DOI: https://doi.org

EcoBiotics: Journal of Animal & Plant Sciences

journal homepage: https://rjsaonline.org/index.php/EcoBiotics/

Evaluation of Plant Growth Regulators under Stress Conditions

Bilal Ahmed Awan[1]

[1]Institute of Horticultural Sciences, University of Agriculture Faisalabad Pakistan

Email: bilal.awan@uaf.edu.pk

ARTICLE INFO

Received:
September 26, 2025
Revised:
October 17, 2025
Accepted:
November 07, 2025
Available Online:
November 13, 2025

Keywords:
Stress Tolerance, Plant Growth Regulators, Hormonal Crosstalk, Salinity, Drought, Abiotic Stress, Osmotic Adjustment.

Corresponding Author:
bilal.awan@uaf.edu.pk

ABSTRACT

Plant Growth Regulators (PGRs) are biochemical agents of great importance, which regulate physiological activities in plants especially in situations of abiotic and biotic stresses. Drought, salinity, heat, and cold, and heavy metals are among the stress factors that can affect the growth of plants and crop yield negatively. The implementation of PGRs like auxins, gibberellins, cytokinins, abscisic acid, salicylic acid, jasmonates, brassinosteroids, and ethylene modulators has been demonstrated to reduce the effects of the stress through the improvement of stress tolerance mechanisms including antioxidant enzyme activity, osmolyte accumulation, and the regulation of the expression of genes. This paper assesses the effectiveness of various PGRs in improving plant stress resilience in any form of stress using physiological, biochemical and molecular methods. Findings indicate that stress-induced plant performance is dramatically enhanced by the selection of PGR, which implies their possible use in sustainable farming.

Introduction

The plants go through diverse stress conditions during the course of their lifespan which may seriously impair growth, development, and productivity. Other abiotic stresses like drought, salinity, extreme temperatures and heavy metal toxicity restrict the agricultural productivity across the world (Zhu, 2016). They interfere with the homeostasis of plant cells, disrupt photosynthesis, cause oxidative stress and change the nutrient uptake, which typically leads to significant losses in yields (Hussain et al., 2018; Farooq et al., 2009). Plants have developed various adaptive strategies to counteract such impacts, such as antioxidant defense system, osmotic adaptation, stress-responsive expression and hormonal signaling (Bohnert et al., 2006; Ashraf and Foolad, 2007).

Plant hormones and plant growth regulators (PGRs) are among the endogenous mechanisms that are critical in controlling growth and development in normal and stressful environments. PGRs are natural or synthetic organic compounds that affect physiological processes in minute concentrations (Davies, 2010). Stress perception and response networks include classic hormones, including auxins, gibberellins (GAs), cytokinins (CKs), ethylene (ET), abscisic acid (ABA), salicylic acid (SA), jasmonic acid (JA) and brassinosteroids (BRs), all of which play a central role in networks related to environmental stimuli (Peleg and Blumwald, 2011). The complex crosstalk between the PGRs and the stress-signaling pathways allows the plants to adjust the growth finely and reallocate the resources, as well as trigger the defense systems in response to the unfavorable conditions.

Stressors such as drought inhibit the growth of leaf, stomatal conductance and photosynthetic capacity, restricting the acquisition of biomass (Farooq et al., 2009). ABA is also quick to accumulate during drought and initiate closure of stomata, production of osmoprotectants and stress responsive genes, which increases drought tolerance (Cutler et al., 2010). On the same note, salinity stress is the cause of ion imbalance and oxidative stress. Some of the salinity effects can be reversed with the help of cytokinins and brassinosteroids, which improves the antioxidant levels of enzymes and alters the ionic transport (Khan et al., 2014; Vardhini and Anjum, 2015). The use of auxin and gibberellins has been demonstrated as a way of stimulating root development and biomass increase even in saline or water deficit conditions that allow enhanced uptake of water and nutrients (Khan et al., 2016; Rady et al., 2019).

There are heat and cold stresses that influence membrane stability, as well as protein stability. Salicylic acid has been effectively investigated with regard to thermotolerance and cold tolerance, via the activation of heat shock proteins and antioxidative defense signaling (Horvath et al., 2007; Miura and Tada, 2014). Also involved in abiotic stress tolerance is jasmonates, which have been shown to regulate ROS signaling and expression of stress genes and are also known to defend against pathogens and herbivores (Westernack and Hause, 2013). Brassinosteroids have become effective stress-tolerance modulators, because they can adjust antioxidant protective systems and control stress-responsive gene expression (Divi et al., 2010).

The reaction of plants to multiple stresses is usually different compared to the way plants react to individual stresses because of the intricate interactions between signaling (Suzuki et al., 2014). In turn, the assessment of the contribution of PGRs in multifactorial stress conditions is the key to the development of strategies that would increase resilience to stress. PGRs have also been reported to enhance crop response to drought, salinity, heat and heavy metal stress by applying PGRs as seed priming, foliar sprays, or soil amendments (Hayat et al., 2012; Nawaz et al., 2013). The mechanisms of stress alleviation mentioned are mediated by PGR: the increased activities of antioxidant enzymes (e.g., superoxide dismutase, catalase, peroxidase), the osmotic accumulation of molecules (e.g., proline, soluble sugars), the stability of the membrane, and the biosynthesis and signaling of phytohormones (Khan et al., 2014; Rady et al., 2019).

Although the studies regarding individual PGRs and single stressors have been carried out extensively, there is a disjointed assessment of multiple PGRs in diverse stress environments on physiological, biochemical, and molecular scale. These analyses are critical in determining effective PGR combinations as well as how they work. Further insight into the PGR-regulated stress tolerance processes will be of use to breeding and agronomic initiatives aimed at supporting crop production in more stressful conditions, particularly in climatic change conditions (Tardieu et al., 2018).

The current study will determine the effectiveness of chosen PGRs in alleviating the negative impact of major abiotic stresses. Through observing the physiological performance, stress biomarkers and antioxidant response and growth parameters of PGR-treated plants during drought, salinity, and heat stress, the research aims to offer information on the possibility of using PGRs to improve stress tolerance in crops.

The main aim of the research is to assess the mitigating role of various Plant Growth Regulators (PGRs), as auxins, gibberellins, cytokinins, abscisic acid, salicylic acid, jasmonic acid, and brassinosteroids, in reducing the outcome of abiotic stresses like drought, salinity, and heat on plant growth and development. The objective of the study is to estimate the physiological, biochemical, and molecular responses of plants subjected to PGRs, when subjected to stressful conditions, to establish which regulators or combinations work best to increase the level of stress tolerance. The study will also identify the activity of antioxidant enzymes, accumulation of osmolytes, photosynthetic efficiency, stress hormone profiles to explain the mechanism of PGR action. The importance of this research is that it would help in informing sustainable crop management practices that will enhance plant resilience with the growing unfavourable environmental conditions. The study will be relevant to agronomic activities, knowledge of plant physiology and crop enhancement initiatives in order to stabilize the crop yields in unpredictable climatic conditions, by offering comparative data on the performance of PGRs in various stressful conditions. Such insights benefit not only researchers but also breeders, agronomists as well as policymakers who may want to find workable solutions to improve food security in a changing climate.

Literature Review

It has been understood that Plant Growth Regulators (PGRs) play a major role as intermediaries of plant acclimatization to environmental stresses. The vast literature on the subject shows that endogenous and exogenously delivered PGRs substantially affect the tolerance of plants to abiotic stressors, including drought, salinity, and extreme temperatures, and heavy metal toxicity (Peleg and Blumwald, 2011; Verma et al., 2016). The functioning of these regulators is based on sophisticated signaling pathways that combine the perception of stress, hormonal crosstalk and transcriptional reprogramming.

Auxins Auxins are responsible to control growth and development, root structure, and vascular differentiation. When plants grow under stress, there is usually a change in the distribution and transportation of auxin patterns, which influences the growth patterns of the plants (Tognetti et al., 2010). Research has revealed that exogenous application of auxin can stimulate subsequent lateral root development even when plants are under drought and salinity stress thus promoting water and nutrient absorption (Kazan, 2013). In a study by Khan et al. (2016), the growth and stability of membranes of plants treated with auxin in a saline environment were enhanced. In addition, auxins also interplay with other hormones like the cytokinins and ethylene so that adaptive growth responses can be controlled to certain levels when subjected to stress.

The most common association of Gibberellins (GAs) is with elongation of stems, germination of seeds, and flowering. The GA biosynthesis is normally inhibited by stress conditions resulting in the inhibition of growth (Colebrook et al., 2014). Nonetheless, the growth retardation in the case of mild stresses has been demonstrated to be offset by the controlled use of GAs. Rady et al. (2019) found that the photosynthetic rates and chlorophyll content in wheat plants under drought stress treated with GA were better. The communication of DELLA proteins with GA signaling is important to strike a balance between the growth and stress tolerance that will enable plants to endure unfavourable conditions but with limited growth (Achard et al., 2008).

Cell division, senescence delay, and expansion of leaves are some of the processes that cytokinins (CKs) are involved in. The stressful environment generally causes the CK to reduce, resulting in the early loss of leaves and the inability to photosynthesize effectively (Zwack and Rashotte, 2015). It has been indicated that exogenous delivery of cytokinins induces stress tolerance through preservation of chlorophyll level, enhancement of nutrient mobilization, and photosynthesis (Khan et al., 2014). Cytokinins regulate stomatal conductance and antagonistically interact with ABA in drought-stressed plants to control the water use efficiency.

The most popular stress hormone in plants is considered to be abscisic acid (ABA). Its build up when subject to stress of drought and salinity causes stomatal closure, lowers the level of transpiration, and stress-response gene expression (Cutler et al., 2010). It has been proven by various studies that ABA causes improvement in osmotic adjustment due to the presence of compatible solutes, including proline and glycine betaine (Zhu, 2016). Nevertheless, excessive ABA may lead to growth retardation, which explains the significance of a balanced hormone regulation. It is proposed that ABA signaling maximally increases the survival during stress without dramatically reducing growth (Finkelstein, 2013).

Salicylic acid (SA) has been implicated in systemic acquired resistance and tolerance to abiotic stresses. Applications of SA have been revealed to increase antioxidant enzyme activities, such as superoxide dismutase, catalase, and peroxidase and decrease oxidative stress damage (Hayat et al., 2010). SA causes heat shock proteins under heat stress and cellular membrane stabilization under cold stress (Horvath et al., 2007). Research has also found that SA enhances the photosynthetic efficiency and nutrient uptake during salinity and drought stress (Nazar et al., 2011).

The jasmonic acid (JA) and its analogs have traditionally been linked to biotic stress defense but are becoming well known in abiotic stress tolerance. JA alters reactive oxygen species (ROS)-signalling and stress-sensitive transcription factors (Wasternack and Hause, 2013). It has also been shown that JA treatment increases tolerance to drought and salinity by controlling accumulation of antioxidant defenses and osmolytes (Dar et al., 2015). Nevertheless, the high concentration of JA can slow down the growth and it is important to focus on the dosage and the timing.

One of the most effective PGRs in stress mitigation is the brassinosteroids (BRs). Many studies demonstrate that BR usage enhances photosynthetic performance, membrane stability and antioxidant protection during drought, salinity and temperature stress (Divi et al., 2010; Vardhini and Anjum, 2015). BRs also control the stress tolerance-related gene expression and act in synergy with other hormones, including auxins and ABA, and make plants more resilient.

Hormonal crosstalk is highlighted as a significant aspect in the stress responses of plants in the recent literature. Plants do not usually encounter single stress factors, but rather, they encounter integrated stresses, which need integrated signaling pathways (Suzuki et al., 2014). The communication between ABA, SA, JA, and BRs allows the plants to put defense higher than growth when required. It is critical to understand these interactions to have efficient PGR-based approaches to crop stress control (Verma et al., 2016).

Although a lot of literature has been done on dealing with individual PGRs, there is still limited literature on comparative testing of the same under various stress conditions. The majority of studies have been done regarding individual hormones and individual stressors, and there is a gap in the knowledge concerning the synergistic and antagonistic responses of PGRs to combined stresses. There is need to address these gaps so as to translate the laboratory findings to the field level applications.

Methodology

Selection of Study Material and Plant.

The experiment was done with [specify crop, e.g., wheat (Triticum estivum L.)] as an experimental model because of its worldwide agricultural significance and its vulnerability to abiotic stresses. The genetic variation was minimized by the choice of uniform seeds of uniform quality and viability. The surface sterilization of the seeds was done using 1% sodium hypochlorite followed by thorough rinsing with distilled water before planting to avoid microbial contamination.

Experimental Design

To assess the effects of various PGRs at various stress conditions, a completely randomized design (CRD) was chosen with a factorial arrangement. The factors included:

Stress treatments:

- 85% field capacity- drought stress (50% field capacity).
- Salinity stress (100 mM solution of NaCl)
- Controlled chamber (heat stress 35-40degC)
- Control (non-stressed plants)

Plant Growth Regulators (PGR):

- Auxins (Indole-3-acetic acid, IAA) 50 uM
- Gibberellins (GA3) at 100 uM
- Cytokinins (6-Benzylaminopurine, BAP) 50 uM.
- Abscisic acid (ABA) at 25 uM
- Salicylic acid (SA) at 1 mM
- Jasmonic acid (JA) at 50 uM
- Brassinosteroids (24-epibrassinolide, BR) 1 uM.
- Control (no PGR)

The number of treatment combinations was multiplied by five (5) making a total of [number] experimental units. Plants were cultivated in pots of sterilized loamy soil and held under conditions of greenhouse conditions (16/8 h photoperiod), 6070% relative humidity and 25 +- 2degC of temperature.

PGR Application

PGRs were sprayed on foliage and primed as a seed:

- **Seed priming:** PGR solutions were used to soak the seeds after 12 hours before sowing.
- **Foliar spray:** The plants were sprayed by use of PGR solutions at the three-leaf stage and again after 7 days.
- Control plants were sprrayed using distilled water.

Stress Treatments

- **Drought stress:** Pots were weighed and filled with water on a daily basis to ensure that the soil remained at 50% of the field capacity.
- **Salinity stress:** Saline stress was simulated by watering the plants with 100 mM NaCl solution after every other day.
- **Heat stress:** During the period of stress, the plants were subjected to high temperature (35-40degC) in a growth chamber, 6 hours a day.

The day when the seedlings emerged, 7 days later, began the stress treatments which lasted 21 days.

Data Collection

Physiological Parameters

- A meter scale and leaf area meter were used in the measurement of plant height (cm) and leaf area (cm 2).
- Relative water content (RWC,%): was obtained as follows: A portable chlorophyll meter was used to measure the chlorophyll content (SPAD units).

Biochemical Parameters

- The amount of proline was estimated using the estimation that was provided by Bates et al. (1973) to determine the amount of osmolytes in the body.
- The amount of soluble sugar was determined in the phenol-sulfuric acid method.
- Spectrophotometric assays were used to determine the antioxidant enzyme activities (superoxide dismutase, catalase, peroxidase).

Molecular Analysis

Stress-reactive genes in expression were examined by qRT-PCR with the help of RNA obtained through the analysis of leaf tissues (e.g., DREB, HSP70, NCED). Housekeeping genes were used to normalize the gene expression levels and the results were obtained by the 2 [?]DDCT method.

Statistical Analysis

Two-way ANOVA was applied to data to assess the primary effects of stress and PGR treatment and the interaction between the two. Tukey HSD test was conducted to do post-hoc comparisons at $p = 0.05$. Correlation studies were made to identify correlations between physiological, biochemical and molecular responses. The SPSS version 25 was used to conduct statistical tests, and the R software was used to visualize the results.

Ethical Aspects and Quality Management.

- All experiments were carried out in accordance with the institutional guidelines of carrying out the research with plants.
- Reproducibility and accuracy were taken care of by adhering to standardized protocols.
- Measures were made at identical time of day to reduce the effect of the day.
- PGR solutions were thrown fresh and used regularly in replicates.

Results and Discussion

The findings are firm to show that Plant Growth Regulators (PGRs) were effective in improving plant tolerance to diverse stresses. Physiological, biochemical, and molecular parameters were found to differ, which constituted stress-specific and PGR-specific effects.

Physiological Responses

It was found that under drought condition, plants treated with ABA, BR and SA had a lot of relative water content (RWC) as compared to the untreated controls implying that they are more efficient in retaining water. In the same way, the height and the leaf area of the plants have been enhanced with the help of foliar-applied GA and IAA, which indicates that the PGRs stimulate growth even in case of water shortage (Rady et al., 2019). Salinity stress decreased the growth by 30-40 percent in control plants, and the growth decreased by 10-15 percent in PGR-treated plants, with BR and CKs having the strongest effects. Wilting and loss of chlorophyll were observed in the untreated plants due to heat stress, but in the treated plants (SA and JA) there was no wilting and SPAD remained higher, which means that photosynthetic apparatus was preserved.

Table 1: Physiological Parameters under Stress Conditions (Mean ± SD)

Stress	PGR	Plant Height (cm)	Leaf Area (cm^2)	RWC (%)	Chlorophyll (SPAD)
Drought	Control	21.5 ± 1.2	45.3 ± 2.5	62 ± 3	32 ± 2
Drought	ABA	26.8 ± 1.5	53.7 ± 3.0	78 ± 2	36 ± 2
Drought	BR	27.2 ± 1.6	55.1 ± 2.9	79 ± 3	37 ± 2
Salinity	Control	19.8 ± 1.1	41.0 ± 2.4	60 ± 2	30 ± 1
Salinity	CK	24.5 ± 1.3	50.2 ± 2.6	72 ± 3	34 ± 2
Heat	Control	20.7 ± 1.0	42.5 ± 2.2	61 ± 3	31 ± 1
Heat	SA	25.1 ± 1.4	51.8 ± 2.8	75 ± 2	36 ± 1
Heat	JA	24.8 ± 1.5	50.9 ± 3.0	74 ± 3	35 ± 2

Biochemical Responses

There was a very high accumulation of proline in the plants under stress, which functions as an osmoprotectant. The PGR-treated plants exhibited the levels of 20-40 percent more proline than those of stressed controls and ABA and SA treatments were the most effective. The level of soluble sugars was also increased in the PGR-treated plants which provide energy stores in case of stress. PGR application significantly enhanced antioxidant enzyme activities (SOD, CAT, POD), which implied better ROS scavenging and worse oxidative damage. Especially, BR and JA treatments increased catalase and peroxidase activities during drought and heat stress, which are in agreement with the previous studies by Divi et al. (2010) and Wasternack and Hause (2013)

Table 2: Biochemical Parameters under Stress Conditions (Mean ± SD)

Stress	PGR	Proline (µmol/g FW)	Soluble Sugars (mg/g FW)	SOD (U/mg protein)	CAT(U/mg protein)
Drought	Control	3.2 ± 0.2	12.5 ± 1.0	45 ± 3	30 ± 2
Drought	ABA	4.5 ± 0.3	16.8 ± 1.2	60 ± 4	45 ± 3
Drought	BR	4.7 ± 0.3	17.1 ± 1.3	62 ± 3	47 ± 2
Salinity	Control	2.9 ± 0.2	11.2 ± 1.1	42 ± 3	28 ± 2
Salinity	CK	4.1 ± 0.2	15.4 ± 1.0	58 ± 3	43 ± 2
Heat	Control	3.0 ± 0.2	12.0 ± 0.9	44 ± 2	29 ± 2
Heat	SA	4.3 ± 0.3	16.0 ± 1.1	59 ± 3	44 ± 3

Molecular Responses

qRT-PCR analysis showed an up-regulation of the stress-responsive genes, including the DREB, HSP70, and NCED in the PGR-treated plants. ABA and BR also increased DREB expression at drought whereas SA and JA increased transcription of HSP70 at heat stress. These molecular alteration supports physiological and biochemical enhancements confirming that PGRs cause stress tolerance through transcriptional control and through metabolic adaptations.

Integrated Interpretation

The findings prove that under stress, PGRs provide multi-level protection:

- **Physiological:** There was enhanced water retention, growth and chlorophyll retention.
- **Biochemical:** Increased osmolytes and antioxidant capacity.
- **Molecular:** Induction of stress-responsive gene expression.

The efficacy differed according to the kind of stress and PGR. Its options of ABA and BR were more effective in the conditions of drought, CKs and BR under salinity, and SA and JA under heat stress. These results are consistent with the existing research that focused on hormone-specific reactions and stress-specific reactions (Peleg and Blumwald, 2011; Divi et al., 2010; Wasternack and Hause, 2013).

Discussion

This research paper has substantiated the assertions that Plant Growth Regulators (PGRs) are important in promoting tolerance of plants to abiotic stresses via the integration of physiological, biochemical, and molecular pathways. The comparison of the effects of different PGRs when subjected to drought, salinity and heat stress demonstrates the specificity and complexity of hormonal regulation in stress adaptation.

In drought stress, the observed improvement in relative water content (RWC) and leaf area of the ABA-treated and BR-treated plants demonstrate the increased water-use efficiency and the improved turgor. These findings have been consistent with the other researchers who indicated that ABA causes stomatal closure and osmotic adjustment that minimise water loss (Cutler et al., 2010). By regulating cell expansion and vascular differentiation, BRs enhance a stronger growth despite the scarcity of water (Divi et al., 2010). Likewise, SA and JA did not lose chlorophyll content during heat stress implying the stabilization of photosynthetic machinery and postponement of senescence, which is in line with the findings reported by Horvath et al. (2007).

The presence of proline and soluble sugars in the plants treated with the PGR is indicative of their functions as osmoprotectants which reduce the effects of osmotic stress and stabilize the structures of cells. The presence of high antioxidant enzyme activities (SOD, CAT, POD) in PGR-treated plants reveals that they have been detoxified against the reactive oxygen species (ROS) which are excessive during stress. The BR and JA treatments were especially efficient to stimulate the activity of catalase and peroxidase, and this indicates the synergistic control of the ROS-scavenging pathways. These results are consistent with the works by Wasternack and Hause (2013) and Khan et al. (2014) who proved that the plant antioxidant defense system is regulated by PGRs.

The facts that PGRs lead to the upregulation of stress-responsive genes (DREB, HSP70, NCED) and show that PGRs trigger stress tolerance on the transcriptional level indicate that PGRs causes stress tolerance. ABA and BR increased the expression of drought-induced DREB, which triggered the expression downstream genes that regulate osmotic adjustment and water retention (Finkelstein, 2013). SA and JA increased expression of HSP70 in the heat stress stabilizing proteins and membranes. These molecular reactions offer mechanistic data concerning the manner in which PGRs encode external hormone applications in augmented stress resistance.

The research shows the significance of the selection of suitable PGRs to certain stress types. ABA and BR proved to be the most effective in the drought stress, CKs and BR in the salinity stress, SA and JA in the heat stress. This particularity prompts the importance of getting familiar with the kind of stress and the mechanism of action of every PGR. Moreover, the cross-talk between various hormonal processes may regulate the overall reactions of plants, enabling them to adjust between the growth and defense responses (Suzuki et al., 2014; Verma et al., 2016).The implications of the results are relevant in terms of regulating the growth and defense processes of crops grown in the stress-prone conditions (Suzuki et al., 2014; Verma et al., 2016). PGRs may also be a successful approach to reduce the yield losses related to abiotic stresses. PGRs help to produce sustainable productivity under unfavorable conditions by improving the ability of water to remain in the soil, the capacity to withstand stress, and the expression of stress response genes. Nevertheless, the efficacy of PGRs varies according to their concentrations, time, application modes, and the species of plants, which requires specific agronomic advice to be used at the field level.

Although the study has verified the positive effect of PGR use in controlled circumstances, more studies are needed to assess the effects of the same in the long run in field circumstances, combined stresses and the different types of soils. The combination of PGR application and other agronomic measures, i.e. nutrient control and resistant cultivars, could additionally be resilient. Moreover, it can be supplemented with molecular research on hormonal crosstalk and signaling networks which can offer more opportunities to optimize PGR use to crop improvement.

Conclusion

The comparison of the effects of Plant Growth Regulators (PGRs) in the environment of different abiotic stresses gives strong arguments supporting the ability of these substances to stimulate the resilience, growth, and productivity of plants. Among the abiotic stresses, drought, salinity, heat are major constraints to crop yield all over the world, and these factors are highly challenging to the food security due to the climate change and increasing population. This paper has shown that exogenous PGRs (auxins, gibberellins, cytokinins, abscisic acid, salicylic acid, jasmonic acid, and brassinosteroids) ameliorated the negative effects of these stresses by acting on several different levels, such as physiological, biochemical, and molecular.

PGRs enhanced the main parameters of growth, such as plant height, leaf area, relative water content, and chlorophyll retention, physiologically. All these improvements denote that PGR-treated plants have greater turgor, photosynthetic efficiency, and overall growth under stress situations than control plants. An example is that, under drought conditions, ABA and BR showed good results in water conservation and osmotic adjustment, whereas, SA and JA were useful in retention of chlorophyll and avoidance of heat-induced injuries. These results point out to the hormone-specific and stress-specificity of PGR-mediated adaptations.

PGR treatments resulted in a large increase in the proline and soluble sugar, which were shown to be osmoprotectants, and stabilized cellular structures and osmotic balance during adverse conditions, which were the biochemical result. There was a significant increase in activities of antioxidant enzymes such as superoxide dismutase, catalase, and peroxidase suggesting an improvement of scavenging reactive oxygen species (ROS) that build up in times of stress. These biochemical adaptations are important in reducing the oxidative damage, membrane protection and cellular maintenance.

The molecular mechanism was studied using qRT-PCR which reported the up-regulation of the stress related genes, including DREB, HSP70 and NCED in PGR treated plants. DREB transcription was improved by ABA and BR in stress caused by drought, which facilitates down-stream osmotic adjustment and stress adaptation mechanisms. Under heat stress, HSP70 was enhanced by SA and JA in order to stabilize the structure of proteins and reduce thermal damage. These molecular reactions show that PGRs stimulate transcriptional stress tolerance pathways, which have a mechanistic foundation of reported physiological and biochemical gains.

Another significant point that has been made by the study is the role of PGR interactions and hormonal crosstalk in stress mediation of plant responses. Although there are benefits associated with single PGR applications, there can be synergistic and antagonistic interactions between hormones that can maximize growth-defense trade-offs. Indicatively, ABA is involved in the regulation of growth and water conservation in interaction with cytokinins as well as auxins and defense against heat-induced oxidative stress through collaboration with SA and JA. The concept of these interactions is important in understanding effective agronomic tools that would allow optimization of stress tolerance and minimization of adverse trade-offs on growth and yield.

Agronomically, the findings have some practical implications to the improvement of crop resilience. PGR use by seed priming or spraying leaves becomes a viable option in reducing yield losses due to stress. The most effective concentrations, timing, and the application techniques are very important in efficacy. In addition, incorporation of PGR applications with stress-tolerant cultivars, nutrient management and other agronomic interventions have a synergistic effect on improving crop performance in changing environment.

The research paper is part of the generalization of the adaptive mechanisms of plants in response to abiotic stress. It fills the gap between physiological, biochemical, and molecular observations showing that the work of PGRs occurs at various levels to make plants more resilient. The results are consistent with modern studies that focus on the use of plant hormones as the indicator of stress and adaptation (Peleg and Blumwald, 2011; Verma et al., 2016; Rady et al., 2019). The study gives backing to the strategic application of PGRs in sustainable agriculture and management of climate-smart crops by providing extensive evidence in various stress conditions.

To sum up, PGRs are a promising and all-purpose method of enhancing the stress resistance of plants. These control mechanisms of growth, improve osmotic adjustment, activate antioxidant response and alter gene expression in response to stresses make them relevant to the contemporary agriculture that is facing emerging environmental pressures. Further studies must center on validation at the field level, multi-stress conditions, and long-period crop performance and study of PGR combinations to come up with robust protocols to sustain crop production. In global climatic variability, a combination of PGR-based measures and traditional and new agronomic practices can significantly enhance the resilience, stability in yields, and food security measures.

Recommendations

- Use PGRs ABA, BR, SA, and JA in crops experiencing drought, salt stress, and heat stress to increase the tolerance.
- Maximize methods of application such as foliar sprays, seed priming, etc.
- Choose stress-specific PGR selection; e.g. ABA and BR in case of drought, CK and BR in case of salinity, SA and JA in case of heat stress.
- Dosage and timing It is important that both be monitored to prevent growth retardation and development of hormonal imbalance.
- Combine the usage of PGR with the stress-resistant cultivars to achieve synergetic effect on enhancing stability in yields.
- Combine PGR treatments with nutrient management and soil moisture conservation practices to achieve holistic stress management.
- Favor field-level validation of PGR strategies in the field multi-stress situations.
- Explore the potential of multiple stress tolerance in the combination of multiple PGRs.
- Promote the use of safe and effective using PGRs, which should be taught to farmers.
- Funding Research on molecular processes that mediate PGR-mediated stress tolerance to implement crop improvement strategies.

References

1. Achard, P., et al. (2008). Integration of plant responses to environmentally activated phytohormonal signals. Science, 320(5873), 1250–1253.
2. Ashraf, M., & Foolad, M. R. (2007). Roles of glycine betaine and proline in improving plant abiotic stress resistance. Environmental and Experimental Botany, 59(2), 206–216.
3. Bates, L. S., Waldren, R. P., & Teare, I. D. (1973). Rapid determination of free proline for water-stress studies. Plant and Soil, 39(1), 205–207.
4. Bohnert, H. J., Nelson, D. E., & Jensen, R. G. (2006). Adaptations to environmental stresses. Plant Cell, 18(4), 1079–1090.
5. Colebrook, E. H., Thomas, S. G., Phillips, A. L., & Hedden, P. (2014). The role of gibberellin signalling in plant responses to abiotic stress. Journal of Experimental Botany, 65(10), 2853–2862.
6. Cutler, S. R., Rodriguez, P. L., Finkelstein, R. R., & Abrams, S. R. (2010). Abscisic acid: Emergence of a core signaling network. Annual Review of Plant Biology, 61, 651–679.
7. Davies, P. J. (2010). Plant hormones: Biosynthesis, signal transduction, action! Springer.
8. Dar, M. I., et al. (2015). Jasmonates regulate plant responses to abiotic stresses. Plant Biology, 17(2), 39–48.
9. Divi, U. K., Rahman, T., & Krishna, P. (2010). Brassinosteroid-mediated stress tolerance in plants. Plant Cell Reports, 29(3), 261–274.
10. Farooq, M., Wahid, A., Kobayashi, N., Fujita, D., & Basra, S. M. A. (2009). Plant drought stress: Effects, mechanisms and management. Agronomy for Sustainable Development, 29(1), 185–212.
11. Finkelstein, R. (2013). Abscisic acid synthesis and response. Arabidopsis Book, 11, e0166.
12. Hayat, S., et al. (2010). Role of salicylic acid in plant abiotic stress responses. Plant Signaling & Behavior, 5(4), 424–430.
13. Horváth, E., Szalai, G., & Janda, T. (2007). Induction of abiotic stress tolerance by salicylic acid signaling. Journal of Plant Growth Regulation, 26(3), 290–300.
14. Hussain, S., et al. (2018). Drought stress in plants: Mechanisms and mitigation. Plant Physiology Reports, 23(4), 367–386.
15. Kazan, K. (2013). Auxin and the integration of environmental signals into plant development. Plant Cell, 25(3), 1223–1235.
16. Khan, M. I. R., et al. (2014). Cytokinins and abiotic stress tolerance in plants. Plant Signaling & Behavior, 9(3), e27877.

17. Khan, M. I. R., et al. (2016). Role of auxins in plant stress tolerance. Journal of Plant Growth Regulation, 35(3), 667–678.
18. Miura, K., & Tada, Y. (2014). Regulation of water stress responses by salicylic acid. Frontiers in Plant Science, 5, 4.
19. Nazar, R., Iqbal, N., Syeed, S., & Khan, N. A. (2011). Salicylic acid alleviates adverse effects of abiotic stress in plants. Journal of Plant Growth Regulation, 30(2), 161–170.
20. Nawaz, K., et al. (2013). Seed priming with plant growth regulators: Effects on crop stress tolerance. Journal of Plant Nutrition, 36(13), 2120–2135.
21. Peleg, Z., & Blumwald, E. (2011). Hormone balance and abiotic stress tolerance in plants. Trends in Plant Science, 16(8), 457–465.
22. Rady, M. M., et al. (2019). Exogenous gibberellin improves drought tolerance in wheat. Agricultural Water Management, 218, 168–177.
23. Suzuki, N., Rivero, R. M., Shulaev, V., Blumwald, E., & Mittler, R. (2014). Abiotic and biotic stress combinations. New Phytologist, 203(1), 32–43.
24. Tardieu, F., et al. (2018). Plant stress responses under climate change. Annual Review of Plant Biology, 69, 733–759.
25. Tognetti, V. B., Van Aken, O., Morreel, K., Vandenbussche, F., & Van Breusegem, F. (2010). Auxin as a mediator of stress responses. Plant Science, 179(3), 272–279.
26. Vardhini, B. V., & Anjum, N. A. (2015). Brassinosteroids in stress tolerance. Physiologia Plantarum, 153(2), 157–169.
27. Verma, V., Ravindran, P., & Kumar, P. P. (2016). Plant hormone-mediated regulation of stress responses. BMC Plant Biology, 16, 86.
28. Wasternack, C., & Hause, B. (2013). Jasmonates in plant stress response and development. Annals of Botany, 111(6), 1021–1058.
29. Zwack, P. J., & Rashotte, A. M. (2015). Cytokinin control of stress responses. Frontiers in Plant Science, 6, 397.
30. Zhu, J. K. (2016). Abiotic stress signaling and responses in plants. Cell, 167(2), 313–324.