Effect of Abiotic Stresses on Growth And Metabolism of The Plant And Stress Tolerance Mechanism

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Abstract- *Naturally growing plants generally counter with the abiotic stress in form of drought, waterlogging, heat, salinity, heavy metal contamination leading to imperative growth and loss in productivity. The abiotic stresses cause morphological, physiological, and biochemical modifications and alters metabolic activities in plants. Although plants exhibit a general defense externally in form of cuticle and internal defense in form of plant growth regulators, signaling molecules like gasotransmitters, volatile organic compounds, reactive oxygen species scavengers, polyamines, molecular chaperones, phytochromes, and compatible solutes against adverse situations. However, the collaborative arrival of these conditions left no chances of survival and recovery in plants. This review is an attempt to address the responses, defense mechanisms, and plant compounds used to combat abiotic stresses. The effective scientific techniques like calcium signal systems, functional genomics technologies, molecular markers assisted plant breeding, should be given more emphasis to develop stress tolerance in plants.*

Keywords- Abiotic stresses, Plant responses, Metabolic modifications, Plant Defense

I. INTRODUCTION

Abiotic stresses in form of drought, flooding, salinity, heavy metals, heat, chilling, and freezing, are a serious menace in agriculture alleviating growth, development, and altering morphological, physiological, and biochemical processes of the plants. The abiotic stress causes a loss of 51–82% of yield annually in world agriculture, with impaired qualitative and quantitative changes in crops (Oshunsanya et al. 2019). The drought and floods accounts for 82 and 19%, whereas of the 73% of global land area, salinity affects more than 4.4 % of topsoil and 8.7 % of subsoil (FAO 2021, FAO 2022). The stress causes significant loss of productivity in forests (Tiwari et al. 2021). During abiotic stresses, the decrease in water availability, photosynthesis, chlorophyll contents, transpiration rate, stomatal functioning, flower bud formation, pollination, nutrients, secondary metabolites, root-shoot lengths, plant biomass, and denaturation of plant proteins are commonly observed (Oshunsanya et al. 2019, Khalid et al. 2019, Yadav et al. 2020).

The oxidative damage that is catalyzed by reactive oxygen species (ROS), like hydrogen peroxide (H_2O_2), superoxide radical (O_2^-), and hydroxyl radical (OH^-), is a significant impact of abiotic stresses resulting in alteration in cellular functioning and growth reduction in plants (Cakmak 2005). The stresses also show the deleterious effects on the production of secondary metabolites like morphine, cocaine, codeine, quinine, alkaloids, colchicines, flavonoids, reserpine, steroids, phenolics, etc. influencing food and natural pharmaceutical products (Akula and Ravishankar, 2011). This research is an attempt to analyze the impact of various abiotic stresses and the responses and defense mechanisms developed in plants to counter the stresses. Further, molecular and genetic responses, metabolites, and elements responsible either for promoting or arresting stress-like situation are also explored.

II. MATERIALS AND METHODS

A comprehensive review of the available literature was conducted for the assessment of the impact of abiotic stresses on the morphology, physiology, and metabolism of the plants, as well as the defense system and various self-modifications developed in the plants against the stresses. Moreover, the effective methods and relevant techniques were also analyzed to recommend a relevant solution to overcome the adverse situation caused due to abiotic stresses.

III. RESULTS

3.1 Drought stress and plant response and defenses

Climate change and high water scarcity are major problems affecting agriculture yield decline projected up to 4.5 times and even 25 times more by 2030 and 2050 across the globe (Caparas et al. 2021). Drought stress due to shortage in rainfall and increased dry spells causes a major setback to crop productivity with impaired osmotic, transpiration and carbon assimilation rate, changes in stress signaling pathways, suppressed root and shoot growth, production of reactive oxygen species, and senescence causing injury to the plant (Ahluwalia et al. 2021). Under prolonged water stress conditions plant growth and productivity are significantly affected (Osakabe et al. 2014).

The stress causes alteration in metabolic functioning suppressing the production of photosynthetic pigments, declining light harvesting and alleviation of reducing powers, affecting dark reactions and biomass yield (Jaleel et al. 2009). In some species, the drought conditions cause alteration in metabolite and lipid profiles including amino acids, sugars and sugar alcohols, and tricarboxylic acid cycle intermediates in leaves (Shen et al. 2022). The drought stress controlled experiment in certain perennial species like Populus trees reveals that the root microbiome decreases under stress conditions; however beneficial, as it causes the production of microbes like *Bacillus arbutinivorans, B. megaterium, B. endophyticus, Streptomyces rochei, Penicilliumraperi, Aspergillusterreus, Gongronellabutleri, Rhizopusstolonifer,* and *Trichodermaghanense,* having potentiality to improve growth and develop drought tolerance in the plant (Xie et al. 2021).

The drought stress in plants is complex mechanisms including various physiological reverberation starting from signal cognition to resistance acquisition in the plant. Drought stress conditions first arise in roots and then pass to shoots (Takahashi et al. 2020). The resistance varies with plant species, phenological stages, and duration of plant exposure to stress. Under low water potential conditions, osmoregulation is mainly based on the synthesis and accumulation of osmoprotectants like sugars, soluble proteins, quaternary ammonium compounds, sugar alcohols, and amino acids (Ozturk et al. 2021).

The plant breeding programs, genomics, and molecular prospects with a focus on alteration in omics technology like proteomics, metabolomics, genomics, glyomics, transcriptomics, and phenomics have the potential to develop stress resistance in plants. Application of osmoprotectants, seed priming, growth hormones, selenium (Se), silicon (Si), and potassium are significant under drought conditions. Moreover, the drought adaptation using hydrogel, microbes, metabolic engineering, and nanoparticles techniques that help in regulating the activity of the antioxidant enzymes helps in improving plant tolerance maintaining cell homeostasis, and alleviating adverse impacts of drought stress in crops (Seleiman et al. 2021). The genome engineering techniques like clustered regularly interspaced short palindromic repeat (CRISPR) or CRISPR-related protein 9 (Cas9) technique are an effective approach to developing drought tolerance in plants under different climate change conditions (Bashir et al. 2021).

3.2 Temperature stress and plant responses and defenses

Temperature stress in form of high, chilling, or freezing, shows a deleterious effect on germination, growth, and photosynthesis, and the plant often dies (Kai and Iba 2014). Global warming resulting in high temperature affects more than 15% of global land with developing countries experiencing damage in principal crop production (Sun et al. 2019). The temperature stress suppresses the growth, metabolism, biochemical reactions, and productivity of the plants (Hasanuzzaman et al. 2013). The tropical and subtropical plants are more sensitive to cold stress compared to temperate plants and even a short spell of low temperature influence growth and yield, with the development and functioning of gametes getting retarded resulting in impaired fertility (Thakur and Nayyar 2013). The high temperature above 30°C mainly affects male and female reproduction, mainly the uninucleate stage of male reproductive development, in the plants (Sage et al. 2015).

The experimental studies conducted on Maize plants reveal that under warm temperature conditions the pollination is mostly affected resulting reduction of 80−90% yield, without affecting leaf area and biomass (Hatfield and Prueger 2015). Heat stress occurring at temperatures more than 10-15°C retarding metabolism, denaturing enzymes, impairs morphology, physiology phenology, and molecular mechanism, and suppresses crop yield and adaptation in plants (Firmansyah and Argosubekti 2020). Under low-temperature stress conditions the formation of the aldolase gene SlFBA4, which plays a significant role in the Calvin-Benson cycle (CBC) is altered in tomato (*Solanumlycopersicum*) plants resulting higher net photosynthetic rate (Pn), fructose-1,6-bisphosphate aldolase activity, and other enzymes of CBC. Further, the increase in germination, height, stem diameter, thousand seed weight, and alleviation in malonaldehyde content is also observed under chilling stress conditions in the plant (Cai et al. 2022).

Plants develop freezing resistance by exposure to a low temperature known as cold acclimation and soluble sugars play a pivotal role in protecting plant cells serving as nutrients, osmoprotectants, and interaction with the lipid bilayer. Higher sugar concentrations initiate leaf senescence, due to the conglomeration of soluble sugars during cold acclimation with a negative impact on plants (Yuanyuan et al. 2010). In cold tolerant plant species, the sensing occurs in the membranes by histidine kinases like calcium-dependent protein kinase (CDPK) and mitogen-activated protein kinases (MAPK), causing the excitement of mechano-sensitive Ca2+-influx channels, which change over the signals to activate the transcriptional cascades (Thakur and Nayyar 2013).

The responses to cold stress in plants are mainly governed by functioning of ICE-CBF-COR genes. The cryo-protectants like sugars, glycine, proline, trehalose, betaine, and polyamines plays significant role in plants defense. Certain antioxidants like non-enzymatic glutathione, ascorbic acid, catalase, superoxide dismutase, enzymatic glutathione reductase, and ascorbate peroxidase get activated to combat the oxidative damage caused due to cold stress (Thakur and Nayyar 2013). During cold stress the osmolytes serving in form of cryoprotectants defends the cellular metabolism by preserving the redox potential and components of vital pathways, safeguarding the solidarity of membranes and cellular organelles, protecting the photosynthetic machinery and substituting as partial antioxidants (Bhandari and Nayyar 2014).

3.3 Salinity stress and plant responses and defenses

Soil salinity is major abiotic stress affecting nearly 800 million hectares of land (Hernández 2019) and reducing global crop productivity by up to 58% (Haj-Amor et al. 2022). Salinity causes morphological, physiological, epigenetic, and genetic changes, increases sodium and chlorine ions and at high concentrations causes the death of the plant cells (Etesami et al. 2021). The stress increases the intracellular osmotic pressure causing an assemblage of Na+ to toxic levels (Zhao et al. 2021). Salinity stress mainly affects seed germination, altering physiological and biochemical mechanisms, and seedling growth in arid and semiarid areas. The salt stress causes ion-specific effects, osmotic stress, and oxidative stress by reducing water availability, influencing the structural organization of proteins, and switching the mobilization of stored reserves (Ibrahim 2016). The symptoms of salinity stress first appear in the root with the deposition of phytotoxic ions causing osmotic stress. Further, the salinity imposes oxidative stress which is mediated by ROS (Reactive Oxygen Species), and nutrient imbalance in the cytoplasm (Acosta-Motos et al. 2017).

An experiment conducted on Maize roots reveals that salinity stress damage root anatomy and shrinkage of 2% and 3% in epidermal and parenchyma cells of the cortex and medulla, respectively. The Leaf anatomy gets deteriorated with suppression in mesophyll and bundle sheath cells and a decrease in chloroplast content. Calcium, magnesium, aluminum, iron, sodium, and chlorine increases, whereas potassium, boron, and phosphor content decreases in the plants (Hasan and Miyake 2017). The experiment in *Camelina sativa* reported that shoot length was highly affected by salt stress without any change in root length however, photosynthetic capacity, shoot, and root weight get retarded. The stress also enhances calcium and magnesium levels in shoots and micronutrients are less affected. The gene expression studies suggest that salinity causes the commuting of Na+ from the cytoplasm to the tonoplast leading to the transfer of Ca+2 and K+ in the cytoplasm in shoots whereas in roots Na+ was exported from the cytoplasm by the SOS pathway and K+ was imported in response to salt (Heydarian et al. 2018).

The salinity tolerance in plants depends on the activation of streaming of molecular networks involved in stress sensing, metabolites, signal transduction, and specific stress-related gene expression. Certain salt overly sensitive (SOS) genes isolated through sos mutants can help us in establishing a relationship between ion homeostasis and salt stress tolerance. Various phytohormones like Jasmonic acid, Abscisic acid, and Salicylic acid can play a significant role in regulating metabolic networks during osmotic stress conditions (Singh and Gautam 2013).

A study of peptide hormones derived from 17 salt stress-inducible small coding genes in Arabidopsis suggests that four genes possess increased salinity stress tolerance and among these one of the genes (AtPROPEP3) has the potential to induce salt stress resistance by treatment with a 13-peptide (KPTPSSGKGGKHN) fragment, providing evidence for salinity tolerance in plants in retaliation to a peptide treatment (Nakaminami et al. 2018). In Plants salt stress-responsive genes communicate specific signals, leading to the initiation of defense response and involving the transporters, and calcium and kinases provoke molecular responses for any signaling within the cell (Shah et al. 2021).

3.4 Heavy metal stress and plant responses and defenses

Heavy metal stress has emerged as a most challenging threat with an adverse impact on agriculture development, growth and productivity mainly in arable soils (Ali et al. 2018). The heavy metals generated through mining activities, increases soil pollution, get absorbed into plant tissue, and can cause cellular injury and senescence (Keyster et al. 2020). The increase in human-induced activities like industrialization had caused exaltation in heavy metal contamination of terrestrial and aquatic ecosystems and most of these are neurotoxic, carcinogenic, and poisonous even at low concentrations (Gaur et al. 2021). Industrial waste and municipal sewage are other important source of heavy metals such as Cu, Ni, Fe, Co, Mn, Zn, Hg, Cd, and arsenic, which are essential micronutrients, however their excess shows deleterious effects on plant growth, physiology, metabolism, and senescence (Ghori et al. 2019).

Heavy metal toxicity affects physiological and biochemical activities depending on the particular metal, its chemical form, concentration, and plant species (Ackova 2018). A study on the impact of toxicity of heavy metals cadmium and nickel on the physiological and biochemical processes in *Pisumsativum* reveals enhancement of lipid peroxidation, hydrogen peroxide, protein carbonylation, proline, oxidized glutathione, phenolics, and reduced glutathione (El-Amier et al. 2019). The drainage water used in agricultural irrigation and unremitting industrial activities also contains heavy metals causing environmental hazards, and are serious threats to human health. The study of macrophytes in the middle Nile Delta reveals high contents of Zn, Cr, and Cd in the upstream and Cu, Mn, and Ni downstream of the drains. The *Phragmitesaustralis* root shows the highest accumulation of the elements, while shoots of *Typhadomingensis* reveal the highest bioaccumulation factor (BAF) (EL-Amier et al. 2020).

Various plants have developed detoxification mechanisms to minimize the deleterious effects of heavy metals. Through chelation strategy using phytochelatins (PCs), a type of Cys-rich peptides derived from reduced glutathione (GSH) in a transpeptidation reaction, plants have their own detoxification method to counter heavy metals toxicity (Yadav 2010). Besides, the compounds like proline (Pro), and arbuscularmycorrhizal (AM) fungi have the potential to combat heavy metal (HM) toxicity, reducing their uptake via binding metal to the hyphal cell wall and releasing extracellular biomolecules to destroy the toxic ions (Emamverdian et al. 2015). According to an investigation of Wheat crops the application of herbicides, Aminopielik D 450 SL and Chwastox 300 SL, has the potential in checking the heavy metal inflation in roots and limiting the transportation to above-ground parts (Skiba and Wolf 2017).

The improvement in phytoremediation technique through plant transformation and nuclear and cytoplasmic genome transformation has the potential in extracting heavy metals from soil (Kozminska et al. 2018). The use of plant-associated microbes like phyto-bacteria or genetically transformed bacteria helps in minimizing metal bioavailability in soil and has emerged as a promising remediation technique for improving heavy metal tolerance in plants (Tiwari and Lata 2018). Application of nano-hydroxyapatite (n-HAP) amended soil with indigenous microorganisms increases shoot dry biomass and suppresses Cd and Pb uptake and diethylenetriaminepentaacetic acid (DTPA) as justified in a pot experiment conducted on coriander (*Coriandrumsativum* L.) (Mi et al. 2022).

3.5 Various other mechanisms to counter abiotic stresses in plants

The plant generally possesses defense organs in form of external cuticle and unsaturated fatty acids, molecular chaperones, compatible solutes, and reactive species scavengers inside the cells against abiotic stresses. The plant responds to stress through upstream signaling molecules like reactive oxygen species, stress hormones, polyamines, gasotransmitters, calcium, and phytochromes and downstream gene regulation factors, like transcription (He et al. 2018). The plant has an effective defense mechanism integrating molecular and cellular responses like the perception of stress signals, target stress-related genes, transcription regulators, transducers, and metabolites against abiotic stresses (Gill et al. 2016). The miRNAs (microRNAs) small regulatory molecules involved in biogenesis pathways are significant in gene expression reprogramming and can play a vital role in plant responses under stress conditions (Morad-Talab and Hajiboland 2016).

Potassium (K) as an essential element can also play a significant role in defending against biotic and abiotic stresses including pests, diseases, salinity, drought, waterlogging, and cold and frost in plants (Wang et al. 2013). The K+ provides abiotic stress tolerance through protein synthesis, enzyme activation, stomatal movement, turgor regulation, photosynthesis, and osmotic adjustment. It also activates antioxidant defense systems. The accumulation of K+ in plants helps to develop stress tolerance against drought, lodging, late-season rains, salinity, cold, frost, and heat waves (Perelman et al. 2022). Similarly, the concentration of Ca2+ serving as an important pervasive intracellular second messenger nutrient, increases during drought, salinity, and cold stress, thus helping the survival of plants under adverse environmental conditions (Pathak et al. 2020).

Synthetic Plant growth regulators, like Thiourea containing nitrogen and sulfur, have emerged as an important compound to counter biotic and abiotic stresses at the cell, tissue, and organ levels in plants (Waqas et al. 2019). Chitosan, a biostimulant used for plant growth and protection has the potential to evoke a signal transduction pathway and produce proteins, genes, and secondary metabolites like hydrogen peroxide and nitric oxide. This polymer when applied before exposure to salt, drought, and heat stress induces the growth and production of secondary metabolites, antioxidant enzymes, and abscisic acid, and can act as an important abiotic stress tolerance compound (Pongprayoon et al. 2022). A study suggests that H_2S also shows plant defense signaling by inducing the expression of pathogenesis and defense-related genes, regulating glutathione metabolism, interacting with phytohormones such as auxin, ethylene, and jasmonic acid, and regulating enzyme activity through post-translational tempering (Chaudhary et al. 2022).

IV. CONCLUSIONS

Abiotic stresses have emerged as a major challenge to future food security. Climate change, global warming, and increasing soil conditions due to salinity and heavy metal contamination are reducing the forest and agricultural areas globally. In order to assure food security for the growing human population and to tackle the challenges of producing more in less area, there is a need to amalgamate system-level information on abiotic stress response pathways, identify stress defensive networks, and apply new scientific techniques to develop crops that can combat abiotic stress conditions with more yield. Understanding proteomic and genomic secondary metabolites and chemical compounds used to develop defenses in the plants should be a priority to sustain the survival and productivity of the plants under stress conditions.

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