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Plant Hormones and Growth Regulators: Mechanisms, Interactions, and Agricultural Applications

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ABSTRACT

Naturally occurring substances called plant hormones are essential for controlling the growth and development of plants. They coordinate several physiological processes inside the plant by acting as chemical messengers. To control their growth and reactions to their surroundings, plants have their own unique set of hormones. Plant hormones come in various forms, such as Ethylene, gibberellins, auxins, cytokinins, and abscisic acid. Every hormone affects plant development differently. For instance, cytokinins stimulate cell division and encourage shoots' growth, whereas auxins encourage cell elongation and root formation. Abscisic acid aids in seed dormancy and stress responses, gibberellins control stem elongation and blooming, and Ethylene is involved in fruit ripening and senescence. These hormones form a complicated network that influences one another's behaviour and reacts to different environmental inputs. Plant growth regulators (PGRs) are used to change a plant's development in various ways, including promoting branching, decreasing shoot growth, increasing return bloom, eliminating extra fruit, or changing the maturity of the fruit. PGR performance is influenced by a wide range of parameters, such as the degree to which the plant absorbs the chemical, the age and vigour of the tree, the dosage, the timing, the cultivar, and the weather before, during, and after application. Farmers and scientists may control plant growth and development to increase crop production, improve fruit quality, and strengthen resistance to stressors by knowing the functions and interactions of these hormones. Plants control several aspects of the hormone response system, such as biosynthesis, metabolism, sensing, and signalling. Furthermore, plants have the rare capacity to regulate the dispersion of hormones in space.

Keywords: *Plant hormones, Plant Growth Regulators (PGRs), senescence, chemical messengers and plant stress*

Introduction

Phytohormones

Plant hormones, also known as phytohormones, are chemical substances produced spontaneously in plants that regulate physiological reactions at low concentrations.

Phytohormones are classified into two groups: growth promoters and growth inhibitors. Growth promoters enhance cell division, expansion, pattern creation, tropic growth, flowering, fruiting, and seed formation. Growth inhibitors involve numerous growth-inhibiting activities such as dormancy and abscission [1]. They also play a significant role in plant responses to biotic and abiotic stressors (Went, n.d.).

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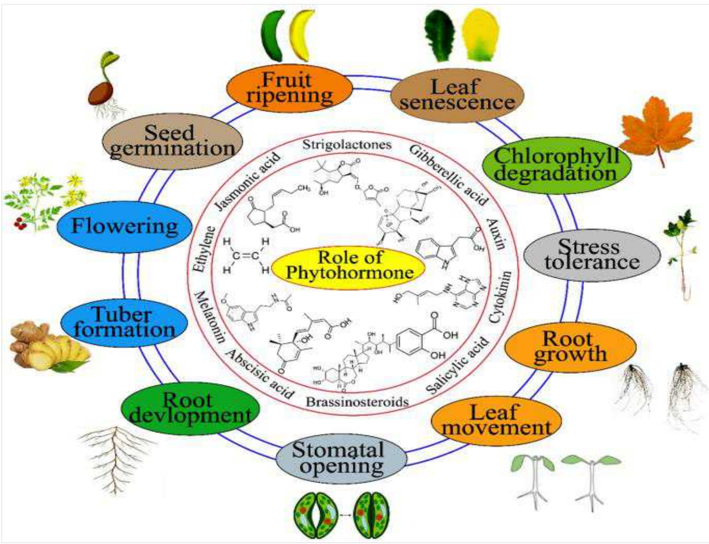


Fig-1: Phytohormones (Altaf et al., 2022)

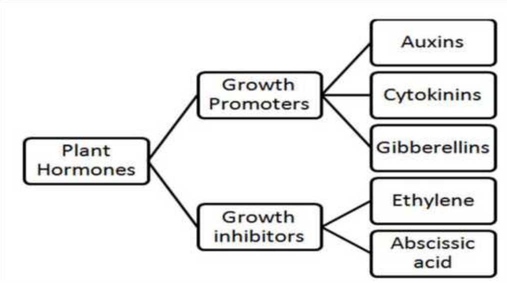


Fig-2 : Phytohormones

Auxins

Auxins were the first plant hormones identified. In 1880, Charles Darwin and his son Francis Darwin discovered that some plant development responses are controlled by "a matter which transmits its effects from one part of the plant to another."1 In the 1930s, biochemists coined the name "auxin". This concept comes from the Greek word "auxein," which meaning "to increase" or "to grow." Indole-3-acetic acid (IAA) is the most common auxin-type plant hormone, regulating many aspects of plant growth and development.3-5 Thus, "auxin" and "IAA" are sometimes used interchangeably [2]. Auxins are a plant hormone that regulates many plant growth and development processes. They are necessary for plant body development. The phytohormone auxin regulates numerous key processes in plant growth, development, and environmental adaptation. Auxin functions are linked to specific biosynthesis, homeostasis, transport, and signal transduction pathways [3]. They are recognized for their capacity to cause cell elongation. They also promote cellular division, vascular differentiation, and root initiation. Auxins enhance cell division and meristem maintenance and play a key role in cellular patterning [4].

Physiological effects of Auxins on plants

Auxins are plant hormones that primarily promote cell elongation. They also promote cellular division, vascular differentiation, and root initiation. Auxins encourage the development of roots, stems, and fruits. The significant physiological impact of auxin is to encourage the elongation of cells in the shoot. They help to initiate roots in stem cuttings and are commonly employed in plant propagation. They encourage flowering in plants, such as pineapples. It also promotes parthenocarpy. Plants' growth regions contain auxins. When the auxin concentration is larger on the shaded side, the cells elongate more quickly, bending the stem tip towards the unilateral light [5].

Cell enlargement

Auxin is a plant hormone that promotes cell elongation by increasing the cell wall extensibility. Auxin also affects cell wall characteristics by causing wall loosening [6]. Cell expansion is an essential element of plant development and morphogenesis. Cells usually grow after exiting the meristem but before becoming mature cells. The surface enlargement of the cell wall can be highly localized, as in tip-growing cells, or more equally distributed across the cell wall surface, as seen in most cells in the plant body. The plant hormone auxin promotes cell elongation by increasing wall extensibility. Plant cell expansion happens when the polysaccharides in the cell wall relax and slip, causing the wall to grow. This process is referred to as stress relaxation and creep. Water uptake causes the majority of the volume to increase into the vacuole located in the centre of the plant cell. The wall's molecular architecture determines the cell's expansion direction, which might be in one or all directions [7].

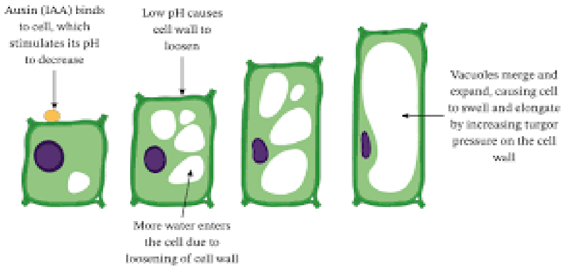


Fig-3: Cell enlargement

Apical dominance and inhibition of lateral buds

Apical dominance occurs when the expanding apical buds of a plant generate the plant hormone auxin (IAA), which suppresses the growth of lateral buds. This causes the plant's vertical length to grow. Auxin travels throughout the plant via the phloem and diffuses into the lateral buds, limiting elongation. Lateral buds are more susceptible to auxin than apical buds. At a concentration where auxin stimulates apical bud growth, lateral buds cannot grow above that level. Decapitating the apical buds is a typical method for promoting lateral development. When the apical bud is destroyed, the lower IAA content permits the lateral buds to develop and produce new shoots, competing for the lead growth [8].

Typically, the end of a shoot contains an apical bud, where shoot growth occurs. The apical bud generates auxin (IAA), a plant hormone that suppresses the growth of lateral buds farther down the stem, towards the axillary bud. The direct theory explains apical dominance by describing how auxin synthesized in the shoot apex travels down the stem into buds and restricts their growth. According to this view, apically generated auxin prevents buds from producing the auxin required for growth. In most higher plants, the expanding apical bud prevents the growth of lateral (axillary) buds, a process known as apical dominance. Decapitation of shoot tips typically leads to the formation of lateral buds [9].

Cell division

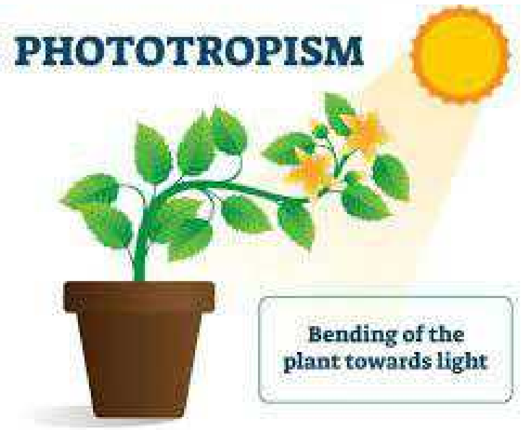
Auxin is a phytohormone that regulates cell division and plant expansion and is essential for their growth and development. Auxin promotes vascular development, root start, and cell elongation. Auxin supports cell division and meristem maintenance while also helping to establish cellular patterning. Plant development thus combines the management of cell proliferation and growth with additional cell expansion and differentiation [10]. Plants naturally produce auxins, a potent growth hormone. They are located in shoot and root tips and help with cell division, stem, and root growth. They can also significantly impact plant orientation by directing cell division to one side of the plant in response to sunlight and gravity.

Root formation

Plant roots are a vital component of plant structure, responsible for plant fixation, water absorption, and nutrient absorption. Plant root systems typically consist of primary roots (PRs) and lateral roots (LRs). Auxin is an important phytohormone that regulates the synthesis of LR and AR. AR production is connected with a high IAA (indoleacetic acid) level. This process can be separated into two parts: a series of founder cell divisions and the extension of the interfascicular cambium next to the vascular tissue [11]. Auxin supports root growth and causes vascular differentiation. It also regulates postembryonic root development and lateral root formation. Auxin promotes the development of meristematic tissues and the commencement of root growth. It also aids in the lateral extension of roots and pre-existing roots. Auxin also helps to form adventitious roots, which are roots that grow from non-root tissue [12].

Tropisms

Plant tropism is the controlled movement of an organ or organism in response to external stimuli like light, gravity, or contact. The stimulus determines the direction of the growth movement. Tropisms enable plants to acquire nutrients, light, water, and nourishment. Plant tropism is the controlled movement of an organ or organism in response to external stimuli. Typically, these stimuli cause hormone transfer, resulting in cell growth or deformation. Auxin is a plant hormone that regulates shoot growth and plays an essential part in tropism, which determines the direction of plant growth. Auxin stimulates cell elongation on a plant's shadowed side, causing it to expand and bend in the direction of the light source. This unequal growth of the two sides leads to the stem's expansion towards the light, known as phototropism. Auxin is broken down when exposed to sunshine due to light fluctuations. The dark side transports more auxin, while the light side transports less. This causes a curvature in the plant stem tip towards the light (*Phototropism & Photoperiodism (Article) | Khan Academy*, n.d.).



Flower formation

Flower development is when blooming plants, or angiosperms, establish a gene expression pattern in meristems. This procedure causes the appearance of a flower, which aids in reproduction. Floral hormones compete with inhibitors to generate flowers. The phloem transports floral hormones between leaves and apices. Their mobility may be hampered by the bulk flow of assimilates and maybe by inhibitors. During reproductive development, auxins determine the position of flower commencement and control organ growth and patterning. Auxins are important in determining the number and identity of floral organs (*principles of flower formation | International Society for Horticultural Science*, n.d.).

Parthenocarpy

Parthenocarpy is the formation of fruit without fertilization. The process results in a sterile fruit without seeds. This means that the pollination produces seedless berries. Parthenocarpy has been observed since antiquity, but it was first defined correctly in 1902 by German botanist Fritz Noll. Parthenocarpy is a significant agricultural characteristic that can accelerate the pace of fruit set in harsh environments. It can be generated artificially by spraying auxin and gibberellins on specific plants [13]. Auxin is a plant hormone that promotes parthenocarpy, or the formation of seedless fruits. The stem tip produces auxin, which promotes cell division, differentiation, and elongation. Unpollinated ovaries can be treated with auxin and its analogues to avoid fertilization and yield seedless fruits in crops such as tomato, cucumber, pear, and watermelon. Auxin analogues can also cause parthenocarpy in Cucurbitaceae plants such as watermelon, cucumber and zucchini. Other plant hormones that promote parthenocarpy in plants include gibberellin (GA) and cytokinin (CK) [14].

Abscission of leaves and fruits

Abscission is a natural process in which plants shed old or undesired parts such as leaves, flowers, fruits, seeds, and petioles. Adverse environmental factors or developmental processes might prompt it. Abscission happens within specialized abscission layers. At the start of abscission, cells become rounder, and the walls separate, resulting in a lack of adhesion [15]. Auxin also contributes to the abscission of leaves and fruits. Young leaves and fruits produce auxin, linking them to the stem. When the amount of auxin decreases, a specific layer of cells called the abscission layer forms at the base of the petiole or fruit stalk. The petiole or fruit stem eventually breaks loose at this point, and the leaf or fruit falls to the ground [16].

Weed killers

Weed killers are chemicals that kill weeds. They are also known as herbicides and are commonly used to manage weeds on farms. Weed killers can eliminate certain weed species without hurting crops. They are often administered before or after emerging weeds (*Agricultural Surfactants Market Size, Share, Global Report, 2032*, n.d.). Auxins are plant growth hormones that can destroy weeds in low quantities. High auxin levels can induce irregular plant growth and even death. Auxins prevent premature leaf and fruit fall and are widely employed to eliminate dicotyledonous weeds while sparing grasses and other monocotyledonous plants [17].

At large dosages, auxin can stimulate ethylene synthesis, causing leaves to fall, stunting growth, and even killing the plant. Auxin can also induce tissue degeneration, and high levels can inhibit growth. Some synthetic auxins, including 2,4-D and 2,4,5-T, are sold as herbicides. Selective weed killers can kill some plants but not others, making them beneficial for eradicating dandelions from a lawn while leaving the grass intact (*Use of Plant Hormones – Higher - Plant Hormones - OCR Gateway - GCSE Biology (Single Science) Revision - OCR Gateway - (BBC Bitesize*, 2023).

Sex expression

Plants exhibit a variety of sex expressions, including hermaphroditic, dioecious, and monoecious. Hormones can also affect sexual expression in plants. For example, in gender diphasic plants, the size of the bulb influences sex expression. When the bulb reaches a particular size, the plant always produces hermaphrodite blooms. Auxin is a plant hormone that influences sex differentiation in certain plants. Auxin can alter the sex of unisexual plants, which have separate male and female plants. Applying auxin to male flowers can change their sex to female. Applying auxin to female flowers can change their sex to male [18].

Auxin can induce female flower expression in cucumber, melon, and hemp while promoting male flower expression in hops and mercury (Yamasaki et al., 2005). Auxin is the primary regulator of plant reproductive organs. It regulates the development of stamen, pollen, gynoecium, and fruit. In addition, auxin is crucial for cell elongation in plants. High auxin concentration stimulates ethylene synthesis, which helps promote femaleness in dioecious plants [19].

Gibberellins

Gibberellins (GAs) are plant hormones influencing various developmental processes, including stem elongation, germination, dormancy, flowering, floral development, and leaf and fruit senescence. GAs are one of the oldest types of plant hormones.

They are diterpenoid weak acids found in higher plants and certain fungi. GAs are crucial in numerous agricultural activities, including root and shoot elongation and fruit patterning [20]. GAs are also utilized in the beer brewing sector. Barley seeds are treated with GA to convert stored starch into sugar, which is then used by yeasts to produce alcohol (*Plant Growth Regulation by Gibberellins – UC Botanical Garden*, 2021).

Physiological Effects of Gibberellins on plants

Gibberellins (GAs) are a broad plant hormone group controlling numerous developmental processes. The following processes occur: stem elongation, germination, dormancy, flowering, flower development, leaf and fruit senescence, cell division, leaf expansion, starch hydrolysis during germination, and fruit maturity [21].

Effect on dwarf mutants

In plants, dwarfism is frequently induced by mutations in genes that regulate the production or signalling pathway of the plant hormone GA. GA is a phytohormone that controls plant height and flowering period. Plants with decreased or interrupted GA signalling have a dwarf phenotype [21]. Gibberellins can assist dwarf plants reach normal size by stimulating stem, root, flower elongation, and fruit growth. Gibberellins can also boost seed germination rates, promote rapid stem and root growth, and cause mitotic division in some plants' leaves [22].

For example, a dwarf pea plant treated with gibberellic acid (GA) can reach the same height as a homozygous tall pea plant. If the GA-treated plant is crossed with a pure tall pea plant, the phenotypic ratio in the following generation is expected to be 50% dwarf and 50% tall. In addition, GA therapy can help reduce dwarfism and bending in mutants. For example, dwarf plants of Setaria Viridis seeds treated with gibberellic acid usually develop, whereas wild-type and dwarf mutants fed with water do not [23]. Dwarfism is frequently caused by gene mutations that regulate the production or signalling pathway of the plant hormone GA [23].

Bolting and flowering

Bolting is a process that sometimes causes blooming stems in horticultural crops before they are harvested, which aids in reproduction. Under adverse conditions, bolting happens in an endeavour to produce seeds; it is also known as a plant's survival strategy. Bolting is the process by which a plant generates a flowering stalk before it matures into seeds. This procedure is known as "going to seed" [24]. Temperature, day length, light levels, and stress circumstances are all potential causes of bolting. Bolting can be problematic since it reduces the quality of the plant's marketable parts. Plants that bolt are engineered to die once they bloom and produce seeds [25].

Gibberellins (GA3) are hormones plant roots and leaves produce as they grow. They are crucial in vegetable and rosette plant bolting, such as lettuce. Gibberellins can break dormancy, promote bud development, stimulate primary stem growth, and promote cell elongation and division [26]. Gibberellins can cause bolting and flowering in many biennial and long-day rosette plants. For example, GA3 can severely encourage bolting in Chinese cabbages. Gibberellins are also implicated in bolting rosette plants like lettuce after exposure to specific environmental stressors, such as long durations of sunlight [27].

Substituting the cold treatment

Gibberellins, a plant hormone, can substitute cold therapy in plants.

Gibberellins are a group of hormones that influence several plant reproductive activities, including flowering. They can also replace the low temperatures biennials need before they begin flowering, termed vernalization. Gibberellins are a broad group of tetracyclic diterpenoid plant hormones. Gibberellins govern a wide range of plant growth and development throughout its life cycle. Cold treatment, known as cold, wet stratification, allows seeds to absorb moisture and break down chemicals. Moisture and colds offer the environmental cues required for germination to occur. Depending on the species, cold treatments might last 10 days and three months (*Let's Think About Seeds: The Cold Treatment*, 2023).

Breaking of dormancy

Breaking dormancy is how seeds germinate after exposure to favourable growing circumstances. Gibberellins are hormones capable of breaking dormancy in seeds and buds. They can also enhance germination and aid in stem elongation. Gibberellins break dormancy in plants that require light to sprout. They increase enzyme production during germination, which degrades stored food and terminates seed dormancy. Gibberellins also promote the activity of hydrolytic enzymes such as alpha-amylase, which aids in mobilizing stored dietary starch [28]. Gibberellin (GA) is a plant hormone that stimulates seed germination in many plant species. It disrupts seed dormancy by increasing the synthesis of enzymes that release stored food reserves. These enzymes include proteases, amylase, and lipase. Light induces the manufacture of gibberellins. It predominantly affects seed cotyledons, stimulating the manufacture of enzymes that aid in the breakdown of seed dormancy [29].

Parthenocarpy

Parthenocarpy is the formation of fruit without fertilization. The process results in a sterile fruit without seeds. This means that the pollination produces seedless berries. Gibberellins (GA) are plant hormones that promote parthenocarpy, a crucial agronomic feature. For example, GA3 can cause parthenocarpic tomatoes to produce smaller fruits with the same shape. GA3 can also produce morphological variations in parthenocarpic apple fruits, such as varying pH levels [30].

GA can substitute pollination and fertilization in producing parthenocarpic tomato fruit. Mutations in pat-3/pat-4, for example, can enhance the concentration of GA1 and GA3 in the ovaries before pollination, potentially resulting in natural facultative parthenocarpy capacity in tomatoes [31]. Gibberellins applied to the leaf next to an emasculated ovary promoted parthenocarpic fruit production in intact plants. Gibberellic acid (GA3) must be applied within one day of anthesis, and the reaction is concentration-dependent [32].

Increase in size of leaves, flowers and fruits

Plants grow through cell division and cell growth, known as meristem. Meristem is a plant tissue composed of undifferentiated cells that can divide and differentiate, allowing roots and stems to expand broader and longer. During meristem initiation, a shorter growth period or a bigger primordium can increase leaf size [33].

Gibberellins are plant hormones that promote cell elongation and division while acting as a developmental switch between seed dormancy and germination and juvenile and adult growth phases. Gibberellins promote blooming, stem and root elongation, and fruit development (Sponsel, 2003). Gibberellins can also help seeds or plants overcome their natural dormancy, allowing them to flourish. As the plant grows, other gibberellin molecules cause cells to elongate, causing the stem to expand. For example, one study discovered that plants cultivated with 10 M GA produced 44.6% greater yield than plants grown without it. The plants had more leaves and a larger specific leaf area. Gibberellins can also improve fruits' shape and accelerate the brewing sector's malting process [34].

Seed germination

Germination is how a plant develops from a seed to a seedling. Seeds remain latent until the conditions are suitable for germination (*Germinating Seeds*, 2021). All seeds require water, oxygen, and an appropriate temperature to germinate. Seed germination is the process by which a seed becomes a plant. It involves the activation of a seed's metabolic pathways, resulting in the growth of an embryo and the emergence of a seedling for germination, water, oxygen, and an appropriate temperature (*Germinating Seeds*, 2021). When exposed to the right conditions, a seed absorbs water and oxygen through its coat. Some seeds require unique conditions to germinate. For example, some seeds must be dormant, and some require cold nights and hot days to help open the coat.

Gibberellins serve as chemical messengers, binding to receptors. This triggers the protein calmodulin, which binds to DNA and produces an enzyme that promotes embryo development. Gibberellins create hydrolases such as amylase. These hydrolases degrade macromolecules in the endosperm to supply nutrition to the embryo. Gibberellins stimulate the development of hydrolytic enzymes in the endosperm. These enzymes increase the synthesis of digestive enzymes such as proteases, amylase, and lipase. These enzymes help to mobilize stored nutrients, inducing seed germination [35]. Gibberellins are used in horticulture to promote seed germination. For example, soaking seeds with gibberellic acid (GA3) before sowing them in a soilless mix might boost the number and rate of germinating seeds.

Flower and sex expression

Gibberellins can enhance flowering in long-day plants while inhibiting blossoming in some perennials. They can also help in stem and root elongation and fruit growth. Gibberellins can enhance maleness in cannabis and accelerate the development of male organs in short-day plants. Gibberellins in cucumbers can increase male flowers' production while inhibiting female blooms' development. In melons, increasing GA concentration can promote the presence of pistils in flower buds [36].

Cytokinins

Cytokinins are a plant hormone that influences plant growth and development. They primarily regulate cell proliferation and differentiation but also influence apical dominance, axillary bud growth, and leaf senescence [37]. Cytokinins stimulate cell division and growth during leaf cell development's proliferation and expansion stages. During leaf senescence, cytokinins decrease sugar buildup, enhance chlorophyll production, and extend the photosynthetic duration [38]. Cytokinins also slow plant senescence by blocking the breakdown of chlorophyll, nucleic acids, proteins, and other plant components. They also redistribute essential amino acids, hormones, inorganic ions, and other substances to other organs [39].

Physiological effects of Cytokinins on plants

Cytokinins have a role in several areas of plant growth and development, including embryogenesis, root maintenance, and callus differentiation into shoots. They influence root elongation, lateral root number, nodule formation, and apical dominance in response to environmental stimuli.

Cell division and morphogenesis

Cytokinins promote cell division. For example, adding cytokinins to tissue culture medium causes cell enlargement, which can lead to leaf enlargement. Cell division and morphogenesis are closely connected processes that play essential roles in embryo and tissue development. Cell division is the process by which a parent cell splits into two or more daughter cells, whereas morphogenesis is the development and differentiation of tissues and organs. Cell division controls the growth and structure of emerging tissues, while tissue morphogenesis influences the rate and orientation of cell division [40].

Cytokinins are plant growth regulators that promote cell division and morphogenesis. They stimulate mitotic cell division, control cell division at cell cycle checkpoints, and aid in organ creation. Cytokinins promote cellular growth, development, and differentiation. This causes plant growth, the formation of shoots and buds, and the production of fruits and seeds. Cytokinins are essential components of plant morphogenesis. They collaborate with auxin, another plant growth hormone, to regulate the morphogenetic differentiation of shoot and root meristems. The cytokinin/auxin ratio determines the root/shoot ratio. If the ratio is low, root development occurs; if the ratio is high, meristematic cells in the callus develop (*Cytokinin: Function, Hormone, Structure & Example | AESL*, n.d.).

Cell enlarged

Cell expansion is the process of increasing cell size. It is a necessary component of organism growth; without it, organisms cannot expand. Cells that cannot increase eventually lose the ability to divide, halting growth. Cell enlargement happens when cell walls relax, and turgor pressure decreases. It is more susceptible to water deficiency than cell division. Plant cell expansion occurs when the cell walls relax and the polysaccharides in the load-bearing network slip and stretch. This process is known as stress relaxation and is necessary for plant growth and development [41].

Cytokinins are plant hormones that stimulate cell growth and differentiation. They can increase plant cell size by elongating cell walls, increasing turgor pressure, and stimulating endoreduplication [42]. Cytokinins stimulate cell division and expansion during leaf cell development's proliferation and expansion stages, respectively. During leaf senescence, cytokinins decrease sugar buildup, enhance chlorophyll production, and extend the photosynthetic duration. Cytokinins interact with auxin, another plant growth hormone, and have opposite effects. For example, cytokinins assist the plant in overcoming apical dominance, whereas auxin encourages it. Instead, cytokinins encourage lateral shoot growth and development [43].

Breaking of seed dormancy

When exposed to the proper environmental conditions (light and water), a dormant seed does not germinate. Seed dormancy can be disrupted through dry storage or cold imbibition (stratification). In Arabidopsis, seed germination occurs in two steps: Testa rupture occurs first, followed by endosperm rupture.

Cytokinins regulate cell proliferation and differentiation, breaking seed dormancy and inducing germination. Depending on the type and dose, cytokinins can boost seed germination by up to threefold. They could be utilized to boost the germination of newly obtained and aged seed samples. However, cytokinins are not the significant enzymes that break seed dormancy. Cytokinins interact with other growth regulators like gibberellins and Ethylene [44].

Counteraction of apical dominance

Apical dominance is the situation in which the apical sections of a shoot prevent the growth of the lateral buds below. The hormones cytokinin and auxin are thought to control apical dominance. Cytokinin can resist apical dominance by acting as an auxin antagonist. Cytokinins can encourage cell division and proliferation in the root and shoot systems [45]. It can counterbalance apical dominance by promoting lateral bud development and encouraging nutrients to migrate toward them. When given to lateral buds, it promotes their growth even when the apical bud is present. It also establishes vascular connections, increasing the flow of water and solutes to the lateral buds. They restore the auxin-induced suppression of lateral buds. They can alter the impact of other hormones without changing themselves. Auxins and cytokinins have an anti-apical dominance effect. Auxins enable the apical bud to dominate, whereas cytokinins promote the formation of lateral buds [46].

Effect of enzymes

Enzymes are biological catalysts that accelerate chemical reactions by reducing the amount of energy required to initiate them. Although proteins comprise most enzymes, nucleic acids can also catalyze processes. Enzymes are substrate-specific, which means they only function on a single substrate. They are also susceptible to temperature variations, inhibitors, and pH. Enzymes are important in plant metabolism, growth, and response to environmental changes. They play an important role as catalysts in biosynthetic pathways, allowing secondary metabolites such as alkaloids, terpenes, and phenolics to be produced [47]. Cytokinins are plant hormones that influence plant growth and development, such as cell division, leaf senescence, and nutrient absorption. Cytokinins enhance cell division in plant roots and shoots while regulating cell division rate, transition time, and cell expansion extent. This, in turn, influences the quantity and size of cells and, ultimately, the size of the leaf. Cytokinins also promote cell wall elongation, turgor pressure, and endoreduplication, contributing to cell growth [48].

Ethylene

Ethylene is a plant hormone that controls growth and senescence throughout its life. It is the first alkene gas discovered to behave as a hormone and is biologically active at deficient concentrations. Ethylene is linked to ageing, including fruit ripening, flower wilting, and leaf and fruit abscission. It also increases germination in various cereals and the sprouting of bulbs and potatoes [49]. Depending on the concentration, time, and plant type, Ethylene promotes or inhibits growth and senescence processes. Commercial fruit-ripening rooms, for example, use "catalytic generators" to convert a liquid supply of ethanol into ethylene gas. Typically, a gassing level of 500 to 2,000 ppm is employed for 24-48 hours [50]. Depending on the species, developmental stage, and concentration, ethylene reactions can be beneficial or detrimental.

Some plants, such as bananas, melons, apples, tomatoes, and avocados, contain significant levels of Ethylene. However, many ethylene producers are sensitive to the hormone and use it to initiate their ripening process [51].

Physiological effects of Ethylene on plants

Ethylene, a plant growth regulator, influences the development of leaves, flowers, and fruits. It can also promote, prevent, or induce senescence, depending on whether the ethylene levels are appropriate or suboptimal.

Abscission

Abscission is a natural process in which plants remove aged or undesirable organs. These organs include leaves, flowers, fruits, seeds, and petioles. Abscission happens within specialized abscission layers. Cells round out and detach from one another when abscission begins. This leads to loss of adhesion. Unfavourable environmental or developmental factors might cause abscission. Abscission is when trees and other plants shed some or all of their leaves in the autumn [52]. Ethylene, a natural plant hormone, can promote abscission or the shedding of organs that have completed their function. Ethylene can induce abscission by inhibiting auxin synthesis and transport, increasing auxin degradation, hastening senescence, and acting on plant cell walls. Ethylene can cause the abscission of leaves, fruits, and flower petals. When auxin levels fall, Ethylene causes senescence and, ultimately, programmed cell death at the point of leaf attachment to the stem. High ethylene concentrations can harm photosynthesis and growth, causing leaf bending and shedding [53].

Ripening

Fruit ripening is a series of processes from the later stages of growth and development until the fruit is ready to be consumed. Fruit ripening alters fruit quality features. The stiffness of the fruit flesh usually softens, the sugar content increases and the acid levels decrease. Fruit ripening is a complex process involving numerous physiological and molecular changes between the later phases of growth and development and when the fruit is ready to be consumed. Ripening makes fruits sweeter, less green, and softer. The acidity of fruit increases as it ripens, yet this does not make it appear tarter (*Ethylene and the Regulation of Fruit Ripening*, n.d.).

Ethylene is a plant hormone that regulates the natural ripening of fruits. It is naturally created within fruits, and ethylene concentration in underripe fruit is relatively low. As the fruit grows, it produces more, accelerating the ripening process, known as the "climacteric" stage. The amount of Ethylene and the rate of ripening vary per variety (Ming-Chun et al., 2015). Ethylene is commonly employed to ripen fruit, but its synthesis, handling, and storage are all environmentally hazardous. The Food Safety and Standards Regulations, 2011 prohibits using carbide or acetylene gas for artificial ripening of fruits due to potential health concerns [54].

Effect on growth

Ethylene is a plant hormone that regulates numerous processes related to plant growth, development, and stress response. It is best recognized for its influence on fruit ripening and organ abscission. Ethylene plays a dual role in stress: it governs a defence reaction, mostly in mature leaves, and a growth response in young leaves. In immature leaves, Ethylene controls both cell division and cell growth.

Ethylene controls root growth by stimulating auxin production and modulating the auxin transport mechanism [55].

Degreening

Degreening is a commercial procedure that involves removing chlorophyll from the skin of citrus fruit to improve the colour of the fruit's peel. The technique involves exposing the fruit to ethylene gas in a temperature and humidity-controlled environment. The ethylene gas degrades the chlorophyll, causing the fruit peel to become orange or yellow. The length of exposure is determined by the fruit's initial green colour and the amount of green surface area. The acceptable ethylene level is 5 ppm. Degreening is a process used to improve the colour of lemons before they are harvested and sold. The internal quality of the fruit is unaffected by the treatment. The success of degreening depends on the type of fruit, the initial colour, the ethylene concentration, and the exposure duration [56].

Ethylene gas is used in the degreening process to break down chlorophyll in citrus fruit skins, removing the green colour and revealing the yellow or orange peel. This process entails injecting precisely calibrated amounts of ethylene gas into a temperature and humidity-controlled atmosphere. The length of the degreening period is determined by the green colour of the fruit during harvest, although it should be kept to a minimum of 2-3 days to avoid quality loss [57].

Senescence

Plant senescence is the process by which plants age. It can occur in stages, with merely leaves dying or the entire plant dying. Senescence is controlled cell death that causes various biochemical and structural changes. This includes proteolysis, chlorophyll loss, and nucleic acid degradation. Senescence is a natural process that ensures the plant's survival. It also indicates abscission. Senescence is the outcome of continuous integration of inherent and external information at the cellular, tissue, and organ level. It continues until fruit growth and maturation are completed when the leaf tissues disintegrate entirely [58].

Ethylene, a gas plant product, can cause senescence, particularly in sensitive species. Ethylene production is highest at the first stage of leaf formation, then reduces till maturity before increasing again during the early stages of senescence. Ethylene exposure can promote early senescence in both leaves and flowers. In addition to other hormones, Ethylene is essential in the growth and senescence of leaves, flowers, and fruits. Ethylene integrates several signals, enabling the emergence of conditions favourable for stage advancement, reproductive success, and organ lifetime [59].

Flowering and Dormancy

Dormancy is the halting of an organism's growth due to environmental change. Both hereditary and environmental factors influence it. The temperature that seeds endure while maturing determines whether they go dormant. The amount of daylight the plant receives is the most critical factor in the onset of flowering. A plant develops best when it receives enough daylight.

Ethylene is a plant growth hormone that promotes flowering and dormancy by affecting the transition from vegetative to reproductive phases of development. Ethylene also increases root apogeotropism, aids root initiation and pollination and stimulates seed germination. Ethylene levels can promote, prevent, or induce senescence, depending on whether it is ideal or suboptimal [60].

Abscisic acid

Abscisic acid (ABA) is a hormone that controls many aspects of plant growth, development, and stress response. ABA-deficient mutants from numerous plant species exhibit reduced seed dormancy and wilty phenotypes, demonstrating that these essential ABA functions are maintained across the plant kingdom. Abscisic acid (ABA) is a hormone that influences plant growth and development. It was first discovered in the 1960s as a growth inhibitor in cotton fruit and sycamore leaves. ABA has a role in several plant developmental processes, including seed and bud dormancy, organ size regulation, and stomatal closure [45].

Physiological Effects of ABA on Plants

ABA is also necessary for growth and development in non-stressed environments. For example, low soil moisture raises ABA levels, causing stomata to close during water stress and drought. Complex regulatory mechanisms govern ABA production, degradation, signal perception, and transmission.

Growth inhibition

Abscisic acid (ABA) is a plant growth inhibitor that can reduce plant growth. ABA is a stress hormone found in mature leaves and other plant tissues. ABA is necessary in plant responses to water stress, and increased ABA concentrations in guard cells during drought stress may contribute to stomatal closure. ABA can also induce the wilting of leaves. Spraying can help reduce growth inhibition in plants, Injecting a solution into interior tissues, Feeding the roots, Applying powder combinations to the bases of cuts, Dip the cutting into a PGR solution., Soak in a diluted aqueous solution (*Plant Nutrition : Plant Growth Regulators*, n.d.).

Dormancy

Abscisic acid (ABA) is a plant hormone that promotes dormancy and stops seeds from developing. ABA levels rise during dormancy and stress, which can prevent germination and growth. ABA also causes leaves, fruits, and flowers to shed and stomata to close. ABA is considered to regulate the shift from dormancy to germination via influencing transcription, RNA processing, post-translational protein modification, and secondary messenger metabolism [46].

Abscission

Abscisic acid (ABA) inhibits plant growth and produces abscission or the shedding of plant parts. ABA stimulates abscission via Ethylene. ABA is a stress hormone that accumulates when plants are subjected to various conditions. It causes stomatal closure, which lowers water loss and protects against microorganisms. ABA is also necessary for seed maturation and maintains a period of dormancy. Abscission is shedding plant parts such as leaves, fruits, and flowers. Abscisic acid (ABA) is a commonly used plant growth inhibitor. It promotes dormancy, which stops seeds from germinating, causes the absence of leaves, fruits, and flowers, and seals the stomata [47].

Seed development and germination

Abscisic acid (ABA) is a hormone that regulates seed dormancy and germination in response to environmental signals. ABA acts by halting embryo growth when the radicle begins to expand, preventing water intake. Seeds that have been quiescent for several days due to ABA will readily absorb water and germinate again once the hormone is withdrawn. ABA is the only plant hormone known to keep seeds dormant. It acts via a gene expression network with the transcription factor ABSCISIC ACID INSENSITIVE 3 (ABI3). ABA receptors are positioned on the cellular periphery and are required to recognize exogenous ABA.

The ABA signal is detected by GCR2, which functions as an extracellular ABA receptor and regulates all key ABA-mediated processes, including seed germination [48].

Stomatal movement

Abscisic acid (ABA) is a plant hormone that controls stomatal movement and water balance. It also aids plants in responding to low water availability. ABA can aid with stomatal motility in several ways. ABA closes stomata, reducing transpirational water loss. ABA lowers guard cell turgor, which limits the aperture of the stomatal pores. ABA alters the permeability of the guard cell membranes, interfering with potassium ion transport. When there isn't enough water, stomata close. ABA stimulates the activity of antioxidant enzymes, reducing CO2 fixation and inhibiting the buildup of reactive oxygen species [49].

Conclusion

Plant growth regulators are pivotal in regulating plant growth, development, and reproduction. They may regulate senescence, blossoming fruiting, and processes like cell division, elongation, and differentiation. Improved crop varieties and quality can increase plant production by better understanding and utilizing these chemicals and potency. The hormones found in plants are a group of tiny molecules that are physically unrelated and originate from several vital metabolic processes. These substances mediate responses to biotic and abiotic stressors and are significant plant growth regulators (Santner et al.,2009). The phytohormones- Auxins, Gibberellins and Cytokinins are regarded as plant growth promoters, whereas Ethylene and Abscisic acid are considered to be growth inhibitors.

A set of genes governs the production of these hormones. The degree to which pertinent genes are expressed determines the amount and action of plant hormones. Plant hormones regulate growth, development, and nutrient allocation, essential for plants to adapt to different environments. Hormones go along specific routes to regulatory locations, reacting to stress by concentrating incredibly little. Phytohormones influence all biological activity, either directly or indirectly (Fahad et al., 2015). According to recent research, hormones have been implicated in regulating these regulatory networks. Apart from these known functions of the phytohormones, many of its utilities are unknown. Therefore, much exploration is required into these phytohormones' synthesis, mode of action, signalling and response. Moreover, their quantification, localization and occurrence in different plants also form exciting research areas.

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