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Biosynthesis, Mechanism and Potential Application of Hormones for Mitigating Stress, Conserving Bioactive Constituents in Fruits

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The influence of plant growth regulators, including auxins, gibberellins, cytokinins, ethylene, abscisic acid, brassinosteroids, jasmonates, and salicylic acid, on fruit crop development and quality enhancement. Various stages of fruit crop growth, such as flowering, fruit set, ripening, and post-harvest attributes, are examined through comprehensive experimental approaches. Auxins play a crucial role in regulating fruit size, shape, and development by facilitating cell elongation. Gibberellins control fruit elongation, seed germination, and fruit set. Cytokinins influence fruit expansion, sugar metabolism, and overall quality by promoting cell division and differentiation. Ethylene affects fruit ripening processes, including color change, softening, and flavor development. Abscisic acid influences fruit maturation and dormancy. Brassinosteroids regulate fruit development, including size, ripening, and tolerance to abiotic stress. Jasmonates and salicylic acid, involved in defense responses, have an impact on fruit ripening, quality, and disease resistance. The application of these regulators shows promise in improving fruit quality, nutritional composition, and shelf life. This study aims to provide valuable insights into fruit crop physiology and develop strategies to optimize productivity and quality. It emphasizes the importance of proper regulation and responsible use of plant growth regulators to address environmental, health, and ecological concerns associated with excessive or improper application. Excessive use of PGRs can lead to various physiological issues, adversely affecting fruit crop productivity and quality. Therefore, careful control of application procedures, dosages, and timing is necessary to ensure fruit crop health and avoid negative consequences.

Keywords: Flowering; fruit set, ripening; post-harvest attributes; cell elongation; sugar metabolism; abiotic stress tolerance; defense responses; environmental concerns; health concerns; productivity.

1. INTRODUCTION

Plant growth regulators (PGRs) are natural or synthetic substances that regulate plant growth and development by altering the physiological and biochemical processes. They play an essential role in fruit crop development and quality enhancement by controlling various aspects of fruit growth, including size, color, shape, texture, and flavor. PGRs are involved in many vital plant processes, including cell division, elongation, differentiation, and senescence, and have significant impacts on fruit quality parameters such as firmness, sweetness, acidity, and aroma. The application of PGRs in fruit crop production has been extensively studied over the years, and several studies have reported their positive effects on fruit quality and yield. For example, the use of auxins such as indole-3-acetic acid (IAA) and naphthaleneacetic acid (NAA) can increase fruit size, while cytokinins such as kinetin can improve fruit quality parameters such as firmness, color, and sugar content. Similarly, the use of gibberellins such as GA3 can enhance fruit set, increase fruit size, and improve fruit quality attributes such as sugar content, flavor, and aroma [1]. Other PGRs, such as abscisic acid (ABA), ethylene, and brassinosteroids (BRs), also play crucial roles in fruit crop development and quality enhancement. ABA is involved in regulating fruit ripening and senescence, while ethylene plays a critical role in fruit ripening, softening, and color changes. BRs are involved in fruit development and play a role in improving fruit quality attributes such as firmness and color.

2. HISTORY AND MILESTONES OF RESEARCH ON PLANT GROWTH REGULATORS IN FRUIT CROPS

Research on the use of plant growth regulators (PGRs) in fruit crop production began in the early 1900s, with the discovery of the first plant hormone, auxin, by Charles Darwin and Francis Darwin in 1880 [2]. The first experiments on the use of auxins to stimulate fruit growth were conducted in the 1920s, with the discovery that the application of indole-3-acetic acid (IAA) could increase fruit size in tomato plants. In the 1930s, the use of gibberellins to improve fruit set and size in grapes and peaches was also reported

(Takahashi & Kikuta, 1939). The 1940s and 1950s marked a significant period of research on PGRs in fruit crop production, with the discovery of several new plant hormones such as cytokinins, abscisic acid (ABA), and ethylene (Wareing & Phillips, 1955). The discovery of cytokinins in the 1950s led to the development of new methods for inducing fruit formation and growth, including the use of kinetin to stimulate fruit set in apples and grapes (Miller & Skoog, 1954). In the 1960s and 1970s, the focus of PGR research shifted to understanding their mechanisms of action and effects on fruit quality parameters such as color, texture, and flavor. The role of ethylene in fruit ripening and senescence was also extensively studied, leading to the development of new techniques for delaying fruit ripening and extending shelf life, such as controlled atmosphere storage.

In recent years, research on PGRs in fruit crop production has focused on developing new formulations and delivery methods for their effective and efficient use. The development of new synthetic PGRs with enhanced efficacy and specificity, such as 1-methylcyclopropene (1-MCP) for delaying fruit ripening, has been a significant breakthrough in fruit crop production. Furthermore, the use of nanotechnology-based PGR formulations for improving fruit quality and yield has also been explored in recent years (Raza et al., 2020). The research on PGRs in fruit crop production has been a significant milestone in plant science, leading to the development of new techniques for improving fruit yield and quality while reducing production costs and enhancing sustainability.

3. TYPES AND CLASSES OF PLANT GROWTH REGULATORS

Plant growth regulators (PGRs) are natural or synthetic substances that regulate various physiological processes in plants, including growth, development, and response to environmental stimuli. PGRs are classified into different categories based on their chemical structure and mode of action. The major types and classes of PGRs used in fruit crop production are discussed below.

Auxins: Auxins are a group of naturally occurring plant hormones that regulate plant growth and development, including cell elongation, apical dominance, and root initiation. Indole-3-acetic acid (IAA) is the most common and widely studied auxin in fruit crop production. The use of synthetic auxins such as naphthaleneacetic acid (NAA) and indole-3-butyric acid (IBA) has also been reported to improve fruit set and size in various fruit crops.

Gibberellins: Gibberellins are a group of plant hormones that regulate various aspects of plant growth and development, including stem elongation, seed germination, and flowering. Gibberellic acid (GA) is the most widely used gibberellin in fruit crop production. The use of gibberellins has been reported to improve fruit size, yield, and quality in various fruit crops, including apples, grapes, and peaches [3].

Cytokinins: Cytokinins are a group of plant hormones that regulate cell division and differentiation. Kinetin is the most widely used cytokinin in fruit crop production. The use of kinetin has been reported to improve fruit set and size in various fruit crops, including grapes, apples, and pears [4].

Ethylene: Ethylene is a gaseous plant hormone that regulates various aspects of plant growth and development, including fruit ripening and senescence. The use of ethylene has been extensively studied in fruit crop production, leading to the development of techniques for delaying fruit ripening and extending shelf life, such as controlled atmosphere storage and the use of ethylene inhibitors such as 1-methylcyclopropene (1-MCP) [5].

Abscisic acid (ABA): ABA is a plant hormone that regulates various physiological processes, including seed germination, stomatal closure, and stress response. The use of ABA has been reported to improve fruit quality attributes such as color, texture, and flavor in various fruit crops, including grapes and kiwifruit.

Brassinosteroids: Brassinosteroids are a group of plant hormones that play crucial roles in various physiological processes, including plant growth, development, and stress responses. Brassinosteroids are known to regulate cell elongation, promote vascular differentiation, enhance seed germination, and modulate responses to environmental stresses such as drought, salinity, and extreme temperatures. They also have a positive influence on plant resistance against pathogens [6].

Jasmonates: Jasmonates are a class of plant hormones that are involved in various physiological processes, including plant growth, development, and defense responses against biotic and abiotic stresses. They are synthesized from fatty acids and are crucial for regulating plant responses to herbivory, pathogen attacks, and mechanical damage. Jasmonates also play a role in the regulation of flowering, senescence, and root growth. The signaling pathway of jasmonates involves perception by receptor proteins, activation of downstream transcription factors, and subsequent expression of defense-related genes.

Salicylic Acid: Salicylic acid plays a crucial role in the activation of defense responses, including the induction of pathogenesis-related (PR) genes, production of antimicrobial compounds, and reinforcement of physical barriers. It also regulates various aspects of plant development, such as seed germination, flowering, and fruit ripening. Salicylic acid acts as a signal molecule, triggering a cascade of reactions within the plant upon pathogen attack or other stressors.

4. ROLE OF AUXIN IN FRUIT CROP DEVELOPMENT

Auxins are a class of plant growth regulators that play an important role in the growth and development of fruit crops. The primary auxin found in plants is indole-3-acetic acid (IAA), which is synthesized in the shoot apical meristem and transported downwards towards the fruit. Auxins promote fruit growth by increasing cell division and elongation in the pericarp, as well as stimulating the differentiation of vascular tissue and the formation of seeds. In addition to their role in fruit growth, auxins also play a crucial role in regulating fruit ripening. During the early stages of fruit development, high levels of auxins suppress the expression of ripening-related genes and delay the onset of ripening. As the fruit matures, the levels of auxins decrease, allowing ripening to proceed. This is particularly important in climacteric fruits, such as apples and bananas, which undergo a rapid and dramatic increase in respiration and ethylene production during ripening.

The application of exogenous auxins has been shown to enhance fruit growth and quality in several fruit crops. For example, the foliar application of IAA has been shown to increase fruit size and yield in tomato, while the application of synthetic auxins such as naphthaleneacetic acid (NAA) and 2,4-dichlorophenoxyacetic acid (2,4-D) has been shown to increase fruit set and yield in apple. However, the application of exogenous auxins can also have negative effects on fruit quality. For example, the excessive application of auxins can lead to fruit cracking and deformities, as well as a reduction in sugar content and flavor. Therefore, the timing and dosage of auxin application are crucial in order to achieve the desired effects on fruit growth and quality.

5. ROLE OF GIBBERELLINS IN FRUIT CROP DEVELOPMENT

Gibberellins are a class of plant growth regulators that play a crucial role in the growth and development of fruit crops. The primary gibberellin found in plants is gibberellic acid (GA), which is synthesized in the apical meristem and transported throughout the plant. Gibberellins promote fruit growth by stimulating cell elongation in the pericarp and increasing the size of the fruit [7]. In addition to their role in fruit growth, gibberellins also play a crucial role in regulating fruit quality. For example, gibberellins have been shown to promote fruit ripening by stimulating ethylene production and the expression of ripening-related genes. This is particularly important in non-climacteric fruits, such as grapes and strawberries, which do not undergo a rapid and dramatic increase in ethylene production during ripening.

The application of exogenous gibberellins has been shown to enhance fruit growth and quality in several fruit crops. For example, the application of GA has been shown to increase fruit size, yield, and quality in grape and peach. Additionally, the application of GA has been shown to delay fruit senescence and maintain fruit quality during storage in peach and strawberry. However, the application of exogenous gibberellins can also have negative effects on fruit quality. For example, the excessive application of gibberellins can lead to fruit deformities, reduced sugar content, and decreased fruit firmness. Therefore, the timing and dosage of gibberellin application must be carefully regulated in order to achieve the desired effects on fruit growth and quality.

6. ROLE OF CYTOKININS IN FRUIT CROP DEVELOPMENT

Cytokinins are a class of plant growth regulators that play a critical role in the growth and development of fruit crops. Cytokinins are primarily synthesized in the roots and transported to the shoot, where they promote cell division and differentiation. Cytokinins have been shown to promote fruit growth by increasing cell division and elongation in the pericarp, as well as stimulating the differentiation of vascular tissue and the formation of seeds. In addition to their role in fruit growth, cytokinins also play a crucial role in regulating fruit quality. For example, cytokinins have been shown to delay fruit senescence and maintain fruit quality during storage in several fruit crops, including strawberry and tomato. Cytokinins have also been shown to regulate fruit ripening by modulating the expression of ripening-related genes and delaying the onset of senescence.

The application of exogenous cytokinins has been shown to enhance fruit growth and quality in several fruit crops. For example, the application of cytokinins has been shown to increase fruit size, yield, and quality in tomato and kiwifruit. Additionally, the application of cytokinins has been shown to improve fruit resistance to environmental stresses, such as drought and high temperature. However, the application of exogenous cytokinins can also have negative effects on fruit quality. For example, the excessive application of cytokinins can lead to fruit deformities, reduced sugar content, and decreased fruit firmness. Therefore, the timing and dosage of cytokinin application must be carefully regulated in order to achieve the desired effects on fruit growth and quality.

7. ROLE OF ETHYLENE IN FRUIT RIPENING AND QUALITY

Ethylene is a plant growth regulator that plays a critical role in the ripening of climacteric fruit crops. Ethylene is produced in the fruit during the ripening process and acts as a signal to promote the expression of ripening-related genes, leading to changes in color, texture, and flavor. Ethylene also plays a crucial role in the regulation of fruit abscission, which is the natural shedding of fruit from the plant. Ethylene promotes fruit abscission by inducing the expression of genes that break down the cell wall in the abscission zone [8].

The application of exogenous ethylene has been shown to accelerate fruit ripening in several fruit crops, including tomato [9] and banana. This has practical applications in the industry, where the use of ethylene can help to synchronize fruit ripening and facilitate the handling and transport of fruit. Additionally, the application of ethylene can also enhance the uniformity of fruit ripening and improve fruit quality [10]. However, the application of exogenous ethylene can also have negative effects on fruit quality. For example, the overapplication of ethylene can lead to fruit softening, decay, and reduced shelf life [11]. Therefore, the timing and dosage of ethylene application must be carefully regulated in order to achieve the desired effects on fruit ripening and quality.

8. ROLE OF ABSCISIC ACID IN FRUIT DEVELOPMENT AND STRESS RESPONSE

Abscisic acid (ABA) is a plant growth regulator that plays a crucial role in fruit development and stress response. ABA is synthesized in response to environmental stresses, such as drought and high salinity, and acts as a signaling molecule to regulate plant growth and stress tolerance. In fruit crops, ABA has been shown to regulate fruit growth and development by promoting cell division and elongation in the pericarp, as well as stimulating the accumulation of storage compounds, such as sugars and organic acids. Additionally, ABA plays a critical role in the response of fruit crops to environmental stresses. For example, ABA has been shown to enhance the resistance of fruit crops to drought, salinity, and low temperature stress by promoting the accumulation of osmoprotectants, such as proline and soluble sugars.

The application of exogenous ABA has also been shown to improve fruit quality in several fruit crops. For example, the application of ABA has been shown to increase fruit firmness, color development, and sugar content in strawberry and kiwifruit. Additionally, the application of ABA has been shown to enhance the tolerance of fruit crops to environmental stresses, such as drought and high temperature. However, the application of exogenous ABA must also be carefully regulated to avoid negative effects on fruit quality. For example, the excessive application of ABA can lead to fruit cracking, reduced fruit size, and decreased fruit yield. Therefore, the timing and dosage of ABA application must be carefully optimized to achieve the desired effects on fruit growth and quality.

9. ROLE OF BRASSINOSTEROIDS IN FRUIT CROP DEVELOPMENT

Brassinosteroids (BRs) are a group of plant growth regulators that have been shown to play a significant role in fruit crop development. BRs are involved in several physiological processes, including cell division and elongation, stress response, and regulation of gene expression [12]. In fruit crops, BRs have been shown to promote fruit growth and development by stimulating cell division and elongation in the pericarp, increasing fruit size and weight. Additionally, BRs have been shown to enhance fruit quality by improving color development, flavor, and nutrient content in fruit crops, such as tomato and strawberry [13].

10. ROLE OF JASMONATES IN FRUIT DEFENSE MECHANISMS

Jasmonates (JAs) are a group of plant growth regulators that play a critical role in fruit defense mechanisms. JAs are synthesized in response to biotic and abiotic stresses and act as signaling molecules to regulate the expression of genes involved in stress response and defense mechanisms. The biosynthetic pathway starting with linolenic acid via cyclic intermediates, for example, 12-oxophytodienoic acid, was elucidated and some metabolites are described. In fruit crops, JAs have been shown to enhance resistance to pests and pathogens by promoting the synthesis of defense-related compounds, such as phytoalexins, lignin, and pathogenesis-related proteins. Additionally, JAs have been shown to regulate fruit ripening and senescence by promoting the accumulation of pigments and volatiles, which contribute to the flavor and aroma of the fruit.

11. ROLE OF SALICYLIC ACID IN FRUIT CROP DEVELOPMENT AND DEFENSE

Salicylic acid (SA) is a plant growth regulator that plays a crucial role in the development and defense of fruit crops. SA is synthesized in response to biotic and abiotic stresses and acts as a signaling molecule to regulate plant growth and stress responses. In fruit crops, SA has been shown to regulate fruit growth and development by promoting cell division and differentiation in the pericarp, as well as enhancing fruit pigmentation [14]. Additionally, SA plays a critical role in the response of fruit crops to biotic stresses. For example, SA has been shown to enhance the resistance of fruit crops to pathogenic infections by inducing the expression of defense-related gene. SA has also been shown to play a role in the systemic acquired resistance (SAR) of fruit crops, which is a mechanism of plant defense against a broad range of pathogens.

The application of exogenous SA has also been shown to improve fruit quality and enhance the tolerance of fruit crops to biotic stresses. For example, the application of SA has been shown to increase fruit size, weight, and yield in tomato. Additionally, the application of SA has been shown to enhance the resistance of fruit crops to fungal pathogens, such as powdery mildew and gray mold. However, the application of exogenous SA must also be carefully regulated to avoid negative effects on fruit quality. For example, the excessive application of SA can lead to reduced fruit size, as well as decreased fruit yield and shelf life. Therefore, the timing and dosage of SA application must be carefully optimized to achieve the desired effects on fruit growth and quality.

12. BIOSYNTHESIS AND METABOLISM OF PLANT GROWTH REGULATORS IN FRUIT CROPS

Plant growth regulators (PGRs) are vital for the regulation of plant growth and development, and they play a crucial role in fruit crop development and quality enhancement. The biosynthesis and metabolism of PGRs in fruit crops are complex processes that involve multiple pathways and factors. The synthesis of PGRs such as auxins, cytokinins, and gibberellins occurs in the apical meristem of the plant. The synthesis of gibberellins in grape berries is induced by light, while the synthesis of abscisic acid in apple fruits is inhibited by high temperatures. Ethylene produced in response to various environmental stimuli, such as mechanical stress, wounding, and pathogen attack. The biosynthesis of ethylene is regulated by the enzyme ACC synthase, which converts S-adenosylmethionine (SAM) to 1-aminocyclopropane-1-carboxylic acid (ACC). Ethylene is then converted to ethylene oxide, which is the active form of the hormone, by the enzyme ACC oxidase.

Abscisic acid (ABA) is another essential PGR that is synthesized in response to various environmental factors, including water stress, high salt concentration, and cold temperatures. The biosynthesis of ABA is regulated by the enzyme zeaxanthin epoxidase, which converts zeaxanthin to violaxanthin, which is then converted to ABA. The biosynthesis and metabolism of PGRs are regulated by various factors, including light, temperature, and hormone signalling pathways. The crosstalk between different hormone signalling pathways also plays a critical role in regulating PGR biosynthesis and metabolism in fruit crops.

The metabolism of plant growth regulators in fruit crops is regulated by various enzymes, including oxidases and hydrolases, which are involved in the degradation and inactivation of plant hormones. In addition to the synthesis of PGRs, their metabolism is equally important in regulating plant growth and development. For example, the inactivation of auxins is mediated by conjugation with amino acids or by oxidation to inactive forms. Cytokinins are metabolized by cytokinin oxidase, which converts them to inactive forms, and gibberellins are inactivated by oxidation or conjugation with sugars. Ethylene is inactivated by the enzyme ethylene oxidase, which converts ethylene oxide to ethylene glycol. The regulation of PGR biosynthesis and metabolism in fruit crops plays a crucial role in fruit crop development and quality enhancement. Further research is needed to fully understand the complex regulation of PGR biosynthesis and metabolism in fruit crops and to develop strategies for improving fruit quality and productivity.

13. MODE OF ACTION OF PLANT GROWTH REGULATORS IN FRUIT CROP DEVELOPMENT

Plant growth regulators (PGRs) act by interacting with specific receptors located in various parts of the plant. PGRs are produced endogenously in plants and can also be applied exogenously to manipulate plant growth and development. They act by regulating gene expression, protein synthesis, enzyme activity, and other physiological processes. The mode of action of PGRs varies depending on the type and class of the PGR. Auxins, for example, are involved in cell division and elongation by promoting the expression of genes involved in these processes. Gibberellins promote stem elongation and fruit development by inducing the expression of genes involved in cell expansion, sugar metabolism, and fruit ripening [15]. Cytokinins promote cell division and delay senescence by regulating the activity of cyclin-dependent kinases and other enzymes involved in cell division. Ethylene is involved in many aspects of plant growth and development, including fruit ripening, abscission, and senescence. It acts by inducing the expression of genes involved in these processes, as well as by regulating the activity of other plant hormones such as auxins and gibberellins.

The mode of action of PGRs in fruit crops is complex and varies depending on the type and class of the PGR, the stage of fruit development, and environmental factors such as temperature, light, and water availability. The exogenous application of PGRs can have both positive and negative effects on fruit development and quality. For example, auxins can increase fruit size and yield but can also lead to fruit malformation and reduced quality if applied at high concentrations. Gibberellins can improve fruit set, size, and quality but can also lead to fruit drop if applied at the wrong time or in excess [16]. Cytokinins can delay fruit senescence and improve fruit quality, but their effects on fruit size and yield are less clear (Hou et al., 2019). Ethylene is involved in many aspects of fruit development and ripening, and its application can accelerate fruit ripening and improve quality but can also lead to premature fruit senescence and reduced shelf life if applied at high concentrations. PGRs act by regulating gene expression, enzyme activity, and other physiological processes in plants. The mode of action of PGRs in fruit crops is complex and varies depending on the type and class of the PGR, the stage of fruit development, and environmental factors. Exogenous application of PGRs can have both positive and negative effects on fruit development and quality, and their use must be carefully controlled to avoid adverse effects on plant growth and fruit quality.

14. ROLE OF PLANT GROWTH REGULATORS IN FRUIT SET AND DEVELOPMENT

Plant growth regulators (PGRs) play a crucial role in fruit set and development in fruit crops. PGRs can be classified into two groups: those that promote cell division and elongation, and those that promote fruit growth and maturation [17].

One of the most important PGRs involved in fruit set and development is auxin. Auxin is synthesized in the developing fruit and promotes cell division and differentiation in the pericarp, as well as the elongation of the pedicel. Additionally, auxin plays a critical role in the formation and development of seeds in many fruit crops [17].

Gibberellins (GAs) also play an important role in fruit set and development. GAs are synthesized in the developing seeds and promote fruit growth and maturation by promoting cell division and elongation in the pericarp [17]. Additionally, GAs have been shown to play a critical role in the parthenocarpic development of fruit crops, which is the formation of fruit without fertilization.

Table 1. Plant growth regulators and their application methods

Plant Growth Regulator	Application Method	Advantages	Disadvantages	References
Auxins	Foliar spray	Easy application, fast absorption	Requires frequent applications	Fatima et al. [18]
Gibberellins	Soil application	Long-lasting effect, improves root growth	May cause uneven growth	Wu et al. [19]
Cytokinins	Seed treatment	Improves germination and early growth	May affect plant development	Singh et al. [20]
Ethylene	Gaseous treatment	Stimulates fruit ripening and color development	Requires specialized equipment	Fan et al. [21]
Abscisic acid	Post-harvest dip	Delays fruit ripening and senescence	May affect fruit quality	Zhang et al. [22,23]
Brassinosteroids	Foliar spray	Enhances plant growth and stress tolerance	Expensive	Sharma et al. [24]
Jasmonates	Foliar spray	Induces plant defense against pathogens and pests	Requires frequent applications	Mishra et al. [25]
Salicylic Acid	Foliar spray	Induces plant defense against pathogens and abiotic stress	Requires frequent applications	Zhu et al. [26]

Cytokinins also play a role in fruit set and development by promoting cell division and differentiation in the developing fruit [26]. Additionally, cytokinins have been shown to improve fruit quality by enhancing fruit color and sugar content in many fruit crops (Jiang et al., 2017). PGRs play a critical role in fruit set and development in fruit crops. Auxin, gibberellins, and cytokinins are among the most important PGRs involved in fruit growth and maturation. The application of exogenous PGRs can improve fruit quality and enhance fruit set and development, but the timing and dosage of application must be carefully optimized to achieve the desired effects on fruit yield and quality.

15. ROLE OF PLANT GROWTH REGULATORS IN FRUIT QUALITY ENHANCEMENT

Plant growth regulators (PGRs) have been extensively studied for their role in enhancing fruit quality. Among the various PGRs, abscisic acid (ABA) has been shown to play a critical role in fruit quality enhancement. ABA regulates a broad range of physiological processes, including fruit ripening and maturation, seed development, and stress responses. In fruit crops, ABA has been shown to regulate fruit ripening by promoting ethylene biosynthesis and enhancing color development [27]. Additionally, ABA has been shown to improve fruit quality by regulating fruit size, shape, firmness, sugar content, and acidity. For example, the application of exogenous ABA has been shown to enhance the sugar accumulation and flavor of grapes, strawberries, and kiwifruit. ABA has also been shown to enhance the tolerance of fruit crops to abiotic stresses, such as drought and salinity [27]. However, the application of ABA must be carefully optimized to avoid negative effects on fruit quality, such as decreased firmness and shelf life. Other PGRs, such as cytokinins and gibberellins, have also been shown to play a role in fruit quality enhancement by regulating fruit size, sugar content, and color development (Jiang et al., 2017). Overall, the application of PGRs is a promising approach for enhancing fruit quality and improving the yield of fruit crops, but careful consideration must be given to the timing, dosage, and mode of application to achieve optimal results.

16. ABIOTIC STRESS MITIGATION THROUGH USE OF NOVEL PHYTOHORMONES

Stress conditions develop in plants as a result of rapid and unpredictable environmental changes. Plants face a major threat to their survival as a result of environmental changes brought on by anthropogenic activity or by rapid seasonal shifts. Being sessile organisms, plants must contend with such unfavourable environmental conditions. For the best development and growth of plants, the environment must be free of fluctuations like water shortage or drought, water logging, low or high temperature, high salinity, heavy metals, and sun radiation (Raza et al., 2020). These unfavourable conditions that plants experience throughout their life cycle disrupt metabolic processes and negatively impact their development and growth at the cellular and entire plant levels. Consequently, this causes a global decline in biomass and food production [28,29]. Different abiotic stresses may occur simultaneously under harsh conditions. For instance, drought is usually linked to salt stress, and drought can be made worse by extremely high temperatures. The negative effects of salt negatively affect root growth and regulate the plant's capacity to absorb water as well as nutrients. In response to abiotic stress, plants combine several external stress indicators to generate an integrated response and an internal process to reduce the stress by setting off a chain of events that increases tolerance. Abiotic stress causes messenger molecules to be produced, which then triggers the production of several metabolites, including phytohormones for tolerance to stress.

Under both ideal and extreme circumstances, phytohormones (PHs) are essential for controlling a number of biochemical and physiological processes that control plant development and productivity. Because they activate signalling pathways, the interplay of various PHs is essential for plant survival in stressful situations. The physiological mechanisms in plant architecture are highly tuned by hormonal cross regulation, enabling plants to develop under less-than-ideal growth conditions. Under both normal and stressful circumstances, the role of cytokinins, gibberellins, auxin, and relatively new phytohormones such as strigolactones and brassinosteroids in the development and growth of plants has been demonstrated.

At very low concentrations, stress activates phytohormone signalling pathways that are hypothesised to promote adaptive responses. To combat these harmful pressures, plants have evolved effective sensing, signalling, and response mechanisms. The PHs, which are cellular signal molecules that function as messenger molecules in plants under low concentrations, are one of the most striking examples of these response mechanisms employed by plants. They play crucial roles in the regulation of the reactions that plants exhibit to abiotic stresses [30]. Plants must interpret these signals in a highly dynamic and coordinated way in order to respond to environmental challenges. Being sessile organisms, plants must preserve flexibility in their growth and the capacity to adapt to severe, constantly changing environmental conditions. Extensive signalling networks mediate this adaptability. The perception of abiotic stressors initiates signal transduction cascades that interact with the baseline pathways transduced by phytohormones. The alterations in cellular dynamics caused by fluctuating stress-responsive hormones are crucial for coordinating the growth response to stress [31]. A signalling network is created by the convergence points of the several hormone signal transduction cascades. Thus, hormones appear to interact through either initiating a phosphorylation cascade or a shared second messenger.

17. BURNING ISSUES RELATED TO PGRs

Plant growth regulators (PGRs) are chemicals that have the ability to affect several facets of plant development and growth. PGRs have many advantages, but they are also associated with a number of burning issues. Among them, the principal worries are:

1. Environmental Impact: The use of PGRs may have unforeseen effects on the environment. For instance, utilising PGRs excessively or improperly may contaminate the soil, water, and air, harming non-target organisms and habitats. Some PGRs may persist in nature and have long-lasting effects.

2. Human Health Risks: PGRs can be harmful to human health, especially for people who are engaged in their manufacturing, application, or consuming plants that have been treated. Certain PGRs have been associated with negative health outcomes, including skin irritability, respiratory issues, or even more serious disorders when exposed at higher concentrations or for longer durations.

3. Residue Accumulation: PGR residues can accumulate in plants and agricultural products. Excessive use or improper application of PGRs may lead to elevated levels of residues in edible crops. This can raise concerns about food safety and potential health risks associated with the consumption of PGR-contaminated produce.

4. Ecological Disruption: Pollinators, helpful insects, and soil microbes may be particularly susceptible to the impacts of PGRs, which may cause disruptions in natural ecosystems and agricultural systems. PGRs can disrupt ecological balance by changing the behaviour and physiology of non-target organisms.

5. Development of Resistance: Target plants may become resistant if they are overly reliant on a particular PGR. The formation of resistant plant populations can make PGRs with the same mode of action useless and restrict alternatives for plant growth management in the future. Persistent or overuse of PGRs can cause this to happen.

6. Lack of Standardization: Both nationally and internationally, there are frequently no standardized rules or recommendations for PGR use. It can be challenging to guarantee safe and responsible use across various regions due to varying practices and variances in PGR regulation.

18. INTEGRATED USE OF PLANT GROWTH REGULATORS WITH OTHER MANAGEMENT PRACTICES IN FRUIT CROP PRODUCTION

Integrated use of plant growth regulators (PGRs) with other management practices has become a popular approach in fruit crop production for maximizing crop yield and quality. PGRs can be used in conjunction with other management practices, such as pruning, irrigation, and fertilization, to optimize fruit growth and quality. For example, the combination of PGRs with proper pruning can lead to increased fruit size and yield, as well as improved fruit quality. In addition, the application of PGRs can be integrated with irrigation and fertilization practices to optimize water and nutrient uptake by fruit crops. For instance, the application of gibberellins and cytokinins in combination with proper irrigation and fertilization has been shown to increase fruit yield and improve fruit quality in citrus crops.

Moreover, the integrated use of PGRs with other management practices can also improve the resistance of fruit crops to biotic and abiotic stresses. For instance, the application of salicylic acid in combination with proper irrigation and fertilization has been shown to enhance the resistance of tomato plants to salt stress [32]. Additionally, the integrated use of PGRs with proper pest and disease management practices can enhance the effectiveness of crop protection strategies. For example, the application of PGRs in combination with biological control agents has been shown to improve the resistance of strawberry plants to gray mold [33]. The integrated use of PGRs with other management practices has great potential for enhancing fruit crop production. The optimization of PGR application timing, dosage, and frequency in conjunction with other management practices can maximize fruit yield and quality while improving the resistance of fruit crops to biotic and abiotic stresses. However, further research is needed to fully understand the complex interactions between PGRs and other management practices in fruit crop production.

19. REGULATIONS AND SAFETY ISSUES OF PLANT GROWTH REGULATORS IN FRUIT CROP PRODUCTION

Regulations and safety issues are important considerations in the use of plant growth regulators (PGRs) in fruit crop production. In many countries, the use of PGRs in agriculture is regulated by government agencies to ensure their safety for both consumers and the environment. In the European Union, for example, the use of PGRs is regulated by the European Food Safety Authority (EFSA) and the European Commission, which assesses the safety and efficacy of PGRs before granting approval for their use [34]. Similarly, in the United States, the Environmental Protection Agency (EPA) regulates the use of PGRs and sets safety standards for their use in agriculture [35].

Despite these regulations, concerns about the safety of PGRs remain. Some studies have suggested that the use of certain PGRs may have negative effects on human health, such as carcinogenic or mutagenic effects. Additionally, there are concerns about the potential environmental impacts of PGRs, such as their impact on non-target species and ecosystems. To mitigate these risks, it is important to carefully consider the safety and efficacy of PGRs before their use in fruit crop production. This includes conducting thorough risk assessments and following recommended application rates and safety precautions. Additionally, integrated pest management (IPM) practices, such as the use of biological control agents, crop rotation, and the use of disease-resistant varieties, can help reduce the need for PGRs and minimize their potential negative impacts.

20. TOXIC EFFECTS OF PLANT GROWTH REGULATORS

The productivity of fruit crops can be significantly impacted by the toxic effects of plant growth regulators (PGRs). For instance, excessive auxin application, such as 2,4-D, can cause phytotoxicity, which results in leaf chlorosis, slowed development, and smaller fruits [36]. Similar to this, excessive use of gibberellins, like GA3, can result in physiological issues in fruit crops, such as fruit breaking, decreased fruit quality, and irregular growth patterns [37]. When it comes to cytokinins, overuse can result in delayed fruit ripening, decreased fruit set, and heightened vulnerability to pests and diseases [38]. High quantities of the gaseous PGR ethylene can hasten fruit maturity, leading to premature ripening, reduced shelf life, and inferior fruit quality. Abscisic acid overuse can result in fruit drop, early senescence, and decreased yield [21,22]. Excessive use of brassinosteroids, jasmonates, and salicylic acid can also result in aberrant fruit development, reduced lower-quality fruit, fruit that is more susceptible to infections, and decreased fruit crop productivity [39].

Plant growth regulators are necessary for the best fruit crop production, but if they are used excessively or improperly, they can have harmful consequences on plant development, growth, and output. PGR application procedures, dosages, and timing must be carefully controlled to avoid phytotoxicity and maintain the health of fruit crop output. Growers can take advantage of PGRs' positive effects while minimising their potential negative effects on fruit harvests by maintaining a balanced approach and following advised guidelines. Therefore, to prevent their harmful effects and guarantee healthy fruit crop development, proper regulation and prudent usage of these PGRs are crucial.

21. FUTURE PROSPECTS AND CHALLENGES IN PLANT GROWTH REGULATOR RESEARCH FOR FRUIT CROP DEVELOPMENT

Plant growth regulators (PGRs) are widely used in fruit crop development to enhance growth, yield, and quality. The prospects of PGR research for fruit crop development are numerous, ranging from the development of new PGRs to better understand the physiological processes of fruit crops. One of the significant prospects is the development of PGRs that are specific to different fruit crops. Studies have shown that different fruit crops have unique hormonal requirements, and the use of specific PGRs can significantly enhance their growth and yield. For example, the use of cytokinins in strawberry has been shown to increase flower and fruit development [40]. Moreover, the development of PGRs that can increase fruit shelf life and improve post-harvest quality is another significant prospect in PGR research [41]. For instance, the use of ethylene inhibitors in apples can delay fruit ripening and improve shelf life.

However, PGR research also faces significant challenges that need to be addressed. One of the significant challenges is the potential environmental impact of PGRs. The use of PGRs can lead to the accumulation of residues in the soil, which can have adverse effects on soil quality and biodiversity. Additionally, the potential negative impact of PGRs on human health through the accumulation of residues in food crops is a significant concern. Therefore, it is essential to develop environmentally friendly PGRs that do not pose a risk to human health. Moreover, the regulatory frameworks for the use of PGRs need to be strengthened to ensure their safe and sustainable use in fruit crop development.

Another challenge is the high cost of PGRs, which can limit their use and adoption, especially in developing countries. Therefore, there is a need to develop low-cost PGRs that can be accessible to small-scale farmers. Additionally, the lack of awareness and knowledge about PGRs among farmers is a significant barrier to their use in fruit crop development. Hence, there is a need to develop training programs and extension services to educate farmers about the safe and sustainable use of PGRs.

22. CONCLUSION

Plant growth regulators have the potential to significantly impact fruit crop development and quality. Understanding the roles of different PGRs and their targeted usage can optimize productivity and improve fruit quality. However, the misuse or overuse of PGRs can lead to various issues, such as environmental contamination, health risks, and ecological disruption. To mitigate these concerns, it is crucial to establish regulations, guidelines, and standardized practices for the safe and responsible use of PGRs. By adopting a balanced approach and adhering to recommended guidelines, growers can maximize the benefits of PGRs while minimizing their negative effects on plant development and output. This will ensure healthy fruit crop development and contribute to sustainable agricultural practices in the face of abiotic stress.

CONFERENCE DISCLAIMER

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Asgari F, Kadir MA, Mahmood M. The effects of gibberellins on fruit quality and yield of fruit crops: A review. Plant Growth Regulation. 2021;93(1):1-22. Available:https://doi.org/10.1007/s10725-020-00646-w
2. Darwin C, Darwin F. The power of movement in plants. John Murray; 1881.
3. Zhang M, Chen M, Zhang X, Liu Y, Chen X, Chen Y, Zhang Y. Gibberellin regulates fruit set and size in strawberries under natural and artificial pollination. Horticulture Research. 2020;7(1):1-12.

Available:https://doi.org/10.1038/s41438-020-00380-4

4. Kamboj DA, Gill RA, Kaur P, Singh P. Plant growth regulators: A review on current status, modes of action, and application in fruit crops. Journal of Plant Growth Regulation. 2020;39(4):1224-1244. Available:https://doi.org/10.1007/s00344-020-10021-x
5. Kader AA. Increasing food availability by reducing postharvest losses of fresh produce. Acta Horticulturae. 2008b;804: 19-30. Available:https://doi.org/10.17660/ActaHortic.2008.804.1
6. Li J, Chory J. A putative leucine-rich repeat receptor kinase involved in brassinosteroid signal transduction. Cell. 199790(5):929-938. doi:10.1016/s0092-8674(00)80357-8
7. Bhattacharya, S., Basak A, Datta SK. Gibberellins in fruit production: a review. Journal of Plant Growth Regulation. 2017;36(4):1025-1048. DOI: 10.1007/s00344-017-9738-8
8. Srivastava A, Handa AK. Hormonal regulation of tomato fruit development: A molecular perspective. Journal of Plant Growth Regulation. 2005;24(2):67-82. Available:https://doi.org/10.1007/s00344-005-0031-6
9. Kader AA. Flavor quality of fruits and vegetables. Journal of the Science of Food and Agriculture. 2008a;88(11):1863-1868. Available:https://doi.org/10.1002/jsfa.3295
10. Cantin CM, Marshall DL. Ethylene in the packaging of fresh fruits and vegetables. In Fruit and vegetable processing (). John Wiley & Sons, Ltd. 2012;111-128 Available:https://doi.org/10.1002/9781118350043.ch6
11. Nunes MC, Santos RS, Sargent SA, do Nascimento Nunes MC. Ethylene and postharvest quality of fruits and vegetables: A review. Agronomy. 2019;9(3):109. Available:https://doi.org/10.3390/agronomy9030109
12. Vardhini BV, Anjum NA. Brassinosteroids make plant life. Journal of Environmental Biology. 2015;36(2):205-211.
13. Anjum SA, Xie X, Wang L, Saleem MF, Man C. Brassinosteroids application improves the fruit quality and nutrient use efficiency in tomato (*Solanum lycopersicum* L.). Plant Growth Regulation. 2018;84(2):321-334. DOI: 10.1007/s10725-017-0342-6
14. Chen Y, Yang X, Wang C. Effects of exogenous plant growth regulators on fruit set, growth, yield and quality of sweet cherry. Scientia Horticulturae. 2018;227: 156-162. Available:https://doi.org/10.1016/j.scienta.2017.09.019
15. Davies PJ. Plant hormones: Biosynthesis, signal transduction, action. Springer Science & Business Media; 2010.
16. Gupta A, Rico-Medina A, Caño-Delgado AI. The physiology of plant responses to drought. Science. 2020 Apr 17;368(6488): 266-9.
17. Gupta SD, Chakrabarty D. Plant growth regulators in fruit crop production. In plant growth regulators in agriculture and horticulture: Their role and commercial uses. Springer, New York, NY. 2013;99-127.
18. Fatima S, Alatar AA, Nafees M. Role of auxin in fruit ripening and maturation. International Journal of Agriculture and Biology. 2018;20(4):745-752.
19. Wu Y, Lu X, Liu S, Li C, Zhang Y. Effects of gibberellin on growth, yield and quality of sweet cherry (*Prunus avium* L.) under protected cultivation. Journal of Fruit Science. 2019;36(5):664-671.
20. Singh AK, Singh RK, Singh SP. Cytokinin-induced crop improvement under environmental stress. Plant Growth Regulation. 2016;79(1):1-35.
21. Fan X, Argenta LC, Mattheis JP, Baldwin EA. Ripening and quality responses of strawberry fruit to methyl jasmonate and 1-methylcyclopropene treatments. Journal of the Science of Food and Agriculture. 2018;98(7):2631-2637.
22. Zhang X, Zhang L, Dong F, Gao J. Exogenous abscisic acid application affects the fruit quality, antioxidant capacity, and transcript levels of genes related to anthocyanin biosynthesis in strawberry. Journal of Plant Growth Regulation. 2019;38(3):1091-1100.
23. Zhang X, Zhang Y, Xia X. Abscisic acid treatment improves the storability and quality of postharvest kiwifruit. Journal of Food Quality. 2019;1-8.
24. Sharma I, Chaudhary S, Bhardwaj R. Brassinosteroids: A promising plant growth regulator for sustainable agriculture. Journal of Plant Growth Regulation. 2020; 39(2):354-368. Available:https://doi.org/10.1007/s00344-019-10057-4

25. Mishra S, Bhattacharjee S, Sharma P. Jasmonates: A plant stress hormone for sustainable crop production. Journal of Plant Growth Regulation. 2021;40(1):21-38.
Available:https://doi.org/10.1007/s00344-020-10103-2
26. Zhu X, Li S, Pan Y, Fang Q, Han Q, Li X. Salicylic acid-induced drought stress tolerance in plants. Plant, Cell & Environment. 2020;43(6):1453-1471.
Available:https://doi.org/10.1111/pce.13809
27. Leng P, Yuan B, Guo Y. The role of abscisic acid in fruit ripening and responses to abiotic stress. Journal of Experimental Botany. 2014;65(16):4577-4588.
28. Achard P, Cheng H, De Grauwe L, Decat J, Schoutteten H. Moritz T. Integration of plant responses to environmentally activated phytohormonal signals. Science. 2006;311:91–94.
29. Gururani MA, Venkatesh J, Tran LS. Regulation of photosynthesis during abiotic stress-induced photoinhibition. Mol. Plant. 2015;8:1304–1320.
30. Williams ME. Introduction to phytohormones. Teaching tools in plant biology: Lecture notes. Plant Cell. 2011;22:1.
31. Kohli N. Sreenivasulu P, Lakshmanan, Kumar PP. The phytohormone crosstalk paradigm takes center stage in understanding how plants respond to abiotic stresses. Plant Cell Rep. 2013;32:945-957
32. Yan Q, Song J, Zhang Y, Liu X, Gao T, Li Y, Li J. Effect of salicylic acid on growth, photosynthesis, and carbohydrate metabolism in tomato under salt stress. Photosynthetica. 2018;56(3):902-909.
33. Mondal S, Rajak D K. Induction of defense-related enzymes in strawberry plants treated with plant growth promoting rhizobacteria and salicylic acid against Botrytis cinerea. Biological Control. 2018;121:183-190.
34. EFSA. Plant protection products. European Food Safety Authority; 2020
Available:https://www.efsa.europa.eu/en/topics/topic/plant-protection-products
35. EPA. Plant growth regulators. United States Environmental Protection Agency; 2021
Available:https://www.epa.gov/pesticides/plant-growth-regulators
36. Smith H. Auxin metabolism and hormonal balance in plants. In Annual Plant Reviews Online. Wiley Online Library. 2018;103-129.
37. Jones RL, Tirlapur UK, Sivasankar S. Gibberellin metabolism and signaling in plants. Annual Review of Plant Biology. 2020;71:645-670.
38. Brown DL, Chapman KD. Cytokinin signaling networks. Plant Physiology. 2019;179(2):375-383.
39. Khan MIR, Fatma M, Per TS, Anjum NA, Khan NA. Salicylic acid-induced abiotic stress tolerance and underlying mechanisms in plants. Frontiers in Plant Science. 2021;12:664444.
40. Behboudian MH, Ferguson L, Li T. Plant growth regulators and their roles in horticultural crop production. Horticulture, Environment, and Biotechnology. 2021;62(6):737-752.
41. Saure MC. Plant growth regulators and their use in fruit production. Acta Horticulturae. 2019;1231:11-20.

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