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INTEGRATING COMPUTATIONAL APPROACHES AND PHYTOHORMONES FOR ENHANCING DROUGHT AND SALT STRESS TOLERANCE IN MARGINAL CONDITIONS

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Abstract

Abiotic stressors caused by climate change create severe problems for global agriculture, where drought, soil salinity, heavy metals (HMs) contamination, and flooding increasingly threaten productivity and food security. There are phytohormones within plants, including ABA (abscisic acid), jasmonates (JA), brassinosteroids (BR), salicylic acid (SA), cytokinins (CK), melatonin (MT) and gibberellins (GA) that play a fundamental role in improving the resistance of plants to adverse conditions by regulating the physiological and molecular mechanisms that modulate the retention and absorption of nutrients, antioxidant defense, stress tolerance, and cellular detoxification. Understanding and implementing phytohormone-based approaches is crucial as the frequency and severity of weather change's effects on agricultural output. These tactics offer a viable path toward resilient crop development. This review highlights the potential of phytohormones as sustainable tools to mitigate abiotic stress (drought and salt) providing a critical reference for future research to improve crop adaptation to abiotic stress conditions to ensure food security. Interestingly integrated computational approaches such as machine learning (ML), and deep learning (DL) have become crucial in forecasting and interpreting stress complex networks. Studies on an advanced level with computational models will be a promising approach to achieving sustainable development goals (SDG).

Ke words: Phytohormones; Abiotic stress; Plant adaptation; SDG; Climate change.

Introduction

Climate change is generating significant environmental imbalances, which often result in various forms of abiotic stress that affect the physiological systems of crops, affecting their productivity (Yang *et al.*, 2024). These environmental changes are usually associated with altered rain patterns and anthropogenic pollution, often causing water scarcity, soil salinization, soil contamination with heavy metals (HMs), and more frequent flood events, which impact the sustainability of agricultural production (Chaudhry & Sidhu, 2022; Ferguson, 2019). Abiotic stress is one of the main constraints in agricultural industry because it interferes with photosynthetic processes and nutrient utilization, which decreases crop growth and yield (Vaughan *et al.*, 2018; Zandalinas *et al.*, 2022; Eckardt *et al.*, 2023). At the same time, urbanization and industrialization have led to the contamination of soils, further exacerbating the challenges to ensuring food security (Shah *et al.*, 2019; Pereira, 2016).

To cope with these challenges, plants have evolved phytohormone-mediated mechanisms that allow them to adapt to abiotic stress conditions. Phytohormones such as abscisic acid (ABA), jasmonates (JA), brassinosteroids (BR), salicylic acid (SA), and cytokinins (CK) play a crucial role in modulating plant responses to these conditions by regulating physiological and molecular processes (Zaid *et al.*, 2021; Mearaji *et al.*, 2021). Some authors report the importance of these phytohormones; for example, ABA is vital for tolerance to abiotic stress through regulating stomatal closure (EL Sabagh *et al.*, 2022; Wani *et al.*, 2016). Similarly, BRs are effective in improving tolerance to abiotic stress and promoting seed germination, while JA and SA increase antioxidant activity and enhance defense mechanisms under abiotic stress (Li *et al.*, 2020; Souza *et al.*, 2017; Ku *et al.*, 2018; Raza *et al.*, 2019). Given the expected increase in climate-related stressors, it is necessary to understand the endogenous modulation and exogenous application of these hormones to harness this crucial element to develop resilient crops. This review analyzes the mechanisms of tolerance to phytohormone-mediated stress under various environmental conditions, offering critical information for future research using computational models and practical applications to improve crop resilience and promote agricultural sustainability in a changing climate.

Phytohormones in drought stress and salt stress tolerance: Drought stress is one of the main constraints in plant production in addition to the effects of urbanization and industrialization. The absence of water resources interferes with the critical physiological processes for photosynthetic processes and nutrient absorption. This type of abiotic stress caused by climate change generates increasingly frequent and much more prolonged droughts (Farooq *et al.*, 2012; Shaffique *et al.*, 2023). If drought persists, plants may suffer a reduction in their growth and yield (Zafer *et al.*, 2023). Therefore, the need arises for effective strategies to mitigate stress in economically important crops. The accumulation of salts in the soil prevents the correct absorption of water and nutrients, affecting photosynthesis and reducing crop yields (Zhi *et* *al.*, 2024; Ameen *et al.*, 2024; Zhou *et al.*, 2024; Bellucci *et al.*, 2024). It is estimated that approximately twenty percent of the global land is affected by soil contamination due to excess salts, which aggravates food security problems (Cheng *et al.*, 2024; Abdelkefi *et al.*, 2024). Therefore, this problem impacts plants, which varies according to species and salinity intensity, so it requires solutions to mitigate the effects on agricultural production (Lamsaadi *et al.*, 2024; Ilyas *et al.*, 2024).

In response to drought and salt stress, plant cells produce free radicals such as ROS, lethal for plant cells. However, the plant has endogenous defense systems to reduce stress but only up to a certain level. After that plant cells show some signs of stress such as chlorosis, stunted growth, and production. The endogenous production of phytohormones tries to lower the level of stress. However exogenous application of phytohormones and microbial inoculation that tend to release phytohormones are sustainable techniques for agriculture production. Given climate change and the different types of stress have developed physiological modifications in plants that allow the generation of phytohormones to drive some of these mechanisms; there is a variety of phytohormones that participate within these physiological and morphological processes, among the most important are discussed .

Role of Brassinosteroids (BRs) in reducing drought and salt stress tolerance: This phytohormone is efficacious in improving plant tolerance to drought there are studies in pepper cultivation where characteristics related to photosynthesis increased, which indicates greater efficiency in water conservation under conditions of water stress (Hu *et al.*, 2013). Other studies reveal that BRs improve seed germination characteristics, root growth, seedling development, and cell expansion, contributing to better performance under these conditions (Bhandari & Nailwal, 2020; Sharma *et al.*, 2022). This hormone has been found to reduce oxidative damage and boost physiological processes, allowing for an improvement in productivity under drought stress (Meena *et al.*, 2024; Basit *et al.*, 2021). In the situation of salinity stress, exogenous applications of BRs have shown improvements in several species of eggplants, supplementation with BRs increased growth and the activity of antioxidant enzymes reduced; sodium and chlorine content, improving cell membrane and plant photosynthesis (Ding *et al.*, 2012; Yu *et al.*, 2020). This indicates that BRs help regulate ionic homeostasis and reduce the damage caused by the accumulation of salts in the plant cell (Zheng *et al.*, 2016; Sun *et al.*, 2015). BRs are also effective in improving stress tolerance by applying them to improve growth characteristics, productivity, seed germination, root development, and photosynthesis under salinity conditions (Anuradha & Rao, 2001; Tanveer *et al.*, 2018). BRs reduce the excessive generation of reactive oxygen species (ROS) and protect against cell damage by improving antioxidant activity and morphological characteristics of plants, as in the case of cucumber and radish, and increase enzyme activity, which improves resistance to salt stress (Ghoname *et al.*, 2023; Djemal *et al.*, 2023; Zhang, 2023).

Salicylic acid (SA) in drought and salt stress tolerance: A very versatile phenolic compound and an important signaling molecule, it is very effective in improving plant tolerance under salinity conditions (Irkitbay *et al.*, 2022; An & Mou, 2011). In a drought environment, SA shows positive effects; in studies carried out on tomatoes, these effects increase the fresh weight of plants, the water potential of the leaves, and the photosynthetic process (Sharma *et al.*, 2017; Kadioglu *et al.*, 2011). On the other hand, (Ali *et al.*, 2018; Shah, 2003) have found that the presence of SA improves the defense system of plants, contributing to tolerance to water stress. The application of exogenous SA in cucumber significantly improved growth characteristics and photosynthetic capacity as well as improved the root system under salt stress (Miao *et al.*, 2020). Some authors stated that the application of SA increased the uptake of mineral nutrients that contribute to the ionic homeostasis of plants (Yildirim *et al.*, 2008). In studies with several crops, the application of SA improved resistance to salt stress by regulating water absorption and enzymatic activity (Li *et al.*, 2022). In tomatoes, the application of SA improved gas exchange and significantly reduced oxidative stress (Ahmad *et al.*, 2023). In addition, SA reduces sodium accumulation and protects cell membranes, thus improving plants' adaptation to these conditions (Jayakannan *et al.*, 2015).

Jasmonate (JA) in mitigation of drought and salt stress: JA allows plants to tolerate drought through physiological systems such as stomatal closure and stimulation of profound root growth; the interaction of JA and ABA allows the closure of stomata, in addition to improving oxidizing activity, in the same way, it increases hydraulic conductivity in roots under drought conditions interacting with some ABA signaling pathways and calcium (Yun-Xia *et al.*, 2010; de Ollas *et al.*, 2013). These effects indicate that JA holds promise for increasing productivity under drought conditions. In the case of peppers, can improve the generation of osmoprotectants, oxidizing and non-oxidizing bioactive activity, nutrient metabolism, and mineral absorption, which allows the establishment of resistance to salt stress (Farooq *et al.*, 2024).

Polyamines (PAs) In drought and salt mitigation: They play a role in regulating physiological processes in vegetable crops, including root growth, leaf differentiation, and fruit ripening (Wallace *et al.*, 2003; Schibalski *et al.*, 2024). There are studies of the exogenous application of this hormone in tomato seedlings, resulting in a higher concentration of PAs in cells, especially in the root zone, favoring plant growth and ion translocation (Blázquez, 2024). In addition, this hormone improves plant resilience in drought by reducing ROS, H_2O_2, and MDA levels. PAs show an important benefit under salinity conditions. Studies have evidence that exogenous application in pepper seeds increases the germination rate and germination rate compared to untreated seeds; conversely, studies carried out on cucumbers have improved crop yield under salt stress conditions (Blázquez, 2024; Zapata *et al.*, 2008; Borromeo *et al.*, 2023).

Melatonin MT is an emerging biomolecule in reducing drought and salt tolerance: MT makes it possible to reduce the effects of stress on plants under drought by improving germination, root growth, and crop quality, improving nutrient absorption (Sharma & Zheng, 2019; Tiwari *et al.*, 2021). According to (Karpets *et al.*, 2023; Khan *et al.*, 2019), MT improves nutrient absorption by relieving osmotic stress and promoting the activation of oxidizing compounds. The combination of (sugar that acts as a signal to improve plant response) and MT helps some plants under salt stress by increasing their growth, chlorophyll content, and essential minerals on the other hand, it reduces sodium absorption and oxidative damage brought on by this stress (Kang *et al.*, 2024). Studies reveal that melatonin improves the recovery of green mustard (*Brassica juncea*) seedlings damaged by the effect of salinity, regulating oxidative stress and increasing critical physiological and biochemical parameters, such as plant growth, enzymatic activities, and phytohormone production, highlighting the potential of melatonin as a treatment to mitigate the adverse effects caused by salinity in crops (Kang *et al.*, 2024).

Role of Cytokinins (CK) in drought and salt mitigation: These perform a crucial function for growth, development, and acclimatization to drought stress in plants. CK regulates cell division and slows down senescence, which favors adaptation to drought stress. Some studies on the exogenous application of CKs demonstrate the restoration of germination potential in seeds and improve crop yields under drought stress increasing relative water content (RWC) and gas exchange (Liu *et al.*, 2020). These act as positive regulators in delaying senescence and improving nutrient uptake by increasing the levels of CKs, plants can maintain their functionality and reduce the negative effects of salt stress by modulating the expression of specific genes such as CKX1 and CKX2 that facilitate acclimatization (Yu *et al.*, 2022). The main distinguishing feature of CK is that it promotes acclimatization and adaptation to stress along with tolerance. Ck plays numerous roles in plant growth and morphogenesis. Plants naturally produce some CKs that mediate cell division and interact with IAA to control apical dominance, branching, and root-shoot ratio in intact plants and tissue cultures. They delay leaf senescence and stimulate the light-independent destination response of seedlings grown in darkness, including greening (Hamid *et al.*, 2024).

Auxins and ethylene role in the regulation of drought and salt stress: One of the critical auxins is indole-acetic acid, which regulates plant growth and mitigates drought stress by modulating root architecture and promoting apical dormancy as a response, it increases tolerance under drought stress conditions (Shi *et al.*, 2014; Verma *et al.*, 2022), overexposure to genes during stress, and the relationship with ABA activate defense mechanisms, allowing the reduction of adverse effects in response to drought stress (Zhang *et al.*, 2023). Auxins contribute to stress adaptation by exiting by regulating root architecture and interacting with ABA to reduce oxidative damage. Auxin application or inoculation with auxin-promoting bacteria can improve nutrient uptake and plant tolerance to salt stress (Jing *et al.*, 2023; Djemal *et al.*, 2023). Ethylene is considered the only gaseous phytohormone; its crucial point is the regulation of the germination process, flowering, fruit ripening, and stress-tolerant senescence (Bungala *et al.*, 2024). Under stress conditions, ethylene regulates stomata closure by promoting the accumulation of certain enzymes (NADPH oxidase), allowing an immediate stress response. In addition, once the stress has ceased, ethylene inhibits ABA-induced stomatal closure, thus allowing effective plant recovery (Tang *et al.*, 2024, Hasan *et al.*, 2024).

Gibberellins (GA) and Abscisic acid (ABA) In modulation of drought and salt stress: The function of GA as a growth hormone in plants promotes cellular elongation and division in each of the phenological stages of the crop (Shani *et al.*, 2024) in drought conditions, the reduction of GA biosynthesis is mediated by some proteins such as *SIDREB,* Studies show that the overexpression of some genes, such as *AtGAMT1*, in transgenic tomatoes decreases the levels of GAs, which allows for an increase in the resistance to water stress in addition to improving the water content in the leaves (Yu *et al.*, 2022). ABA is considered a key phytohormone in the response of plants to drought stress since it regulates stomatal closure, the synthesis of compatible osmolytes (de Ollas *et al.*, 2013), ABA is crucial in the regulation of growth and stress tolerance in some plants, it is commonly referred to as a stress hormone due to the role it plays based on responses to adverse conditions such as drought. ABA is also essential in the generation of growth through the regulation of some guard cells and stomatal conductance which helps prevent drought stress by reducing the effects of dehydration and water loss, this modulates the architecture of the plant favoring the development of lateral roots and adaptive alterations such as the reduction of the diameter of the xylem allowing the absorption of water through the use of the plant deeper levels (Sharma *et al.*, 2022).

Integrating computational approaches for stress forecasting: The intricacy of plant physiological reactions to stress, and phytohormonal management has significant limitations. Several technical developments help plant stress science get beyond these obstacles, leading to large datasets derived from the various levels of the plant defense mechanism (Vasileiou *et al.*, 2024; Espinel *et al.*, 2024). To effectively describe plant stress responses, including genetic variation, gene and protein expression, and metabolite production, artificial intelligence (AI) tools in particular, Machine Learning (ML) and Deep Learning (DL) have become essential for data processing and interpretation (Hamed *et al.*, 2024; SaberiKamarposhti *et al.*, 2024). AI is a rapidly developing field of computer science that holds enormous promise for resolving many of the intricate issues facing the contemporary world. Advanced fuzzy logic models have been used for wastewater treatment, artificial neural networks (ANN) and the fuzzy inference system ANFIS have been used to estimate the production of biosurfactants by bacteria and advanced DL tools have been used in plant science. In that regard, AI technologies are useful for predicting stress, identifying species, modeling plant distribution, identifying disease and stress, and using agrochemicals in precision agriculture. Significant advancements in advanced agriculture research have been made possible by (ML) approaches, which in particular can forecast the results of a variety of intricate biological processes, including gene complex networks, protein interactions, and ideal growing conditions (Kashyap *et al.*, 2024; Son *et al.*, 2024).

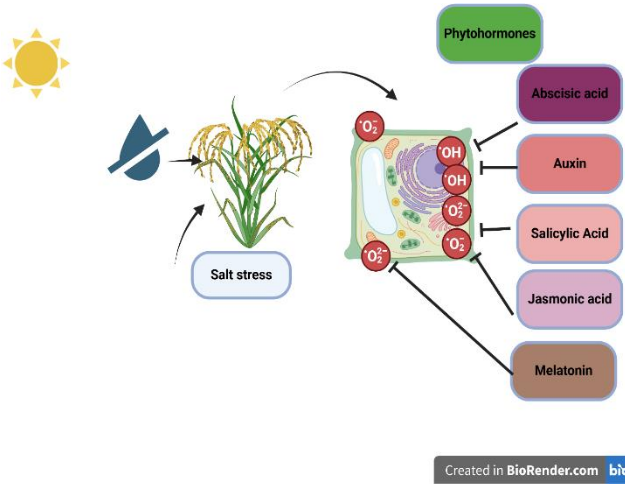

Fig. 1. Role of phytohormones in drought and salt stress tolerance. The figure was created by using the online software www.biorender.com.

Conclusion and Future Prospective

Plants have evolved crucial mechanisms thanks to phytohormones to adapt to various types of abiotic stresses including drought, soil salinity, HMs, and floods. It has been determined that over time the endogenous regulation and exogenous application of phytohormones such as ABA, JA, BR, SA, MT, GB, and IAA allow the strengthening of the defense systems of some plant species promoting essential processes for water absorption, antioxidant activity and cellular detoxification as shown in figure 1. These phytohormones also facilitate the development of root systems and adaptive structures under stress conditions, improving the resilience of economically important crops. Given the growing impact of climate change on agriculture, phytohormones present crucial tools to improve crop resilience and promote agricultural sustainability. This review provides key documentary support for future research in the management of phytohormones, encouraging their use and their corresponding producing microbes to mitigate abiotic stress and strengthen food security in an environment of constant climate change.

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