Review Article

Connotation of Plant Growth Regulators on Seed Germination

ABSTRACT

Seed germination is a complex physiological process influenced by various internal and external factors. The initial requirements for seed germination include **suitable temperature** (depending on the seed type), **moisture**, and **oxygen**. The endosperm serves as a reservoir of food and contains hormones that initiate seed germination. Both **endogenous** (produced within the seed) and **exogenous** (externally applied) hormones play a crucial role in germination and the early growth of seedlings. Plant growth **activators** enhance seed germination and promote growth, while **retardants** inhibit both germination and growth processes and may induce dormancy. Growth inhibitors, therefore, can be strategically applied to prolong seed viability during storage. Furthermore, various **exogenous chemicals** are employed to regulate seed and plant growth processes. These hormones and chemicals not only influence germination but also help determine the **seed's chemistry**, providing insights into its physiology and predicting its behavior under different conditions.

KEY WORDS

Growth, inhibitors, exogenous, endogenous, Auxins, Anti-auxins, activators, inhibitors

INTRODUCTION

Seed is in fact a fertilized egg or a zygote with food reserve in the form of endosperm and the safe cover called seed coat (Figure 1). **Seed germination** refers to the growth and development of the zygote into an embryo, ultimately leading to the formation of a seedling under appropriate conditions.

The process of germination occurs in **three distinct phases**:

1. **Imbibition** – the uptake of water by the seed.
2. **Metabolism of stored food** in the endosperm to provide energy for growth.
3. **Reactivation of metabolism**, which results in **radicle protrusion** (the emergence of the root).

This process activates the metabolic activities inside the seed, enabling the growth and development of the **plumule** (shoot system), which eventually forms the seedling.

Seeds germination is the growth of zygote to the development of embryo that results in the formation of the seedling on availability of several appropriate conditions. The germination proceeds through three phases, as shown above. It is also a process for activation of metabolic activities inside the seed to grow and form the plumule [i].

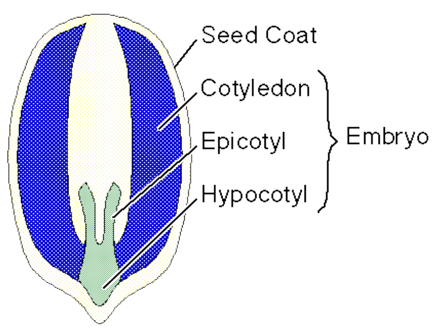

Figure 1: Seed Structure

Under suitable conditions of **temperature**, **oxygen**, and **moisture**, the seed begins to germinate, and the embryo grows into a **seedling**. For further growth into **plantlets**, these seedlings require water, minerals, and oxygen. In addition to these external factors, seeds rely on **specific hormones** for proper growth and development. Seed germination involves numerous **physiological**, **morphological**, and **biochemical changes** under favorable conditions, all of which are regulated by **endogenous** (internal) and **exogenous** (external) factors. Among these internal components, **phytohormones** (plant hormones) play a crucial role in regulating germination and overall plant growth and development.[ii].

Following are different factors involved in the diverse stages of germination process carried out in controlled environment with the help of growth hormones

1. ***IMBIBITION***

The imbibition phase starts with the absorption of water into the seed. The water is taken inside the seed through pores, cracks, and spaces in the seed coat, and is absorbed by the seed tissues. This water absorbed by the dry seed, involves transfer of water by cell wall and macromolecules of endosperm, i.e., proteins and polysaccharides. These water molecules show retention inside the seed by electrostatic forces like hydrogen bonding (Figure 2).

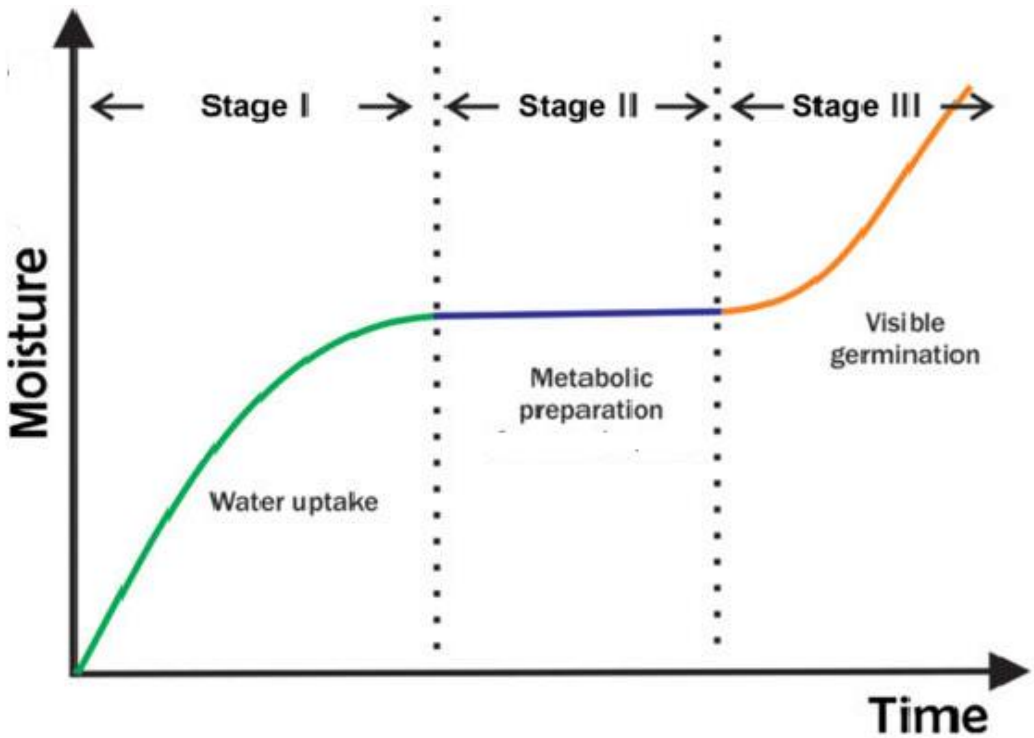

Figure 2: Germination of Seed

2. TEMPERATURE

Different seeds show germination at varied temperatures. Most of seeds germinate between 25-30°C, some seeds require high temperature higher than normal (30-40 $^{\circ}$C, summer crops) and some requires very low even up to 5°C (winter crops). Temperature below its standard required temperature retards or inhibits the embryonic activities or germination process whereas high temperature terminates hormones production and cell division. High temperature promotes abscisic acid production and ultimately dormancy is attained [iii].

Temperature plays a key role in seed germination, and it affects the cell energy status and enzymes activity (e.g., lipase, alanine aminotransferase, aspartate aminotransferase, and especially ribonuclease) takes place as the temperature increases and the ATP content rises. The rate of protein synthesis decreases with increasing temperature. Since germination involves several stages, each has its cardinal temperature scale; the temperature response can differ during the germination period because of its complexity [iv]. The temperature reaction of a seed depends on variety, seed quality, the length of time after harvest, and other factors. The germination process requires different temperature changes depending on the rate of respiration and sugar metabolism. The specific role of temperature differs among seed types; it not only affects the duration of germination but also regulates the water necessary to initiate the germination process [v].

3. *OXYGEN*

As germination starts in seed, it respires vigorously to consume food and release the energy required for its growth. Oxygen deficiency affects or may abort the seed germination. Oxygen is used in respiration and speeds up the metabolism reactivation during seed imbibition, seed coat or testa inhibit the respiration, hence imbibitions lead to the softening of the seed coat and hydrolysis of endosperm to generate energy in the form of ATP. Due to imbibition, phenolic compounds are enzymatically oxidated by polyphenol oxidases (catechol oxidase and laccase) and peroxidases. The key role of oxygen in the molecular networks regulating seed germination and dormancy through the hormonal activation of ethylene, gibberellins, and the emerging role of mitochondria in respiration of embryo [vi].

4. ***PHYTOHORMONES*** are plant hormones present in very low concentrations and can control different developmental conditions, ranging from embryo to well-developed plants. Synthetic plant hormones are exogenously applied for controlled crop production. These exogenous and endogenous plant hormones control all growth and development activities, like cell division, enlargement, flowering, seed formation, dormancy, and abscission. Phytohormones are of different types based on their structure and functions. There are different classes of such hormones.

   i. Auxins
   ii. Gibberellins
   iii. Abscisic acid
   iv. Cytokinins
   v. Brassinosteroids
   vi. Jasmonates
   vii. Ethylene

The seed cotyledons treated with different concentrations of auxins or with varying concentrations of diverse cytokinins show an increased urease activity, compared to the control. The optimal effects can be observed for each of 500 μmol of auxins and 300 μmol of cytokinin treatments. A gradual increase in urease activity occurs in cotyledons treated with various concentrations (0.2-1.0 mM) of Brassinosteroids, in comparison to the control. These hormones play an important role in plant physiology and are responsible for growth and development [vii]. These are of different structures and may perform similar functions. Based on their action, plant hormones are classified as

- Seed growth activators
- Seed growth Inhibitors

Auxins

Auxins play an important role in the growth and control of the different stages of plant development. Auxins also play an important role in seed development. It regulates the growth of the embryo, the development of endosperm, and the rupture of the seed coat. Auxin's level varies in growing seeds. In various stages, these are directly involved in the growth of fertilized seeds after the availability of moderate environmental conditions. Auxin is released as the endosperm develops after seed germination. Auxin means "to grow". They are widely used in agricultural and horticultural practices. They are found in growing apices of roots and stems and then control all plant activities and hence are responsible for plant growth.

Natural Auxins occurring in plants are of five different types, Indole-3-acetic acid (IAA, 1), Indole butyric acid (IBA), phenylacetic acid, indole propanoic acid, and chloroindole-3-acetic acid. Auxins are also known as indoles. Indoles are benzene rings fused with pyrrole and have a general formula C_8H_7N. Indole-3-acetic acids, IBA, and its derivatives are also known as auxins, and found in plants as plant growth regulators. The auxins are responsible for cell division and also responsible for geotropism, phototropism, and hydrotropism.

Auxins are present in the shoot buds and induce shoot apical dominance [viii]. Synthetic 2,4-D (2,4-Dichlorophenoxyacetic acid), and NAA (Naphthalene acetic acid) are extensively used as pro-auxins to improve the growth of plants.

Mechanism of Action

Auxins play an important role in embryo development after seed imbibitions. The concentration of auxin controls the differentiation of the embryo into different organs of the plant, including the shoot apex, primary leaves, cotyledon(s), stem, and root.

The auxins are transported by the polar transport system through parenchyma cells. The cytoplasms of parenchyma cells are neutral (pH=7) where auxins release proton and become anion (IAA^-). It cannot pass through a hydrophobic portion of the plasma membrane as an anion, but it does pass through special auxin efflux transporters called PIN (Peptidyl-prolyl cis-trans isomerase**)** proteins**.** The adjacent cells to the cytoplasm (apoplast) are acidic (pH=5) in nature, IAA^- enters the acidic environment of the apoplast, and it is again protonated to form IAAH that is neutral. This uncharged molecule can then pass through the plasma membrane of adjacent cells through diffusion or via influx transporters. Once it enters the cytoplasm, it loses a proton to form IAA^- anion. PIN proteins are found around the cell and direct the flow of auxin [ix].

Auxin effects are some on the cell to initiate the patterns of gene expression and movement of ions in and out of the cell and reduction in the redistribution of PIN proteins. Inside the cell auxin increases the longitudinal cell size and ultimately the rate of cell division increases. The auxin may bind to a cell-surface receptor or called an Auxin-binding protein (Figure 3).

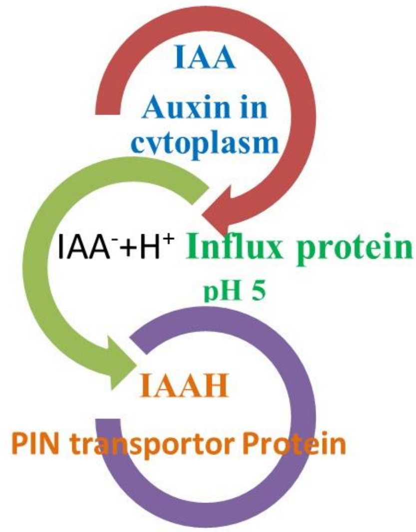

Figure 3: Mechanism of transportation of Auxins

Functions

- It carries the fertilization of the ovum by sperm and transformation into a zygote.
- It carries the transformation of the zygote into the embryo and initiates germination in collaboration with gibberellins (Figure 4).
- It induces the development of a seed coat after fertilization and the development of the embryo,
- It plays a role in the differentiation and division of endosperm and therefore proceeds to further stages.

- There is storage of auxins in a developed embryo.
- It is responsible for cell elongation of seeds endosperm and ultimately growth of plumule and radicle.

- Induces parthenocarpy *i.e.* development of fruit without fertilization e.g. in tomatoes
- It is responsible for fixing newly formed leaves in plumule and keeps them green for a longer period.
- Useful in stem cuttings and grafting where it initiates rooting.
- Promotes flowering e.g. in pineapple.
- Auxins in combination with abscisic acid induce dormancy in seeds (Figure 5).
- 2,4-D is widely used as a herbicide to kill undesirable weeds of dicot plants without affecting monocot plants. When it is sprayed on leaves, it gets absorbed through the leaves and is transferred to the meristems of the plant. Unrestrained herb growth is controlled by curl-over of weak stem, leaf sarcastic effect that turns over the plant death [x].

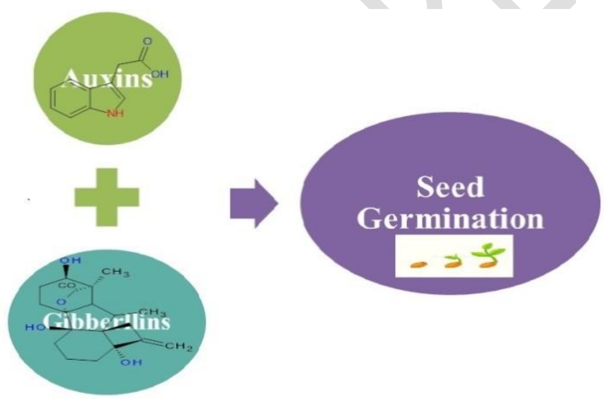

Figure 4: Seed Germination by Auxins

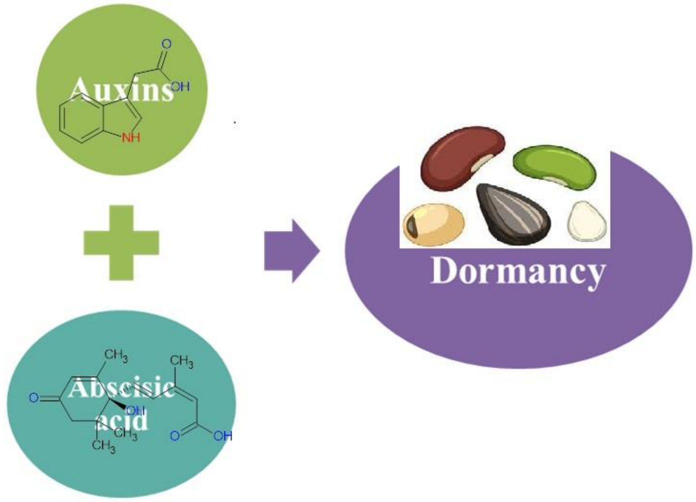

Figure 5: Seed Dormancy by Auxins

Gibberellins

Gibberellins (**2**) are of a wide variety, more than 100 gibberellins (GA_1, GA_2, GA_3…..) are found in seeds and in plants also. These are acidic in nature due to the presence of the –COOH group. It is used for the pre-treatment of seeds as they produce amylase, resulting in germination. Gibberellins are the plant regulators, involved in the regulation of the growth and influencing different developmental processes which include stem elongation and germination and enzyme induction [xi].

As water absorption takes place inside the seed, imbibition starts. The hormone signal in seeds like Gibberellic acid activates the DNA in the cells; a gene for amylase gets activated resulting in the production of the amylase enzyme inside the cells. The amylase starts working in the endosperm area. There amylase breaks down starch into sugar which is transported to the hypocotyl or embryo of seed. The sugar content increases the respiration rate in the embryo for its growth. The radicle protrusion from the seed coat results in the initiation of germination (Figure 4).

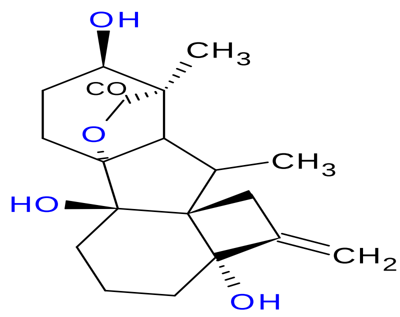

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Fig. 6. Chemical structure

Mechanism of action

Gibberellins are transported in plants in a non-polar way. It is translocated in bounded form as gibberellins-glycoside linkage. In suitable conditions such as light, temperature, and water seed absorbs water and gets imbibed. It stimulates the production of gibberellins.

Gibberellin is transferred to the aleurone layer of endosperms to synthesize amylase. It increases the mRNA in order to code the amylase production. The amylase acts on the starch molecules in the endosperm, producing soluble maltose or sugar molecules. The maltose is then turned into glucose and is available as a food for developing embryo (Figure 7). This glucose is used by the embryo during the respiration process to provide the energy needed for its growth [xii].

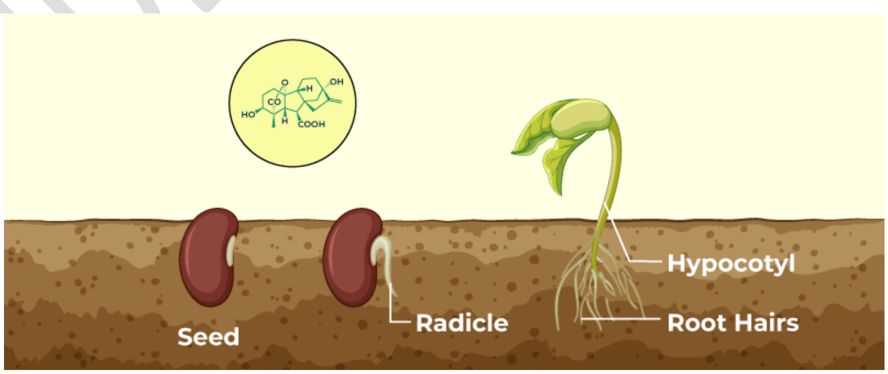

Figure 7: Seed Growth by Gibberellins [xiii]

Functions

- It delays senescence.
- It induces the formation of hydrolytic enzymes such as proteases, lipase, and amylase in the endosperm of germinating grains, barley seeds, and others.
- It breaks dormancy and initiates seed germination.
- Seeds pre-treated with gibberellins shows increased germination rate.
- A pretreated seed also show an increased radicle and hypocotyl length.

Cytokinins

Cytokinins (**3**) primarily play an important role in cell division process. Cytokinins are naturally synthesized in plants where rapid cell division occurs e.g. root apices, shoot buds, and young fruits. There are two types of cytokinins adenine-type cytokinins such as kinetine, zeatine (corn kernels, coconut milk), and benzylaminopurine, and phenylurea-type cytokinins like diphenyl urea and thidiazuron (TDZ). Most adenine-type cytokinins are synthesized in roots, tissues and cambium. Phenylureacytokinins are not found in plants these are usually synthetic. Cytokinins are transported inside plants through xylem [xiv].

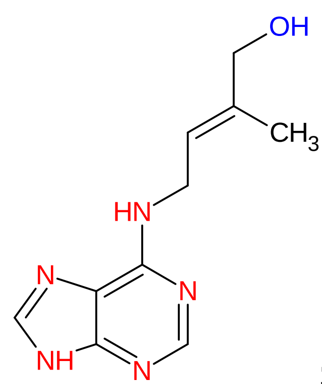

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Fig. 8. Cytokinins

Mechanism of action

Cytokinins bind to receptors found inside the endoplasmic reticulum membrane, triggering the activation of histidine kinases. These activated histidine kinases convert the phosphate groups to histidine phosphor transfer proteins. Phosphorylated AHPs, in turn, transfer the phosphate group to type-B response regulators (RRs), it enter the nucleus and regulates the expression of specific target genes involved in cell division, shoot growth, and apical dominance. This regulatory process ultimately leads to increased cell division and lateral shoot growth of developing embryo [xv]. It works in collaboration with auxins that are involved in sugar formation and strigolactone and hence play a key role in the development of embryo (Figure 9).

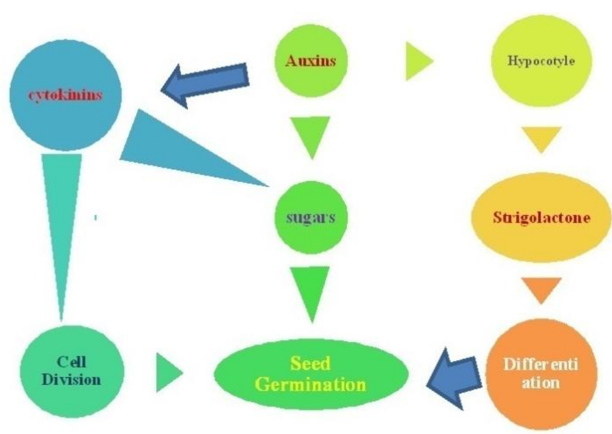

Figure 9: Cytokinins mode of action with Auxins and Strigolactone [xvi]

Functions

- It promotes seed germination by increasing the action of auxins.
- It also inhibits the action of abscisic acid thus breaking seed/bud dormancy.
- It promotes lateral and adventitious shoot growth and is used to initiate shoot growth in plant tissue culture.
- It reduces the apical dominance by controlling the action of auxins.
- Stimulate the formation of chloroplast in leaves.
- Promotes nutrient mobilization.

Abscisic Acid

Abscisic acid (ABA, **4**) is a sesquiterepenoid (C_{15}) plant hormone that regulates plant growth, development and stress responses, and reduces dormancy. It is synthesized from carotenoids (C_{40}) via oxidative cleavage. ABA catabolism is initiated by several modifications such as oxidation and conjugation. The movement of ABA inside a plant is important for the immediate responses to drought stress. It is also called stress hormone as it increases the tolerance of plant against drought.

It is a growth-inhibiting phytohormone and works in collaboration with Gibberllins. It inhibits plant metabolism and regulates abscission and dormancy.

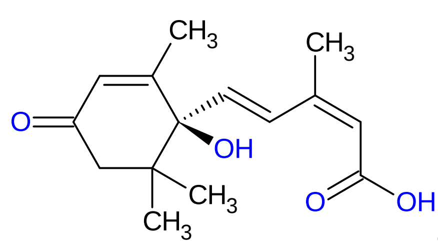

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Fig. 10. Abscisic Acid

Mechanism of action

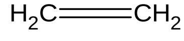
Abscisic acid binds with specific receptors associated with G-proteins located on the plasma membrane of plant cells. ABA binding with G-proteins initiates the production of secondary messengers like calcium ions and atomic oxygen. The secondary messengers are responsible for protein phosphorylation an event, leading to modifications in gene expression. The altered gene expression activates stress-responsive genes and triggers the closure of stomata, enabling plants to conserve water during drought and stress conditions.

Functions

- Induces abscission of leaves and fruits.
- Inhibits seed germination.
- Induces senescence in leaves.
- During drought, it accelerates dormancy in seeds that are useful for storage.
- Stimulates closure of stomata preventing transpiration under water stress.

Ethylene

Ethylene (**5**) occurs in gaseous form. It is synthesized in the ripening fruits and tissues undergoing senescence. It regulates many physiological processes and is one of the most widely used hormones in agriculture. Ethylene supports seed germination along with seedling growth through increased hypocotyl elongation. Ethylene inhibits primary root growth by reducing cell expansion. In this way, it can act as a growth promoter as well as an inhibitor.



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Mechanism of action

Ethylene diffuses through the cell membrane and binds to receptors in the endoplasmic reticulum of plant cells. The binding of ethylene to its receptors triggers the activation of the transcription factor EIN_3. EIN_3 expresses the genes associated with the "constitutive triple response," causing the plant to display a unique growth pattern characterized by a thickened and shortened stem, radial swelling, and horizontal growth.

Functions

- It regulates the seed dormancy by softening the seed coat and, therefore ends dormancy.
- It helps the ripening of fruits.
- It stimulates the rapid elongation of petioles and internodes.
- It promotes the abscission of leaves and flowers.
- It reduces root growth or radicle growth in seeds and increases root hair formation in early plantlets thereby increasing the absorption surface.

Brassinosteroids

Brassinosteroids (**6**) are a class of poly hydroxylated steroids that have been recognized as a class of phytohormones . It promotes stem elongation and cell divisions in plants.

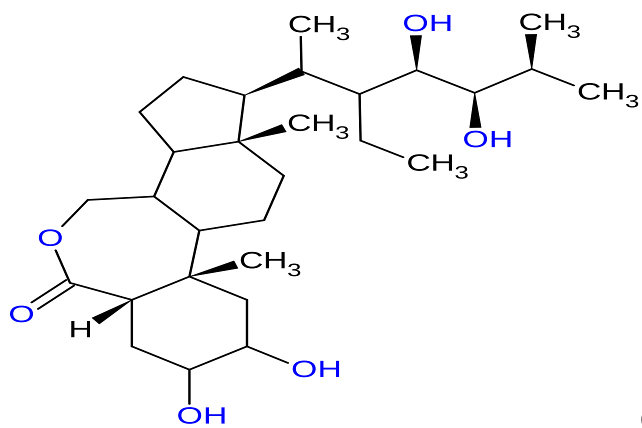

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Fig. 11. Brassinosteroids

Mechanism of action

Brassinosteroids initiate the binding to receptors on the cell surface and trigger the activation of a receptor complex. It, in turn, phosphorylates and activates the Kinases. The phosphorylates and activates the transcription factor of genes, that regulates the expression of cell elongation, cell division, and stress responses, leading to enhanced growth and improved stress tolerance in plants (Figure 12).

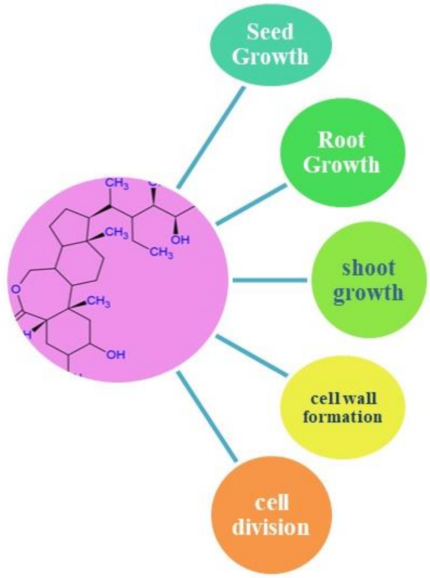

Figure 12: Function of Brassinosteroids in seed growth and germination

Functions

1. Brassinosteroids hormones play a role in promoting germination.
2. Seed dormancy and germination are regulated by the plant hormones, abscisic acid (ABA) and gibberellin (GA) both.
3. Hormones act antagonistically with each other. ABA induces seed dormancy in maturing embryos and inhibits germination of seeds. GA breaks seed dormancy and promotes germination.
4. BR stimulates germination and raises the possibility that it is required for normal germination. BR mutants exhibit a germination phenotype in the presence of ABA. Thus, the BR signal is needed to overcome the inhibition of germination by ABA (Figure 8).

Jasmonates

Jasmonates (Jas, **7**) are important plant hormones that mediate stress responses and are prone to have inhibitory effects on seed germination, thus acting as plant growth inhibitors or growth retardants.

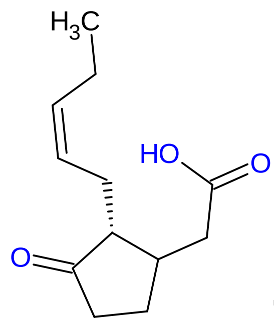

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Fig. 13. Jasmonates

Functions

- By studying mutants overexpressing JA, one of the earliest discoveries made was that JA inhibits root growth.
- JA plays many roles in flower development. The same genes promote male and female fertility.
- JA and methyl jasmonates inhibit the germination of non-dormant seeds and stimulate the germination of dormant seeds.
- Jasmonates–treated seeds are resistant to germination and such seeds after germination show good growth and save plants from the attack of spider mites, caterpillars, aphids, and fungal pathogens.
- Jasmonates can be used as a signal to close the traps and to control the release of enzymes and nutrient transporters which are used in plant digestion. However, not all carnivorous plants rely on the jasmonate pathway in the same way.

5. EXOGENOUS GROWTH REGULATORS

Natural PGRs are usually in small amounts to control essential functions inside the plants. Occasionally there is a need for some exogenous assistance in agriculture through plant extraction or synthetic plant growth regulators to assist some metabolic or growth functions in seeds or plantlets. Furthermore, the production of natural PGRs through biosynthesis is restricted due to technical issues. There are many synthesized compounds that are phytohormone analogs to natural plant growth regulators. These compounds can easily be synthesized, but their mode of action needs to be studied for further structural optimization and mechanism exploration.

- **Urea and thiourea** derivatives possess growth-inhibiting properties and increase salt tolerance in wheat and are useful to save plants from chlorophyll degradation of chlorophyll in seeds. It may cause dormancy and save seeds from germination [xvi].

- Synthesized **pyrazole derivatives** can cause the seedling’s growth and impede root growth. It is analog to the natural phytohormone. The hypocotyl length of seedlings can be increased after treatment with pyrazole derivatives. The comparative analysis of plant growth regulating the activity of new synthetic low molecular weight. In this regard, the elaboration of new effective ecologically safe plant growth regulators on the base of synthesis. Low molecular weight heterocyclic compounds like derivatives of pyrimidine, pyrazole, and oxazole are extensively used in agriculture as plant growth regulators, herbicides, fungicides, and antibacterial agents [xvii].

- **Pesticides** are highly toxic chemicals used as herbicides in crops. There are four commonly used pesticides such as, emamectin benzoate, alpha-cypermethrin, lambda-cyhalothrin, and imidacloprid that can inhibit seed germination. The seed germination get slow down if these pesticides are already present in the soil and this effect is more pronounced when seeds are sown in the soil containing such hazardous chemicals [xviii].

- The synthesized dichloroacetamides are proved to be a novel PGRs that basically effect the growth of roots [xix].

- The derivatives of dehydroamino acids 2,3-dehydroaspartic acid dimethyl ester, potassium salt of 2-amino-3-methoxycarbonylacrylic acid and 1-methyl-3-methylamino-maleimide possess plant growth-regulating properties. Dehydroamino acids, 2,3-dehydroaspartic acid, and dimethyl ester shows the most stimulating activity on all test.

- Series of **alkyl silatranes** as PGRs. These compounds are growth accelerators of wheat and maize. In maize, 3-aminopropyl silatranes gave the best results at 100 μmol L^{-1}, whereas for wheat 3-chloropropyl silatraneis good growth accelerators at 200 μmol L^{-1} [xx].

- **Urea derivatives** can exhibit extraordinary inhibition activity on root growth the inhibition activity is higher than that of the commercially available herbicide clopyralid. 1-phenethyl-3- (3-(trifluoromethyl) phenyl) urea, potent inhibition activity on root growth of *Arabidopsis* [xxi].

- **Ureas, carbamates and oxamates** exist in nature and as synthetic compounds. These exhibit a wide spectrum of biological activity. A number of compounds with core imidazolidin-2-one and aryl moieties as urea and carbamate derivatives are also proved as plant growth regulatory activity especially show influence on and development of seeds [xxii, xxiii].

- **Aspartic acids** The derivatives of dehydroamino acids 2,3-dehydroaspartic acid, its dimethyl ester, potassium salt of 2-amino-3-methoxycarbonylacrylic acid and 1-methyl-3-methylamino-maleimide are synthetic plant growth-regulators. Dehydroamino acids 2,3-dehydroaspartic acid dimethyl ester possess the growth activating property and is effective on different crops along with environment friendly. These can be used in the form of microcapsule formulations through which PGRs can be releases by diffusion. It may be helpful in the future as favorable agro-formulations with a constant and targeted release for plant growth regulation [xxiv].

- Bojack et al. [xxv]synthesized 2,3-dihydro-1-benzofuran-4-**carboxylates and quinolones.** It can regulate the affinity of seed to compete against the drought and cold stress in wheat, corns, and canola.

- **Indazoles** (**8**) are organic heterocyclic compounds in which the benzene is fused with pyrazole. It is rarely found in nature for growth regulation or particularly germination process. It is found in *Nigella sativa* or black cumin is the only source of indazole alkaloid. Synthesized indazoles are also found to be plant growth regulators by inhibiting the germination of seeds. Derivatives 3-aryl-1*H*-indazoles show their effects on seed germination and early growth. The arylindazoles are growth inhibitors of root and shoot lengths of wheat and sorghum, especially at a high concentration (100 ppm). At lower concentrations, growth inhibition seems to be less pronounced. Seed germination and early growth of plantlets also depend on the nature of substitution on the aryl group [xxvi].

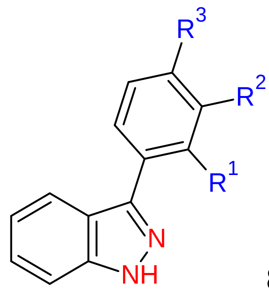

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Fig. 14. Indazoles (8)

- **Indazole-3-acetic acids** are found to be depressants of seed germination and hence can be successfully used for crop seed storage in extremely hot weather in Pakistan. In wheat effect of these compounds on early growth is acceleration in all concentrations. In sorghum at high concentrations, these compounds were proved to have an inhibitory effect more pronounced on root and shoot growth while at low concentrations its effect is negligible. 3-Arylindazole-1-acetic acids are supposed to delay the germination of seeds simply by lowering the metabolic process during imbibition. However, it accelerates early growth of seeds [xxvii].

- **Coumarins and Coumarin-3-acetic acids** Coumarin (1-benzopyran-2-one, **9**) is the secondary metabolite in some plants like legumes, clover, and medicinal plants. These hormones possess a variety of biological functions i.e. anti-oxidants, anti-inflammatory, anti-coagulant, antibacterial, antifungal, and other pharmacological actions. Coumarins are growth retardants or can suppress the function of auxins while coumarin-3-acetic acids although are not synthesized in plants, their growth retardant effect is more pronounced and are called anti-auxins [xxviii]. Synthesized coumarins are growth retardants and inhibit the germination process along with the early growth of plantlets.

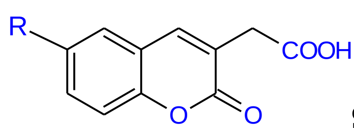

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Fig. 15. Coumarins and Coumarin-3-acetic acids

Coumarin-3-acetic acids: A number of synthesized coumarin-3-acetic acids are proven to be growth inhibitors and inhibit the seed germination process. These are used to induce dormancy. Coumarin-acetic acids are more potent growth inhibitors in comparison to coumarins themselves. By experiments, it was observed to be more germination inhibitor in comparison to abscisic acid (Figure 16). Such compounds can be used as herbicides and can induce seed dormancy during storage.

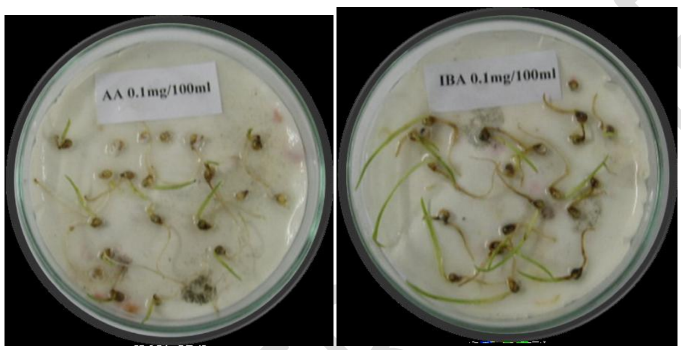

Figure 16: Role of Abscisic Acid and Indole butyric Acid (IBA) on seed germination [xxviii]

CONCLUSION

Plant growth regulators play a vital role not only in seed germination but also in early growth of plantlets. Auxins play an important role in seed development, regulating the growth of an embryo, development of endosperm, and rapture of the seed coat. The concentration of auxin controls the differentiation of the embryo into different organs of the plant, including the shoot apex, primary leaves, cotyledon(s), stem, and root. Gibberellins are used for pre-treatment of seeds to produce amylase which results in germination. After imbibition, the sugar content increases the respiration rate in the embryo for its growth. The radicle protrusion from the seed coat results in the initiation of germination. It involves in regulation of growth and influencing different developmental processes which include stem elongation and germination and enzyme induction.

Cytokinins are naturally synthesized in plants where rapid cell division occurs e.g. root apices, shoot buds, and young fruits. Abscisic acid is a growth-inhibiting phytohormone and works in collaboration with Gibberllins. It inhibits plant metabolism and regulates abscission and dormancy. Ethylene supports seed germination along with seedling growth through increased hypocotyl elongation. Brassinosteroids promote stem elongation and cell divisions. Jasmonates mediate stress responses, and are prone to have inhibitory effect on seed germination, thus acting as plant growth inhibitors or growth retardants. Some exogenous compounds are used in agriculture as plant growth regulators to assist some metabolic or growth functions in seeds or plantlets. There may be a restricted production of natural PGRs through biosynthesis due to some technical issues. There are many synthesized compounds such as urea, thiourea, pyrazole, aspartic acids, quinolones, indazoles, coumarins, and coumarin-3-acetic acid derivatives that are phytohormone analogs to natural plant growth regulators. These compounds are used to promote and retard the growth and metabolic process.

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Details of the AI usage are given below:

1.

2.

3.

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