Plant growth regulator-mediated response under abiotic stress: A review

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ARTICLE INFO

ABSTRACT

Plant growth regulators (PGRs) are essential for regulating how plants respond to abiotic stress by activating their proliferation and development pathways. Abiotic stressors that plants encounter during their development cycle are attempted to be managed by growth regulators. Growth hormones are chemical messengers that control a plant's regular growth and responsiveness to external stimuli. They control tissue development and differentiation, which controls how quickly plants develop. PGRs are necessary for the plant's reaction to abiotic stress. In addition, hormones in plants allow them to recognize adverse environmental circumstances. The plants' ability to biosynthesize phytohormones allows them to adapt to their environment. Abscisic acid aids plants in dealing with salt and drought stress, whereas ethylene aids plants in salinity, overwatering, cold, and drought. Plants may recover from mechanical damage and drought stress with the help of jasmonic acid. Research has also offered some tips for maximizing the ability of growth regulators to strengthen crops' tolerance to abiotic stressors.

ARTICLE HIGHLIGHTS

- PGRs play a vital role in helping plants to tolerate abiotic stress.
- Research on the use of PGRs to improve crop tolerance to abiotic stress is promising.
- PGRs can help plants to tolerate abiotic stress by altering their physiology and morphology.
- PGRs have the potential to be used as sustainable tools to mitigate the effects of climate change on agriculture.

1. INTRODUCTION

Global agricultural output suffers enormous losses due to abiotic stress, which comprises elements such as salt, drought, and severe temperatures [1]. The degree to which plants react to abiotic stressors varies. The stress factors already present have been amplified by several human activities. They are unable to realize their full genetic potential due to all these stressors, which also reduce agricultural output. Abiotic stressors are becoming the main danger to agriculture productivity globally due to increased worries about climate uncertainty [2]. Complex abiotic plant stress conditions arise due to the intricate interplay of stress impacts and responses across various levels of plant structure. To enhance their resilience against stressors, plants possess intrinsic biochemical mechanisms that function at the cellular level [3]. Heavy metals adversely affect plant's processes such as photosynthesis, respiration, division and elongation of cells, and mineral nutrition. [4,5]. Reactive oxygen species (ROS) is produced as a result of their harmful effects. The structure of cellular processes is harmed by the oxidative stress caused by heavy metal stress [6]. All these toxic effects reduce the growth and yields of plants, in severe cases, may also result in the plant death [4,7]. To maximize crop growth and production under stressful circumstances, knowledge of the processes connected to these mechanisms is essential. The regulating activities of plant growth regulators (PGR) are one of the significant and frequently studied elements of abiotic stress tolerance [8]. PGR is chemicals that have a significant impact on how plants differentiate and grow. They serve as chemical messengers for intracellular communication in addition. Auxins and gibberellins (GAS) primarily promote cell lengthening; cytokinins, which promote cell division, and fruit ripening, among other plant processes. Abscisic acid (ABA) promotes plant senescence and the disintegration of plant parts while also assisting in the preservation of plant water

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relations [9]. The steroid hormones polyamines and brassinosteroids, in addition to these five naturally occurring PGR types, are also known to have impacts on plant growth regulation and are the focus of extensive investigation [10]. Each of these natural PGRs can affect nearly all aspects of plant growth and development to increase stress resistance, despite being unique in terms of both chemical properties and the way they typically exhibit typical responses [11]. It has been demonstrated that increasing endogenous PGR levels under stressful conditions affect the growth of stress tolerance by aiding plants in several ways. Due to improvements achieved in the exact analysis of PGR employing reliable and effective physiochemical techniques as well as improvements made in molecular and genetic approaches, PGR research has drastically changed in connection to plant adaptation to abiotic challenges. A broad variety of compounds have been synthesized with clearly defined growth regulatory roles, in addition to the naturally occurring PGR. Numerous of them have been demonstrated to have a variety of applications for boosting plant growth, production, and output quality. In addition, significant work has been done in showing how such PGR might potentially improve agricultural plants' abiotic stress responses. The numerous physiological and pharmacological components of PGR in connection to its participation in abiotic stress are discussed in this review.

2. METHODOLOGY

2.1. Literature Search

Articles from PubMed, Google Scholar, and Scopus were used to compile the data. Plant growth, hormone, stress, biotic stress, abiotic stress, ABA, GAS, jasmonates (JAs), and heavy metal were the search terms utilized. There were many different kinds of pertinent books, summaries, and articles. The electronic databases were searched, and 400 articles were found. After 2000, papers that appeared in credible scientific publications were included. After duplicate entries were eliminated, there were 250 articles left. The authors next checked the titles and abstracts of the remaining papers for data relevance. One hundred and fifty articles were created as a result of this approach. A total of 109 studies were chosen for the investigation after applying the inclusion (including specifically matched articles from our study related to PGR and stress) and exclusion criteria (excluding duplicate articles, personal opinions, book chapters, conference abstracts, full copies not available, and low-quality paper).

## 3. ABA MECHANISMS AND FUNCTION

Early in the 1960s, researchers established that the phytohormone ABA released seeds from dormancy [12]. Later, research revealed that it may have a part in plant development and plant stress adaptation [13]. ABA is produced in plastids through the methylerythritol phosphate route from carotenoids, a derivative of isopentenyl diphosphate [14-17]. ABA, often referred to as the "stress hormone," plays a crucial role in regulating multiple processes that enhance a plant's ability to withstand stress. Stressful conditions are known to impact about 10% of the expression of genes involved in protein-coding [18]. This hormone controls many crucial plant processes, such as seed dormancy, nutrition storage in growing seeds, tolerance to desiccation, and the cessation of embryonic development during seed maturation [18-20]. In addition, it is crucial for the production of various osmolytes and proteins. Depending on the type of disease, ABA may positively or negatively affect the defense response [21-23]. The potential of plants to adapt to drought circumstances is made possible by ABA's involvement in several plant growth processes and its stress-related responses. In times of drought stress, ABA induces the closure of stomata, which, in

turn, reduces water loss by lowering the transpiration rate. Moreover, ABA fosters the elongation of root cells and gradually enhances hydraulic conductivity, facilitating plants in recovering from water scarcity [24]. For instance, ABA affects how seeds develop and spread, how water is regulated in plant bodies through the opening and closing of stomata, and how plants react to environmental stresses [Figure 1]. The concentration of ABA in the leaves rises when there is a water deficit because it is biosynthesized in the roots and transported there by the xylem. The production and redistribution of ABA during the abiotic stress response led to stomatal closure and a decrease in transpiration rate, which restricts cell growth. ABA signals through phosphatases and kinases, which upregulate hormone-responsive transcription factors and fast responses to various stresses [25]. In addition, ABA regulates physiological responses in plants subjected to abiotic challenges by interacting with other phytohormones and mediating physiological responses through its signaling. It is crucial to remember that ABA mobilizes and activates a number of biochemical defenses, such as the biosynthesis of proline, antioxidants, ROS detoxifying enzymes, heat shock proteins, and unsaturated fatty acids, as well as the strengthening of cuticular waxes, which aids plants in partially reversing the negative effects of abiotic stress. Reducing stress causes the ABA level to return to pre-stressed levels and reverses the stress-induced rise [26]. Increased levels of ABA enable plants to reduce water loss through the closure of stomata, while simultaneously enhancing the plant's water status due to improved root hydraulic conductivity [27]. ABA also helps the root and aboveground sections of the plant communicate through stomatal closure, metabolic adjustments, and gene expression [28].

Since this regulatory mechanism is more strongly influenced by soil moisture levels rather than the water content of leaves, it is likely that ABA functions as a chemical signal produced by stressed roots [29]. The responsiveness of stomata to ABA is impacted by multiple factors, such as leaf age, environmental conditions (including the plant's nutritional status), the ionic composition of the xylem sap, and the water content of the leaves. These variables influence the sensitivity of stomata to ABA and can vary among different plant species and cultivars. The differences in ABA supply to the active area of guard cells may explain the variations in ABA-mediated stomatal responses [30]. Under stressful conditions, the volume of guard cells actively responds to signals to minimize carbon dioxide (CO_2) efflux for photosynthesis and reduce transpirational water loss [31]. The increase in ABA within guard cells prompts stomatal closure, leading to a reduction in transpirational water loss. In response to stress, gene expression related to stress protection produces essential proteins for signal transduction mechanisms within cells. The regulation of stress-inducible gene expression occurs through the interaction of transcription factors with specific cis-regulatory regions [32].

4. GAS MECHANISMS AND FUNCTION

One of the most well-known and earliest subclasses of regulatory hormones, the GAs are involved in a variety of plant developmental processes, including seed germination, inter-nodal elongation, forced blooming, and fruit formation [33]. Recent investigations utilized modern biochemical and genetic methods to investigate the genetic foundation, genes encoding the manufacture of GAs, and deactivation enzymes [34]. The GAs group has more than 250 members, although just a few of them play significant physiological roles in plant development [35]. The control of the GAs at the cellular level is intricate. For instance, enzymes from tiny multi-genic families that each play a distinct expression pattern control the phases of the GAs metabolic pathway. However, GA biosynthesis is highly correlated
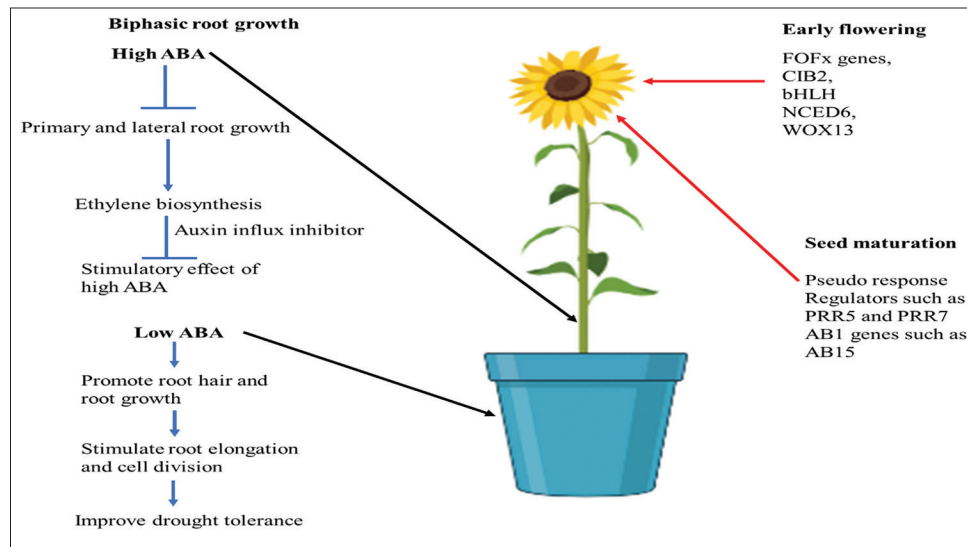
Figure 1: The underlying molecular mechanisms of drought response in plants mediated by abscisic acid.

with two gene families that encode GAs: GA20-oxidases (GA20ox) and can accelerate the last steps in the creation of bioactive GAs. Nuclear-localized GID1 is the receptor protein for GA, and binding of GA to the receptor protein facilitates interactions with the repressor protein DELLA [36]. The DELLA protein's protein-protein interaction domain interacts with the F-Box protein, which, then, calls for the SLY1 complex to be ubiquitinated by the SCF-E3 ligase complex [37]. The DELLA repressor protein is ubiquitinated by the 26S proteasome and is then degraded, helping to bind transcription factors to the GA-inducible genes' promoter region [38]. Therefore, GA mediates signaling by breaking down repressor proteins, which cause a variety of biochemical reactions [39]. Thus, GA generated in plant tissues, whether from endogenous production or exogenous application, lessens the negative effects of stress, and aids in developing plants' stress tolerance [40]. For instance, the rice seed yield and tolerance to drought stress were improved when endogenous GA levels were reduced by GA2ox6 ectopic expression under water deficiency conditions. GA's role in redox equilibrium, plants can adapt to less-than-ideal growth environments. GRAS transcription factors are essential in plant growth and signaling [41]. Liu *et al*. showed that abiotic stress treatments such as NaC and H_2O_2 increased the GRAS40 expression in tomatoes [42]. During the vegetative and reproductive stages of tomato development, SlGRAS40 is interrelated with auxin/GA pathways. Salt and drought resistance were also developed through transgenic SlGRAS40 plant expression [43].

5. JAS MECHANISMS AND FUNCTIONS

Methyl jasmonate, jasmonic acid (JA), and jasmonoyl isoleucine are significant members of the family of JAs, which are naturally occurring plant oxylipins [44]. In addition, JAs help plants defend themselves from disease and insect damage. According to recent studies, JAs can alter how plants develop and respond to various abiotic challenges, including those caused by heavy metals, heat, light, drought, salinity, and flooding [45]. JAs generally increase gene expression and control some physiological and biochemical responses to protect plants from the harmful impacts of environmental stressors.

The JAs, which include JA and its derivatives, are hormones produced by plants that control a number of developmental processes, such as the growth of roots, the development of stamens, flowering, and the aging of leaves. In addition, they increase resistance to abiotic stressors such as ozone, ultraviolet rays, hot temperatures, and cold. JAs are well-known stress hormones generated from lipids that regulate how plants respond to biotic and abiotic stresses, including pathogen infections and herbivore attacks [46]. Pathogen infections and insect bites are the two main types of plant biotic stressors. They both seriously impair crop development and production, affecting the economy and human health [47]. JAs can increase antioxidant capacity and the production of various osmoprotectants, such as proline and glycine betaine, helping maintain plant cells' integrity under various biotic conditions [48]. The photoassimilates can also be remobilized to the vegetative sinks by these growth regulators, enhancing plant growth under adverse conditions. Plants can use direct defense systems, such as creating harmful substances, phytoalexins, and proteinase inhibitors to combat infections in herbivores [49].

JAs' physiological and biochemical effects on *Vicia faba* and *Artemisia absinthium* (leaf senescence) have been documented for the 1st time (growth inhibition) [50,51]. This group of growth regulators affects plant species in a variety of ways, from promoting physiological processes to inhibiting them. Smaller petioles were produced by plants treated with JAs than control plants [52]. Barley, plants treated with JA (2.5 106 and 2.5 104 147 M) had slower seedling development. The growth of the seedlings was unaffected by the lower concentration, though [53]. Jasmonate concentrations above 50 mM accelerate the aging process in leaves by causing chlorophyll damage and the breakdown of chloroplast proteins [54].

6. METHYL JASMONATE BIOSYNTHESIS AND ACCUMULATION

JAs are cyclopentanones that are formed from fatty acids and are members of the family of oxylipins, which are produced by plants through the oxidative metabolism of polyunsaturated fatty acids. JAs are present in almost all higher plants, but their concentrations are higher in flowering and reproductive tissues and significantly lower in mature leaves and roots [55].

The octadecanoid pathway in plants is used to synthesize that JAs Linolenic acid synthesis in plants is facilitated by phospholipase D and deficient anther dehiscence in the lipids of the chloroplast and anther plastid membranes, respectively. JA, which is created from linolenic

acid as a precursor, is, then, oxygenated by the enzymes lipoxygenase, allene oxide synthase, and allene oxide cyclase to create 12-oxo-phytodienoic acid (AOC). After that, OPDA is converted into JA and, then, catabolized by JA carboxyl methyltransferase [56].

7. METHYL JASMONATE (EXOGENOUS) IN REDUCING ABIOTIC STRESSORS IN PLANTS

7.1. Salt Stress

One of the biggest issues with agriculture globally is salinity, especially in arid and semiarid areas. Heavy salt stress affects plants in three different ways. First, the osmotic action of salt in the soil decreases water retention and nutrient imbalances, such as competition between Na^+ and K^+, interfering with the uptake of critical minerals [57-59].

7.2. Drought Stress

A key environmental stressor that can trigger anxiety is drought stress. ROS affects several organelles that control plant growth and development, lower plant output, and speed up lipid oxidation, nucleic acid breakdown, and chlorophyll loss. These occurrences usually result in oxidative damage and hasten the senescence of plants [60]. Plants can use various defense strategies in response to drought stress by changing their cellular metabolism and increasing the activity of oxygen-scavenging enzymes.

This means that MeJA effectively improves plants' capacity to endure drought by altering a variety of biochemical and physiological traits, such as increasing the activity of oxidative enzymes and organic osmoprotectants [61] [Figure 2].

7.3. Micronutrients Toxicity

Although boron is a crucial mineral for the healthy growth of higher plants, there is a very little window between its lack and toxicity [62]. High levels of boron in the soil can increase the production of ROS, cause lipid peroxidation and H_2O_2 to build up in plant cells and tissues, and reduce plant development and crop output [63,64].

7.4. Chilling Stress

Chilling stress is a post-harvest concern that has positive economic implications. Physiological abnormalities brought on by chilling damage symptoms might interfere with normal cell metabolism, break down unsaturated fatty acids, and induce peroxidation in plant tissues with membrane lipidosis. MeJA has successfully treat tomatoes chilling damage [65], and loquat [66]. It causes the activation of some defensive substances (such as heat shock proteins and phenolic compounds) to shield these crops' cell membranes against chilling damage. By modulating arginine metabolism and increasing the production of heat-shock proteins in tomato, the exogenous administration of MeJA also reduces the effects of chilling injury [67].

7.5. Biochemical Parameters of Plants Modulated by Heavy Metals Stress

Oxidative stress is brought on by heavy metal concentrations above a certain threshold, which harms plant tissues and changes their morphophysiological characteristics [68,69]. Copper and cadmium reduced cell extension, diminished potassium leaf uptake, and inhibited soil-borne root and shoot growth. They also prevented photosynthesis in *Phaseolus coccineus* L. due to its extraordinary capacity to respond to environmental metal toxicity through a system involving signaling molecules that might strengthen stress reaction responses [70]. The best signaling chemicals have been identified as Jas [71]. MeJA administered exogenously so significantly lessens plant heavy metal damage by increasing enzyme activity and secondary metabolites. Heavy metal toxicity leads to the generation of ROS in plants such as non-radical molecules (singlet oxygen [O2] and hydrogen peroxide [H_2O2]) and free radicals (hydroxyl radical, ·OH; superoxide anion, $O_2^{·-}$; alkoxy radical, RO·; and hydroperoxyl radical, $HO_2^·$) [3] [Table 1]. Production of ROS is a part of normal metabolic processes occurring in cellular organelles such as peroxisomes, chloroplasts, and mitochondria, but their overaccumulation under heavy metal toxicity leads to damage to cellular molecules such as carbohydrates, lipids, deoxyribonucleic acid, and proteins [72,73]. Cu and Fe undergo auto-oxidation, resulting
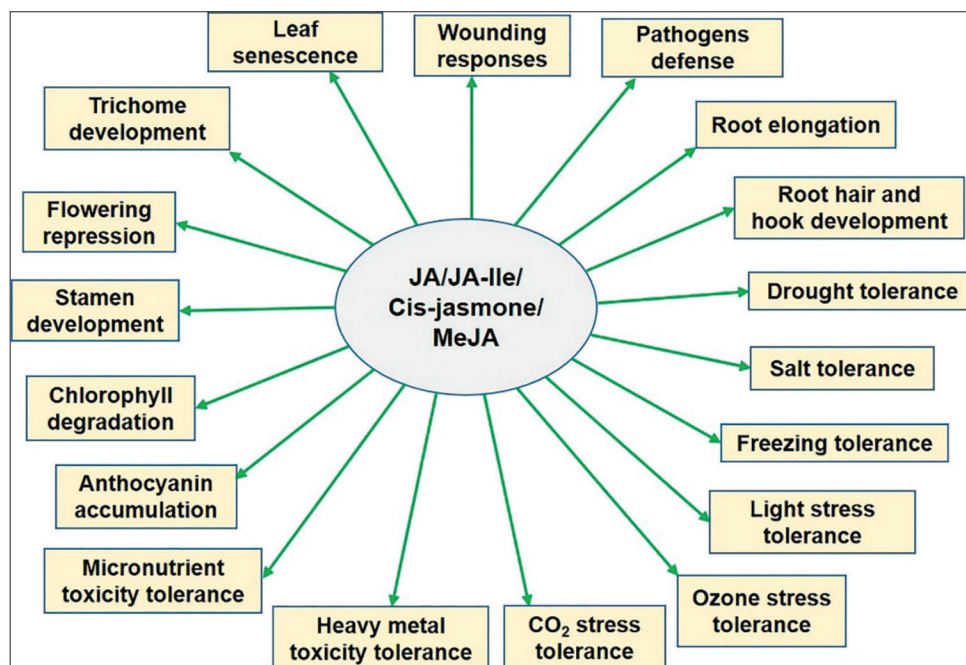

Figure 2: A layout of the different potentials of jasmonic acid and its derivatives.

Table 1: Effect of heavy metals on plant growth metrics.

S. No.	Plant	Heavy metal	Metal doses	Parameter affected	References
1.	*Artemisia annua*	Al	0.01, 0.10, 1.00 and 10 mM	Shoot and root length; dry weight; and dry leaf yield	[86]
2.	*Brassica juncea*	Cu	3–5 ppm	Shoot and root length	[87]
4.	*Brassica juncea* and *Brassica napus*	Cd	10 and 30 mg kg^{-1}	Plant height, weight, and total leaf area	[80]
5.	*Brassica napus*	Cd	10 μM	Root and shoot dry and fresh weight	[88]
6.	*Cenchrus ciliaris*	Cd	30 and 60 mg l^{-1}	Shoot and root fresh weight	[89]
7.	*Cicer arietinum*	Cd	150 μM	Shoot and root length and weight	[90]
8.	*Cicer arietinum*	Cd	25, 75, 150 μg mL^{-1}	Root length; number of leaves and branches	[91]
9.	*Cicer arietinum*	As	5 mg/kg^{-1}	Shoot and root dry weight	[92]
10.	*Citrus aurantium*	Cr	200 ppm	Shoot and root length	[93]
12.	*Cynodon dactylon*	Cd	30 and 60 mg l^{-1}	Shoot and root fresh weight	[89]
13.	*Eichhornia crassipes* (Mart.)	Pb	100, 200, 400, 600, 800 and 1000 mg l^{-1}	Plant height, dry weight, shoot length, and root length	[94]
20.	*Ipomoea aquatica*	As	20 and 40 mg kg^{-1}	Plant height and biomass	[95]
21.	*Lactuca sativa*	Cd	1, 10 and 50 μM	Plant dry weight	[96]
22.	*Lactuca sativa*	Cr	5, 10 and 20 mg l^{-1}	Root and leaf length; and fresh seedling weight	[97]
23.	*Laguncularia racemosa*	Cr	0.05 and 0.50 mg l^{-1}	Stem length; root and stem dry weight; and total dry weight	[98]
24.	*Lolium perenne*	As	100 mg/kg^{-1}	Plant dry weight	[99]
25.	*Oryza sativa* cultivars Indica, Ediget, X-Jigna, and Furat	Pb	1.2 mM	Plant height, tillers number/plant, panicles number/plant, and spikelets number/panicle	[81]
28.	*Pisum sativum*	Cd	1 and 6 mM	Shoot fresh biomass; and shoot dry biomass	[100]
29.	*Pteris cretica*	As	20 and 100 mg kg^{-1}	Shoot and root dry biomass	[101]
30.	*Raphanus sativus*	Pb	2.5 mM	Plant height; plant weight; and plant dry weight	[102]
31.	*Sassafras tzumu*	Cd	5, 20, 50 and 100 mg/kg^{-1}	Plant height; root, branch and leaf biomass	[4]
33.	*Sorghum bicolor*	Cr	2 and 4 ppm	Shoot and root length; fresh leaf weight; and leaf dry weight	[103]
34.	*Spinacia oleracea*	Pb	1.5, 3 and 15 mM	Plant fresh and dry weight	[104]
35.	*Spinacia oleracea*	As	20 and 100 mg/kg^{-1}	Shoot and root dry biomass	[101]
39.	*Vigna radiata*	Cr	120 μM	Shoot and root length; shoot and root fresh weight; shoot and root dry weight	[105]
42.	*Zea mays*	Cd	10 and 20 mg l^{-1}	Shoot and root dry weight	[106]
43.	*Zea mays*	Cd	400 and 800 μmol l^{-1}	Root length; plant height; plant weight; and plant dry weight	[107,108]
44.	*Zea mays*	As	3, 10 and 30 mg kg^{-1}	Shoot and root dry weight	[108]

in ROS generation mediated by a fenton-type reaction [74]. In a study by Georgiadou *et al.* (2018), Zn and Cu toxicity in *Ocimum basilicum* caused a reduction in overall antioxidant capacity and concentration of total proteins. Cu and Zn toxicity also caused oxidative or nitrosative stress, as observed in increased concentrations of H_2O_2 and NO in the *Ocimum basilicum* plants [75]. The effect of three heavy metals at 0, 500, 1000, and 2000/mg/kg^{-1} concentrations was explored on bamboo (*Indocalamus latifolius*) plants grown in a greenhouse [76]. It was revealed that the concentrations (1000 and 2000/mg/kg^{-1}) induced a reduction in a number of indices related to photosynthesis, such as intercellular CO_2 concentration (μmol CO_2 mol^{-1}), photosynthetic rate (μmol CO_2 m^{-2}/s^{-1}), and conductance of H_2O (mol H_2O m^{-2}/s^{-1}). A decline was also observed in net assimilation and transpiration. A corresponding decline was also observed in morphological indices such as the reduced number of emerged plants and reduced shoot length [76]. Cd stress adversely affected the chlorophyll synthesis and modulated the photosystem I (PS I) and photosystem II (PS II) in tobacco leaves [5]. Downregulation of ROS scavenging and reduced expression of proteins linked with ferredoxin-dependent nitrogen metabolism caused blockage of photosynthetic electron transport. It severely inhibited both the photosystems (PS I and PS II). Downward trend in photosynthetic light-response parameters and photosynthetic gas exchange parameters with increasing concentrations of Cd (5, 20, 50, and 100 mg/kg) in Sassafras tzumu seedlings indicates a significant negative impact of cadmium contamination on the photosynthetic efficiency and overall physiological health of these seedlings [4]. Young plants of *Virola surinamensis* were evaluated for responses to different Cd concentrations (30, 45, and 60/mg/l^{-1}). Cd stress caused a reduction in stomatal conductance, leaf water potential, and transpiration. In addition, the reduced maximum photochemical efficiency and electron transport rate were accompanied by a decline in photosynthesis [77].

7.5.1. Effect on plant growth parameters

Chen *et al.* [74] investigated the toxicity of copper in rice seedlings the length of the roots gradually decreased as the $CuSO_4$ concentration rose from 20 to 50 M. The shoot length, however, was unaffected [78]. Bimetal combinations of heavy metals Cd, Zn, Cu, and Pb treatment were given to *Brassica juncea* plants [79]. Combinations of PbCd, CuZn, and CuCd caused the greatest inhibition of *B. juncea* seedlings biomass growth. The inhibitory effect was weakest in the seedlings treated with ZnCd combination. The metal combinations also caused necrotic spots on the plant leaves and also inhibited the leaf surface growth. *B. juncea* and *B. napus* plants had shown a reduction in fresh weight, plant height and total leaf area when grown under the stress of Cd metal (10 and 30 mg/kg) [80]. *Pisum sativum* plants grown in polluted and non-polluted soils of South Cairo and Giza provinces of Egypt were compared [7]. Analysis of soil of polluted farms revealed the presence of heavy metals such as Pb, Zn, As, Fe, V, Co, and Cd, the concentrations of which were higher than the tolerable limits. It was found that the fresh weight (1654 kg/acre) and dry weight (126 kg/acre) of the plants collected from the polluted farms reduced significantly as compared to the plants collected from the non-polluted farms (5223 kg/acre and 404 kg/acre, respectively). Fruit production also decreased by 85.2% in the plants grown in polluted soil [7]. Rice cultivars – Indica, Ediget, X-Jigna, and Furat were grown in soil supplied with 0.6 mM and 1.2 mM solution of Pb. The soil was treated with the Pb solution 1 month before the transplantation of rice seedlings. Agronomic traits of the cultivars, such as height of the plants, tillers number/plant, panicles number/plant, and spikelets number/panicle, reduced significantly under the effect of 1.2 mM concentration of Pb [81]. Cu stress' effects on the morphology of *Cannabis sativa* plants have been investigated. Cu treatment to the plants decreased their dry weights and shoot and root lengths [82]. Three cereal crops, *Zea mays* L., *Triticum aestivum* L., and *Sorghum bicolor* L., were examined to determine how detrimental amounts of Cu affected them [83]. After 4 weeks of Cu treatment, it was discovered that all growth features, including the fresh weight of shoots and roots and the dried weight of roots, had decreased (75 mol/l^{-1}). The length and intensity of the Cu treatment were positively correlated with the decline. All of the growth indices for *Phragmites australis* and *Salix purpurea*, including total fresh weight, shoot length, and number of roots, significantly decreased [84]. *S. tzumu* seedlings grown under Cd stress (5, 20, 50, and 100/mg/kg^{-1}) showed a decrease in root, branch, and leaf biomass as well as reduced plant height [4]. Reduction in the number and diameter of xylem vessels was recorded in *Aechmea blanchetiana* plant due to Pb toxicity [85]. Xylem vessels are the main conducting elements in angiospermic plants and are responsible for the conduction of water and mineral elements from roots to all other plant parts. Reduction in their number and diameter can significantly lower the supply of water and minerals to plant parts, reducing their overall growth. Table 1 displays how different heavy metals affect the factors of plant growth.

8. CONCLUSIONS AND FUTURE PERSPECTIVES

Plant hormones play a crucial role in the growth and development of plants under abiotic stressors. The stress circumstances change the quantities of these compounds that aid in plant adaptation by affecting how well stomata function, plant water balance, and antioxidant status are maintained. In response to stress, endogenous PGR levels in plants either rise or fall, depending on the cultivar, the length of the stress, and the severity of the stress. Although stressed plants always exhibited a rise in ABA and a reduction in cytokinins, different abiotic stress stimuli have distinct impacts on GAS, auxin, and polyamine levels.

Recent years have seen significant advancements in our knowledge of the mechanisms controlling the biosynthesis, metabolism, and signaling functions of naturally occurring PGR. In addition, PGR commonly modifies gene expression by initiating or inhibiting the degradation of transcriptional regulators. Progress in understanding the molecular underpinnings of hormonal physiology has resulted in the discovery of genes involved in manufacturing various PGR and genes that code for their receptors. In addition, knowledge of stress-related gene modifications has been essential in identifying the function of PGR in plants' response to abiotic stressors. Efforts must be made to use their advantages as a different tool for managing abiotic stressors. Furthermore, it is widely known that polyamines and brassinosteroids have a role in regulatory plant development and stress tolerance. However, additional investigation is required to determine the mechanism behind their stress-protective functions, particularly in light of their interactions and interrelationships with other PGR and stress-responsive genes.

9. AUTHORS' CONTRIBUTIONS

According to the guidelines and criteria established by the International Committee of Medical Journal Editors, all authors fulfilled the necessary qualifications to be considered as authors. They collectively agreed to submit the article to the current journal, provided final approval of the version to be published, participated in the conception and design of the study, collected and analyzed data, critically revised the article for important intellectual content, and accepted accountability for all aspects of the work.

10. FUNDING

There is no funding to report.

11. CONFLICTS OF INTEREST

The authors report no financial or any other conflicts of interest in this work.

12. ETHICAL APPROVALS

This study does not involve experiments on animals or human subjects.

13. DATA AVAILABILITY

In this review article, all the data that were produced and examined are included in the study.

14. PUBLISHER'S NOTE

This journal remains neutral with regard to jurisdictional claims in published institutional affiliation.

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