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NL Journal of Agriculture and Biotechnology

(ISSN: 3048-9679)

Volume 2 Issue 3 june 2025

Editorial

Integrating Bioremediation, Plant-Microbe Interactions and Mineral Nutrition in Plant Stress Physiology for Sustainable Agriculture

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DOI: 10.71168/NAB.02.03.113

Received Date: May 13- 2025 **Publication Date:** May 29- 2025

Plants continuously face a wide array of environmental challenges. They, as sessile organisms, are constantly challenged by a variety of environmental stresses, both abiotic such as drought, salinity, heat, and heavy metals and biotic, including pathogens and pests. As global environmental changes accelerate, understanding and enhancing plant resilience is becoming a central focus in agricultural and ecological research. Plant stress physiology seeks to unravel the complex responses plants deploy to detect, mitigate, and adapt to these stresses at molecular, cellular, and whole-plant levels. In the current era of rapid climate change and environmental degradation, insights from stress physiology are vital. They help us understand how plants maintain growth and productivity under unfavourable conditions and provide the basis for breeding or engineering stress-resilient crops. Heavy metal pollution has become a pressing global concern due to its long-lasting impact on ecosystems, agriculture, and human health. Industrialization, mining, improper waste disposal, and excessive use of agrochemicals have led to the accumulation of toxic metals such as lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), and arsenic (As) in soil and water. These contaminants are non-biodegradable and can persist in the environment for decades, posing serious risks to food safety and biodiversity.

The present topic brings together recent advancements in plant stress physiology, bioremediation, mineral nutrition and plant-microbe interactions, highlighting their interconnected roles in promoting sustainable plant growth and ecosystem health. It explores the mechanisms by which plants perceive, respond to, and adapt to stress. From hormonal regulation and gene expression changes to metabolic adjustments and cellular repair mechanisms, this field offers valuable insights into how plants survive under adverse conditions. Such knowledge is crucial for developing stress-tolerant crop varieties and improving agricultural productivity in increasingly unpredictable climates.

Meanwhile, bioremediation- the use of living organisms, biomaterials particularly plants, biopolymers and microbes, to clean up polluted environments—has gained significant traction. Plants capable of phytoextraction, phytostabilization, or rhizofiltration, microbes of bioaccumulation, biovolatalization, biosorption and other mechanisms and biopolymers of chelation mechanism that can remove or neutralize contaminants from soil and water. The success of bioremediation is often closely tied to the presence and activity of beneficial microbes that enhance the plant's ability to tolerate and detoxify pollutants.

Bioremediation offers an environmentally sustainable and cost-effective solution for mitigating heavy metal contamination. This process involves the use of living organisms, such as plants, biopolymers, fungi, algae, and microorganisms, to remove, immobilize, or transform toxic metals into less harmful forms. Unlike conventional remediation methods that are often expensive and disruptive to the environment, bioremediation techniques can be applied in situ with minimal ecological disturbance. Advancements in molecular technologies have deepened our understanding of the metabolic pathways and stress responses that underpin bioremediation. Along with the identification of specific genes, transporters, and enzymes responsible for metal detoxification, which can be targeted to improve the performance of bioremediation agents.

Mineral nutrition plays a fundamental role in shaping how plants respond to environmental stresses. Under conditions such as drought, salinity, extreme temperatures, and heavy metal toxicity, the availability and balance of essential nutrients become critical determinants of plant resilience. This issue explores the intricate relationship between mineral nutrition and plant stress physiology, highlighting how nutrient management can mitigate stress effects and support sustainable crop production.

Essential minerals not only contribute to basic metabolic functions but also act as key players in stress signaling, antioxidant defense, osmotic adjustment, and membrane stability. For example, potassium helps regulate osmotic balance and stomatal movement during drought stress, while calcium serves as a secondary messenger in signalling pathways triggered by various stressors. Micronutrients like zinc, manganese, and iron support enzymatic activity and help neutralize reactive oxygen species generated during stress conditions.

Thus, integrating plant-microbe interactions, plant stress physiology, and mineral nutrition offers a holistic path to sustainable agriculture. This strategy supports resource-efficient farming, improves soil health, and enhances resilience to climate variability all while maintaining or increasing crop yields.

Citation: Dr. Binny Sharma. "Integrating Bioremediation, Plant-Microbe Interactions and Mineral Nutrition in Plant Stress Physiology for Sustainable Agriculture". NL Journal of Agriculture and Biotechnology 2.3 (2025): 01-02.