentration ranges while minimizing adverse effects [57].
- **Selecting PGR Formulations Based on Crop Type, Growth Stage, and Environmental Conditions:** Tailoring PGR formulations to specific crop types, growth stages, and environmental conditions is essential for maximizing efficacy. Research has emphasized the need to consider factors such as temperature, humidity, and soil moisture when selecting PGR formulations and application practices [58].

Conclusion

Harnessing PGRs as Essential Tools for Sustainable Root Growth and Crop Productivity: Plant Growth Regulators (PGRs) play a pivotal role in shaping root architecture, enhancing resource acquisition, and improving crop productivity in agricultural and horticultural systems. By modulating root growth and development, PGRs offer valuable tools for optimizing plant performance, particularly under challenging environmental conditions. Their ability to promote root elongation, branching, and resilience to abiotic and biotic stresses makes them indispensable for sustainable agriculture and food security. Integrating PGRs into crop management practices can enhance root dynamics, nutrient uptake efficiency, and stress tolerance, contributing to the development of resilient and high-yielding crop varieties.

Future Directions in Research and Application of PGRs for Root System Enhancement

As our understanding of plant-PGR interactions continues to advance, future research holds promising avenues for exploring novel applications and formulations of PGRs to enhance root system dynamics further. Key areas for future investigation include elucidating the molecular mechanisms underlying PGR-mediated root responses, optimizing PGR dosages and application methods for specific crop and soil conditions, and developing environmentally friendly and sustainable PGR formulations. Moreover, there is a growing need to integrate PGRs with other agronomic practices, such as precision agriculture, crop breeding, and soil management, to maximize their efficacy and minimize environmental impacts. By harnessing the full potential of PGRs and leveraging interdisciplinary approaches, we can unlock new strategies for sustainable root system enhancement and crop improvement, paving the way for resilient and productive agricultural systems in the face of global challenges.

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Conflict of Interest

No authors declared Conflict of Interest

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