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RESILIENCE AND RESPONSE STRATEGIES OF PLANTS TO ABIOTIC STRESS : A REVIEW

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ABSTRACT

Abiotic stress factors, including extreme temperatures, drought, salinity, and heavy metal toxicity, pose significant threats to plant and microbial ecosystems, which adversely affects the agricultural sector. Abiotic stressors disrupt the normal physiological and biochemical processes of organisms, leading to cellular damage, reduced growth, and diminished productivity. Understanding the mechanisms underlying abiotic stress responses is crucial for the development of effective mitigation strategies. Key mechanisms include osmotic regulation and antioxidant defense systems, which allow organisms to adapt to adverse environmental conditions. The impacts of abiotic stress are wide-ranging, affecting crop yields, food security, and natural ecosystems. Rising global temperatures and changing precipitation patterns exacerbate the frequency and severity of abiotic stress events, making it imperative to find sustainable solutions. Mitigation strategies encompass a range of approaches, from traditional breeding and genetic engineering to agronomic practices and ecosystem-based approaches.
***Keywords* :** Stress, Mitigation, Genetic engineering, Ecosystem

Introduction

Crops have been exposed to a different challenging environment since their emergence. Numerous physical and chemical factors, including extreme temperature, drought, flood, salinity, heavy metals, ultraviolet (UV) radiation, among others, can be detrimental to their survival (Figure 1, Waqas *et al.*, 2017). These challenges, commonly grouped together under the termabiotic stress and it caused a significant decline on food production and overall agricultural productivity, lead to adverse impact on food security (Wania *et al.*, 2016). Abiotic stress is referred as the detrimental effects of non-living factors within a particular environment on living organisms. Approximately 90% of cultivable lands are susceptible to experiencing one or multiple of the aforementioned stresses (dos Reis *et al.*, 2012), leading to as much as a 70% reduction in yield for essential food crops (Mantri *et al.*, 2012). Among these stresses, salt stress is mostly affecting the crop yield as observed by the ongoing global increase in salinity on arable lands (Munns and Tester, 2008). The majority of plants face extreme difficulties in surviving when sodium chloride (NaCl) concentrations surpass 200 mM (Flowers and Colmer, 2008). This high salinity significantly disrupts various stages of their life cycle, including seed germination, establishment of seedling, vegetative and reproductive growth (Guo *et al.*, 2012, 2015, 2018), primarily due to issues related to ionic toxicity, osmotic pressure, oxidative harm, and nutrient deficiencies (Zhao *et al.*, 2010). Furthermore, it is closely linked to drought, which is another widespread global concern and can be exacerbated by extreme temperatures (Slama *et al.*, 2015).

The demand for food production must be increased twofold by the year 2050 in order to accommodate the rising needs of a growing global population. Crop plants have developed two primary approaches to cope with challenging environmental conditions, as they are unable to control their surroundings. These strategies involve either avoiding stress or tolerating it. Unlike animals, plants cannot move to escape unfavorable conditions, so they have evolved sophisticated mechanisms to avoid stress. One notable example of this is adjusting their life cycle so that the sensitive growth periods occur either before or after the stress event. Tolerance mechanisms primarily rely on biochemical and metabolic processes, which are genetically regulated. These mechanisms serve to counteract, neutralize, or endure the adverse environmental conditions.

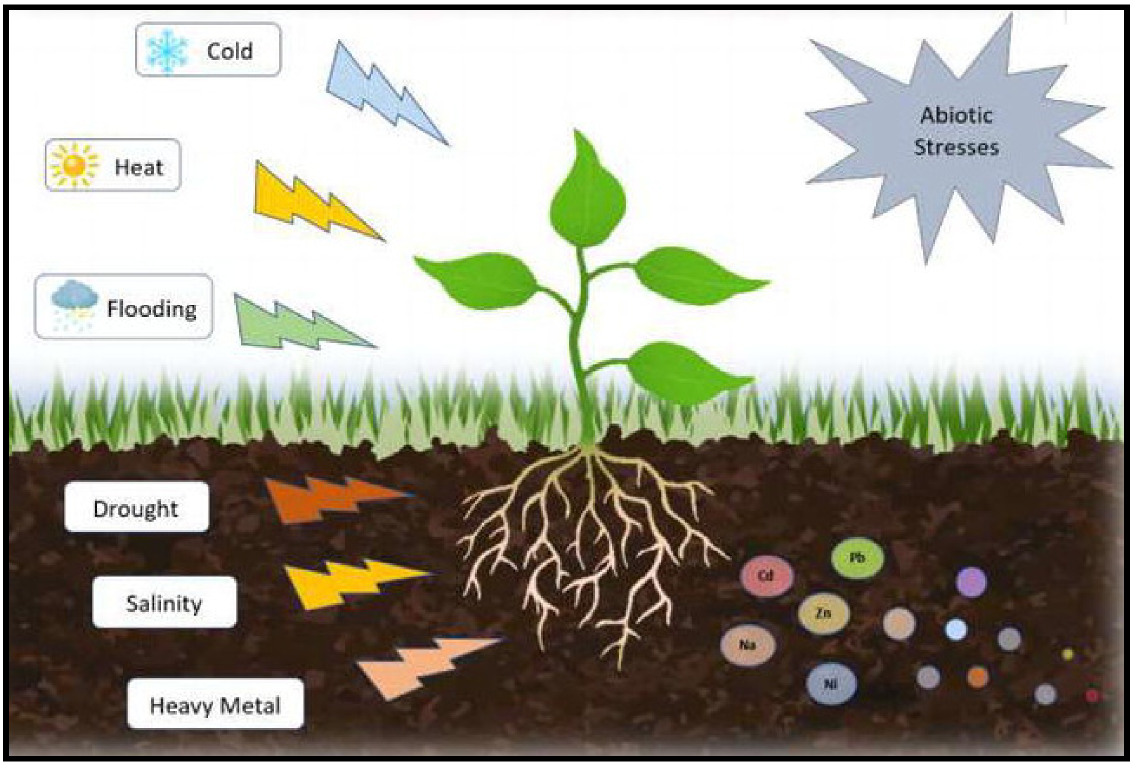

Fig. 1: Abiotic Stresses affecting the plant (Source: Kul *et al*., 2021)

Mechanism employed by plant under abiotic stress

(a) Temperature Stresses

Temperature levels that exceed or fall below the optimum range impede the growth and development of crop plants and are categorized as heat stress and cold stress, respectively (Kotak *et al.,* 2007). Both heat stress and low-temperature stress have negative impacts on seed germination, photosynthesis, reproductive growth, and crop yield. Additionally, they lead to the occurrence of oxidative stress (Hasanuzzaman *et al*., 2013a). Extreme temperature stress, whether in the form of heat or cold, may completely prevent seed germination, a phenomenon known as thermo-inhibition (Takahashi, 1961). In cereals, heat stress induces spikelet sterility, shortened the duration of grain-filling, and disrupts various physiological processes in the plant. Consequently, these effects have a detrimental impact on grain yield (Xie *et al.,* 2009; Xu *et al.,* 1995). Cold stress results in inhibited plant growth, a compact and bushy appearance, diminished leaf expansion, leaf discoloration (chlorosis), wilting, and in severe cases, cell death (necrosis) and also causes cellular dehydration due to the formation of ice crystals (Hasanuzzaman *et al.,* 2013b). Plants use various mechanisms to endure heat stress and cold stress, which may involve changes in leaf orientation, adjustments in membrane lipid composition, transpiration cooling, through morphological and phenological modifications, by shortening their life cycle through early maturation (Hasanuzzaman *et al.,* 2013a).

Tolerance mechanisms encompass morphological and anatomical adaptations in response to both heat and cold stress. On a molecular level, heat stress triggers the activation of heat stress transcription factors, thereby stimulate the production and accumulation of molecular chaperones like heat shock proteins (HSPs) and other transcripts. These molecular chaperones play a crucial role in safeguarding plant metabolism (Mittler *et al.*, 2012). Plants manufacture antioxidants to counteract the harmful consequences of the excessive accumulation of reactive oxygen species (ROS). They produce a range of enzymatic and non-enzymatic ROS scavengers, which play a vital role in detoxifying the plant system and preventing programmed cell death during heat stress. Similar toheat stress, calcium signaling and antioxidants also play a significant role in enhancing tolerance to cold stress in plants. Additionally, plants are capable of tolerating or recovering from cold stress through repair mechanisms that involve restructuring the plasma membrane and accelerating the synthesis of osmolytes (Hasanuzzaman *et al.,* 2013b).

(b) Drought

Insufficient water availability has an adverse effect on the growth, development, and production of plants. Drought conditions lead to a decrease in the water potential of leaves by altering cell turgor pressure. This reduced water availability within the plant triggers the production of abscisic acid (ABA), which in turn results in the closure of stomata. Stomatal closure reduces the assimilation of carbon dioxide (CO_2), impacting the photosynthetic process. The plants exposed to drought condition faces cell peroxidation damage, accompanied by the accumulation of reactive oxygen species (ROS). Additionally, there is a decrease in the electron transport rate, leading to oxidative stress and a subsequent disruption of physiological processes of the plant. Changes in metabolites like sugars, acids, amino acids and carotenoids directly impact the quality of the produce during drought condition (Ripoll *et al.,* 2016). Plants employ various strategies to cope with drought stress, including speeding up their life cycle, developing specialized structures or process of water absorption and retention, making osmotic, metabolic, and morphological adaptations, modifications at gene level to better handle or endure drought conditions.

(c) Flood

Crop plants depend on the unimpeded exchange of atmospheric gases for their like photosynthesis and respiration, respectively. The primary obstacle to the diffusion of gases typically arises when water saturates the root zone in flooded soils or accumulates above the soil surface during flood condition (Bennett and Freeling, 1987). Extended periods of flooding lead to a shift in the composition of soil microorganisms, favoring anaerobic microorganisms that rely on alternative electron acceptors instead of oxygen. This shift has the consequence of increasing the accumulation of reduced and harmful forms of mineral ions like nitrite and ferrous ions in the soil. These conditions are unfavorable for most plants, as they are not adapted to thrive in such soils. When an adult plant experiences short-term anaerobic stress due to factors like poor drainage or periodic flood condition, it directly affects root development by reducing the level of oxygen around the roots. These changes in the roots can subsequently lead to alterations in shoot development, driven by metabolic changes occurring in the roots (Boru *et al.*, 2001). The quiescence strategy involves stopping plant growth to save energy, which can be used later when the floodwaters recede. This strategy is crucial for plants tolerance to flood condition because if they remain underwater for an extended period, they will eventually die due to the depletion of their reserved food material. In contrast, elongation growth is a processinduced by plants to keep their height above the water surface. This strategy is associated with tolerance to flash flood. Plants naturally undergo complex changes in their anatomy and metabolism to function under anaerobic conditions. One such adaptation is the presence of intracellular air spaces for continuous gas exchange from the plant's canopy to its root system known as aerenchyma (Bailey-Serres and Voesenek, 2008). The adjustments in plant metabolism in response to submergence stress are influenced by several plant hormones like ethylene, gibberellin, and abscisic acid (ABA).

(d) Salinity

Elevated salt concentrations in the soil have two significant effects on plants. First, they reduce the osmotic potential of the soil solution, leading to water stress in plants. Second, they induce severe ion toxicity, particularly because sodium ions (Na+) cannot be efficiently stored in vacuoles as they are in halophytes (Figure 2). Finally, the salts interact with mineral nutrition can lead to imbalances and shortages in essential nutrients (Flowers and Yeo, 1995). The ionic stress is mainlyoccurred due to sodium toxicity to crops. In specific saline soils, this ion toxicity is worsened by the high alkaline pH levels. The strategies employed to resist excessive salt levels can be broadly categorized into two groups: (1) avoidance and (2) tolerance mechanisms, which encompass cellular and molecular approaches (Fu *et al.*, 2011).

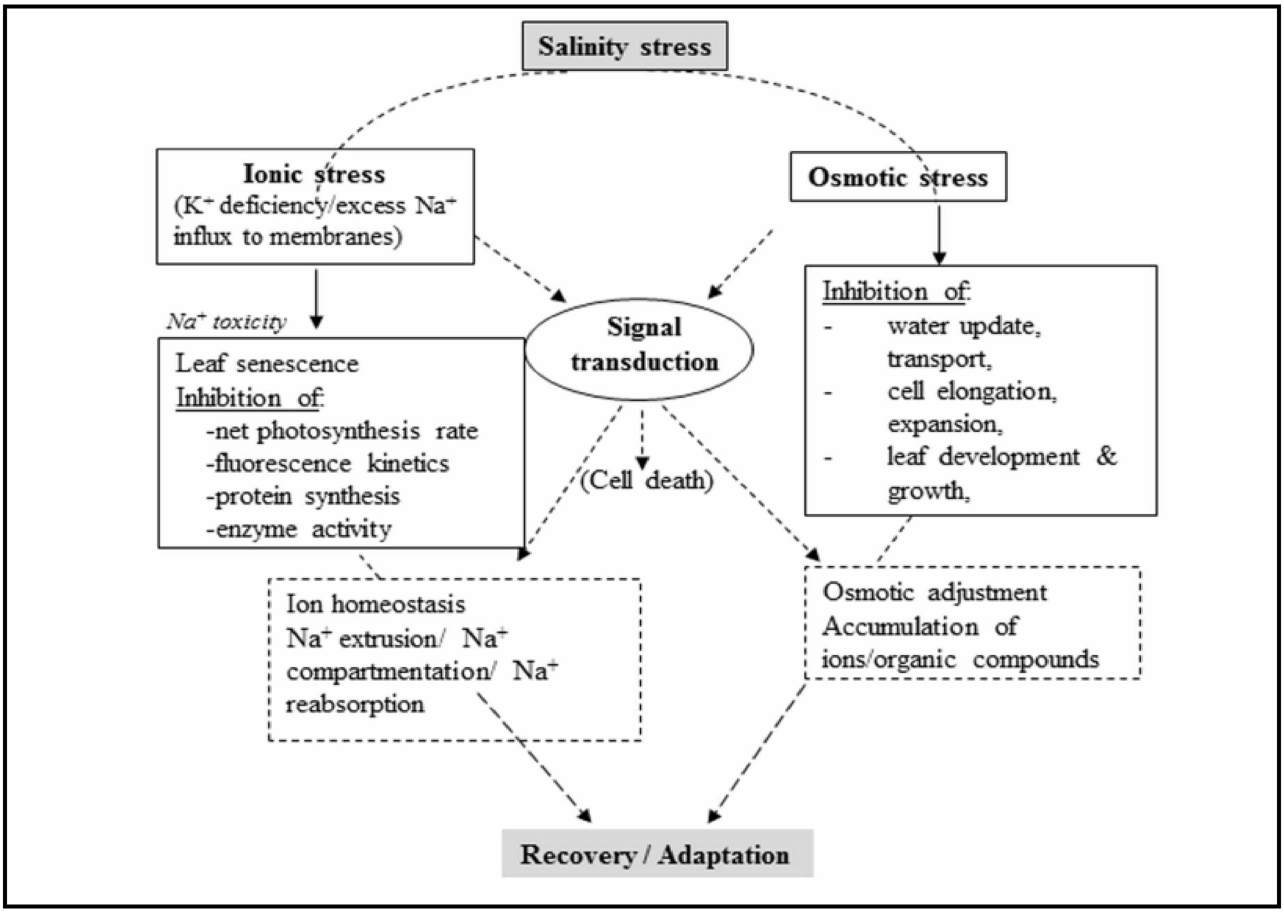

Fig. 2 : Adverse effect of salinity to plants and their adaptation (Horie *et al.,*2012)

The accumulation of compatible solutes, such as proline, nitrogen-containing compounds like glycine betaine, polyols, polyamines, and substances from the late embryogenesis abundant (LEA) superfamily, in response to salinity is a significant mechanism. This mechanism primarily functions to reduce the intracellular water potential of plants, thereby restoring the lost water potential gradient (Verslues *et al.,* 2006). Osmotic adjustment takes place when there is an increase in solute concentration inside a plant cell, allowing it to maintain a positive turgor pressure. To achieve this, the cell actively collects solutes, which leads to a decrease in the solute potential, encouraging the flow of water into the cell. Osmotic adjustment helps mitigate the adverse effects of stress on the growth and crop yield.

(e) Heavy metal

The problem of metal contamination is on the rise in cultivated regions. Plants' reactions to metals depend on the concentration of the metals. The various sources of heavy metals in the soil are represented in the figure 3. Certain heavy metals, such as Cd, Cu, Mn, Bi, Zn, and others, naturally occur in soils at specific levels. However, an increase in their concentrations serves as an indicator of pollution in a particular area. Elevated levels of these heavy metals pose significant adverse effect because they possess strong accumulative properties and can be highly toxic. Anthropogenic sources are the primary contributors of pollutants to soil (Chibuike and Obiora, 2014). Elevated levels of metal concentration have immediate detrimental impacts, such as the suppression of cytoplasmic enzyme activities and the harm caused to cell structures due to oxidative stress (Jadia and Fulekar, 2009).

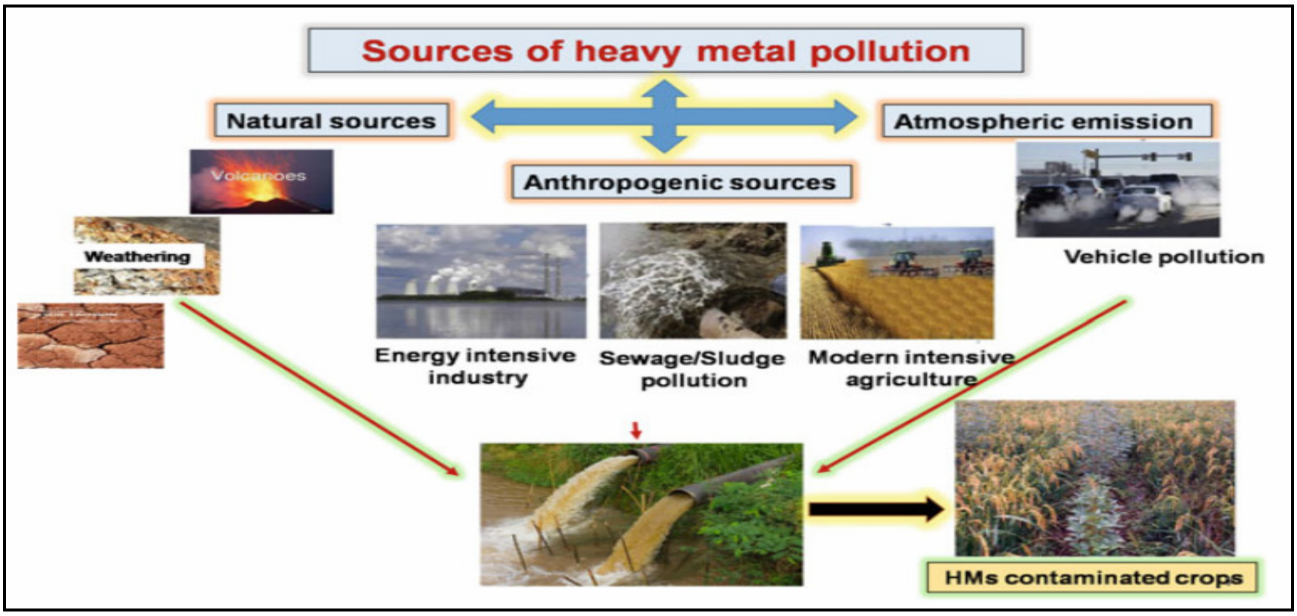

Fig. 3 : Sources of heavy metals (Akhtar *et al.,* 2023)

Improvement strategies under abiotic stress

Cultural practices involve adjusting planting time and altering the planting density of crops to prevent or mitigate the impact of stressful conditions (Hasanuzzaman *et al.,* 2013b). Additional methods encompass the application of protective substances such as osmo-protectants, phytohormones, signaling molecules, and trace elements. These applications are aimed at safeguarding plants, particularly in challenging conditions like heat stress. Genetically modified crops that incorporate heat shock proteins and heat shock transcription factors have demonstrated enhanced heat tolerance in various crop species, including maize, rice, carrots, and tobacco (Hasanuzzaman *et al.,* 2013a). Wheat crops that have been genetically engineered to produce antifreeze proteins from winter flounder fish exhibit improved frost tolerance. These antifreeze proteins interact with developing ice crystals within plant cells, effectively impeding their growth, thus enhancing the plant's ability to withstand freezing temperatures (Khanna and Daggard, 2006).

Metabolic engineering involves enhancing the production of specific metabolites to increase stress tolerance in plants. Desirable gene transformation methods play a crucial role in introducing genes that governed the traits like tolerance or resistance to stress into high-quality breeding lines. Another strategy to combat drought stress involves inoculating plants with bacteria that promote growth and help them withstand adverse conditions. There are various sources of variation for submergence tolerance within the crop species. There is a need to identify new genetic resources with significant ability to withstand submerged condition to widen the gene pool of modern crops. In the context of rice, a robust submergence-tolerant Quantitative Trait Locus (QTL) known as Sub1 is currently being used as marker in breeding programme and gene transformation techniques (Neeraja *et al*., 2007).

The approaches for enhancing the salt tolerance of plants have been achieved through traditional breeding methods. These methods involve extensive screening of land races and germplasm (Roy and Sengupta, 2014), as well as the use of transgressive segregation (Shahbaz and Ashraf, 2013) and triple test cross techniques (Sadat Noori and Sokhansanj, 2004). Genetic engineering has also been employed as a tool to create salt-tolerant crop varieties. This involves the incorporation of genes or QTLs that regulate salt stress signaling at the cellular level into crop plants (Hossain *et al.* 2007). Additionally, advanced molecular biology techniques, such as genomics, transcriptomics, proteomics, and metabolomics, collectively referred to as omics tools, are used to identify and functionally characterize the molecular components and mechanisms associated with salt tolerance (Figure 4**,** Inan *et al*., 2004).

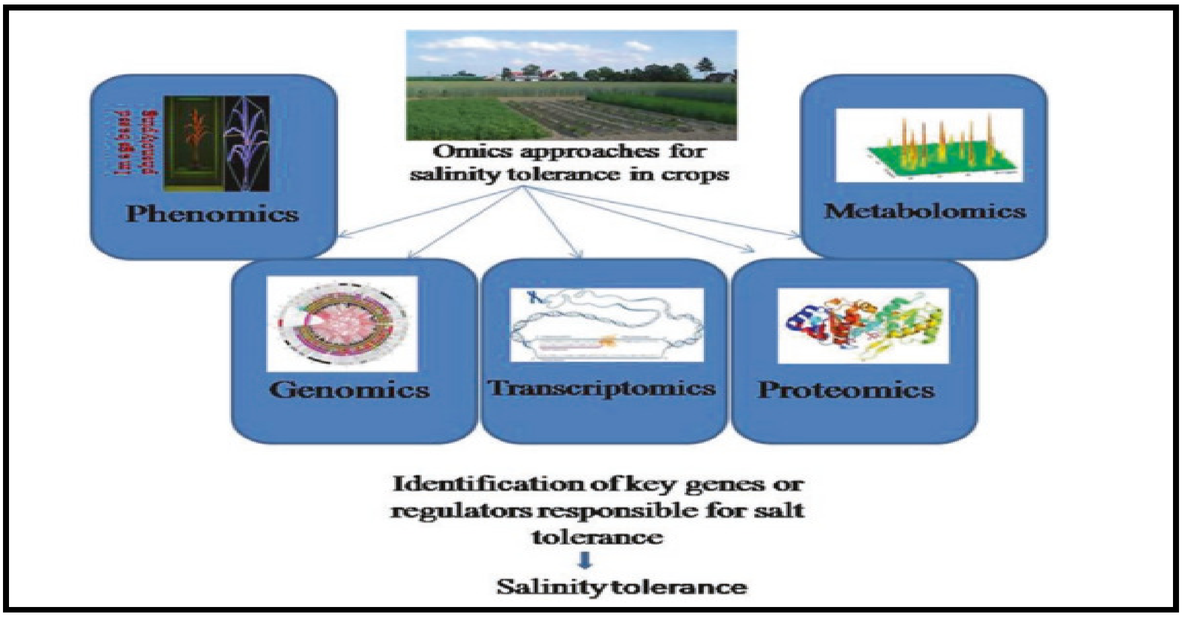

Fig. 4 : Omics-based approaches (Inan *et al.,* 2004)

The heavy metals are eliminated from the soil through bioremediation process. Bioremediation approach primarily encompasses two methods: phytoremediation and microbial remediation, which are used for removing heavy metals from soil. Phytoremediation involves the use of plants to either capture and isolate environmental contaminants or change them into non-harmful forms (Cunningham and Berti, 1993). Bioremediation is a broader concept that includes all techniques and processes aimed at converting a polluted environment into an uncontaminated state. Bioremediation primarily relies on the use of microbes (Boopathy, 2000) or microbial processes to break down and transform environmental contaminants into less harmful or non-toxic forms (Garbisu and Alkorta, 2003).

Conclusion

Crop plants uses two main mechanisms *viz.*, avoidance and tolerance to cope with the challenging environmental conditions. The increasing challenges posed by climate change and its related stress factors, there is a need for innovative strategies to increase the crop productivity and global food security. Through research involving transcriptomics, genomics, and metabolomics, scientists have uncovered complex pathways and identified genes linked to stress tolerance.

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