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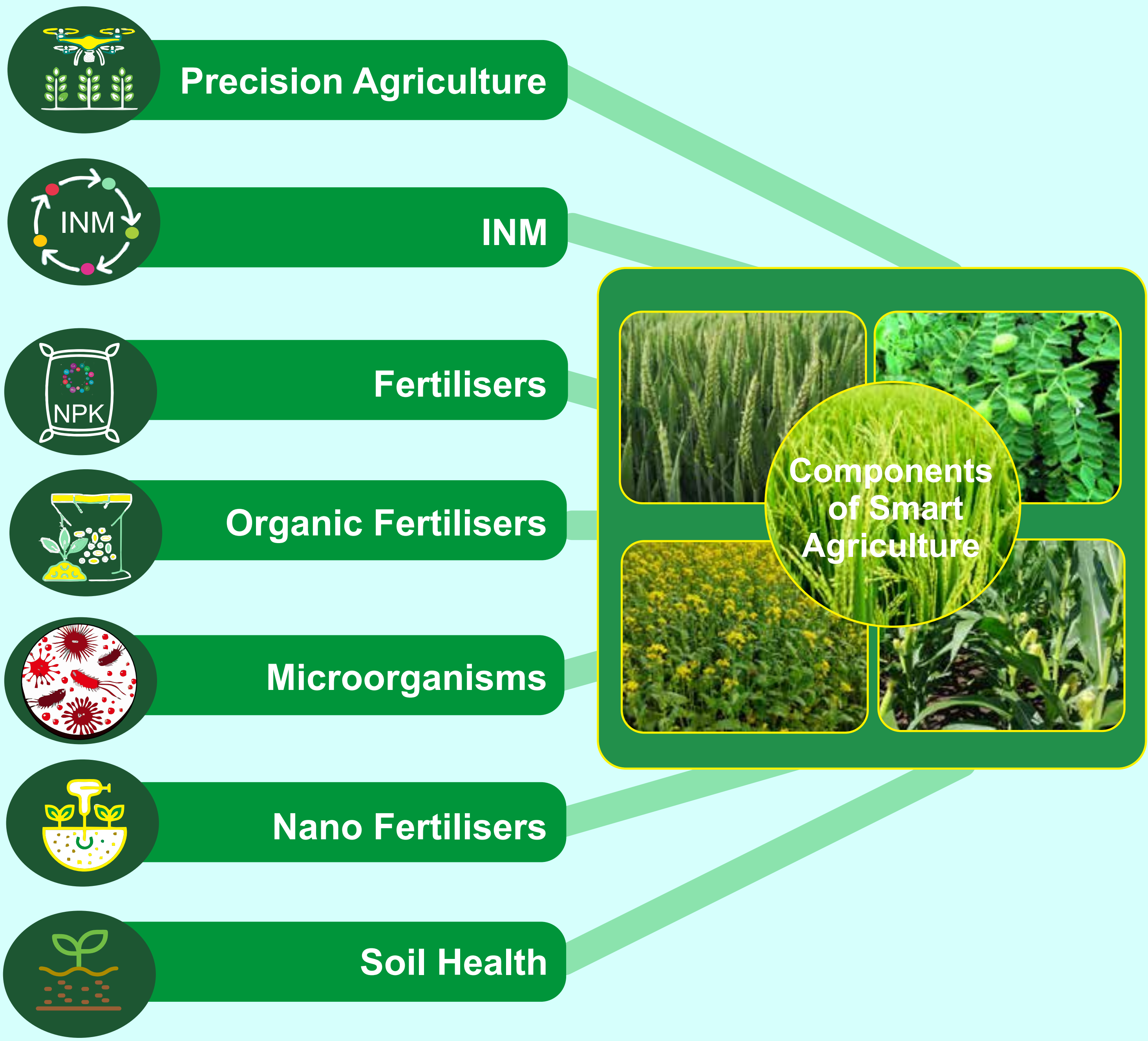

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Micronutrients in Abiotic and Biotic Stress Management for Food and Nutrition Security

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Abstract

Micronutrient deficiencies in soils and crops have been increasing globally, with prevalence of multi-micronutrient deficiencies being reported in several countries. Among these, zinc (Zn) and boron (B) are the dominated ones. In India, widespread deficiencies of Zn, B, iron (Fe), and other essential micronutrients have been documented, resulting in significant reductions in both crop productivity and quality. Furthermore, deficiencies of micronutrients such as Zn and Fe extend beyond agricultural impacts, adversely affecting human health leading to micronutrient malnutrition. Micronutrients, although required in small amounts, are essential and indispensable for a wide range of physiological, biochemical, and molecular functions that enhance plant resilience to both abiotic and biotic stresses. Abiotic stresses such as drought, heat, salinity, heavy metal toxicity, anaerobic, and oxidative damage, along with biotic stresses caused by pathogens and pests, continue to limit crop productivity and quality on a global scale.

The paper reviews recent advances in understanding the roles and functions of essential micronutrients - Zn, B, Fe, manganese (Mn), copper (Cu), molybdenum (Mo), chlorine (Cl), and nickel (Ni) - in mitigating stress responses in plants. These elements contribute to stress tolerance through multiple mechanisms, including the scavenging of reactive oxygen species, reinforcement of cell wall structures, modulation of stress-associated gene expression, and interaction with key signaling pathways. Furthermore, emerging approaches such as bio-fortification, seed priming, and nanotechnology are highlighted as promising strategies for harnessing micronutrients to enhance plant adaptation under stress conditions. Finally, the paper highlights existing knowledge gaps and outlines future research directions aimed at promoting sustainable, climate-resilient agriculture that ensures food and nutrition security.

Key words: Micronutrients, abiotic stress, biotic stress, zinc, boron, food security, nutrition security

Introduction

Global food security is increasingly threatened by stresses that lower crop yield and quality. Abiotic factors such as drought, salinity, and extreme temperatures can reduce yields by over 50%, while biotic stresses from pathogens and pests add further losses (Mittler 2022). Climate change intensifies these challenges, compromising food security for the burgeoning population, underscoring the need for resilient crops and sustainable farming systems. Micronutrients, required in small quantities (<100 mg kg^{-1} dry matter), are critical as enzyme cofactors and regulators of biochemical pathways. They play a disproportionate role in plant metabolism and stress adaptation. Deficiency or imbalance disrupts antioxidant activity, hormone signaling, and structural integrity, thereby heightening stress sensitivity. In light of evolving climate change crisis, managing micronutrient is increasingly vital for sustaining crop resilience (Semba et al., 2022).

Micronutrients in Abiotic Stress Management

Antioxidant Defence and ROS Mitigation

Under stress, reactive oxygen species (ROS) can harm proteins, lipids, and nucleic acids. Micronutrients serve as essential cofactors for antioxidant enzymes, enabling them to neutralize these harmful molecules and shield cells from oxidative stress and biomolecular damage. This protective role is vital for maintaining both cell survival and proper function. Some of the key micronutrients include:

Zn, Cu, Mn → Cofactors of superoxide dismutase (SOD)

Fe → Cofactor of catalase (CAT) and peroxidases

Mo → Supports nitrate reductase, maintaining redox homeostasis

Zn, Cu, Mn and Fe support antioxidant enzymes (SOD, CAT, APX/GPX) in detoxifying ROS under abiotic /biotic stress is depicted in **Figure 1**. The key roles of micronutrients under abiotic stress are summarized in **Table 1**.

Case studies on the effect of Zn+B on fenugreek under salinity and B foliar spray reducing *Sclerotinia* lesions are shown in **Figure 2**.

Specific Stress Responses

Drought: Zn improves stomatal regulation and proline synthesis, whereas B maintains membrane stability.

Salinity: Zn and Mn enhance antioxidant systems, and B supports ion homeostasis and osmolyte accumulation.

Temperature Extremes: Cu and Fe protect chlorophyll and electron transport chains, and Zn upregulates heat shock proteins.

Heavy Metals: Zn and Mn reduce the uptake of Cd and Pb, and Mo improves nitrogen metabolism under toxicity.

Anaerobic stress: Zn enhances the activity of alcohol dehydrogenase and ethanol concentration, which is correlated with root growth under stress conditions.

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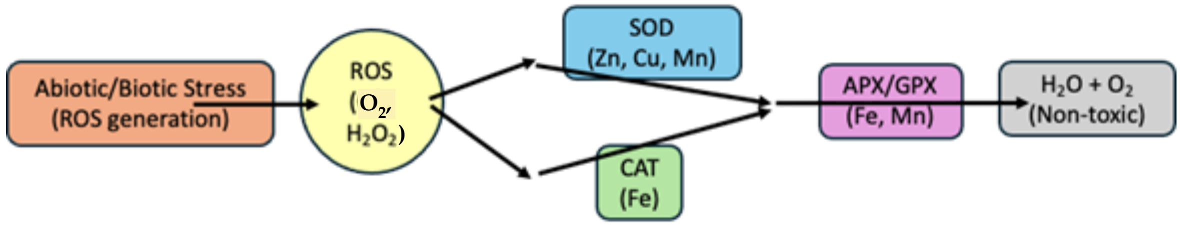

Figure 1. Micronutrient mediated antioxidant defence in plants (Source: Dumanovic et. al., 2021)

Table 1. Role of micronutrients in abiotic stress tolerance (Source: Khan et al., 2024; Cale et al., 2024)

Micro-nutrient	Key function	Stress target	Example evidence
Zn	Cofactor of SOD, regulates stomata	Drought, salinity	Fenugreek under 120 mM NaCl improved yield with Zn+B foliar spray
B	Cell wall stability, SAR priming	Pathogens, drought	Reduced *Sclerotinia* lesion size in *B. napus*
Fe	Chlorophyll synthesis, electron transport	Heat, chlorosis	Maintains PSII efficiency under heat stress
Cu	Cofactor of SOD, antimicrobial	Heat, fungal/bacterial	Cu fungicides effective against downy mildew
Mn	Cofactor of peroxidase, lignification	Salinity, disease	Enhances peroxidase activity in cereals
Mo	Nitrogen metabolism, detoxification	Heavy metals	Supports nitrate reductase in legumes under toxicity

Oxidative stress: Zn helps in the proper functioning of the antioxidant defence system and protects cells against oxidative damage.

Chen et al. (2021) demonstrated that coating maize seeds with Zn significantly reduces the accumulation and toxicity of B in the plant, even when grown in high-B soils. The study found that Zn seed coating also helped protect plants by altering the expression of stress-related genes, offering a simple and effective strategy to alleviate such toxicity in maize crop.

Micronutrients and Climate Change

Researchers at Harvard University, USA reported that climate change is making the food crops less nutritious, with their findings published in Nature. The study showed that when CO concentrations rise to around 550 ppm (compared to the current ~420 ppm), the levels of essential nutrients such as Fe, Zn and proteins in six major staple crops—including wheat, rice, maize, and soybeans—decline noticeably. This conclusion was based on a 10-year study conducted

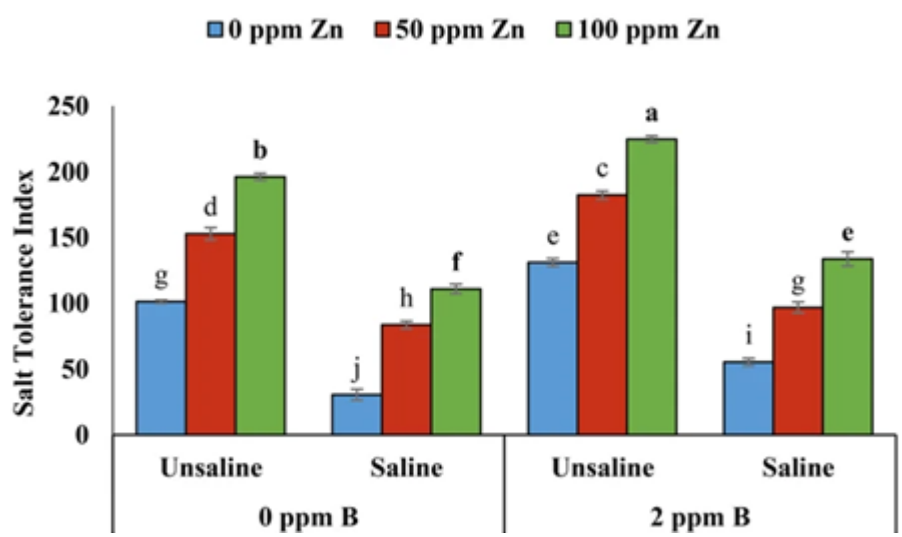

Figure 2. Effect of foliar application of Zn and B on salt tolerance index of fenugreek grown under salinity stress (values represent means±S.E. Significant differences among row spacings were measured by the least significant difference (LSD) at *p*>0.05 and indicated by different letters) (Source: Khan et al., 2024)

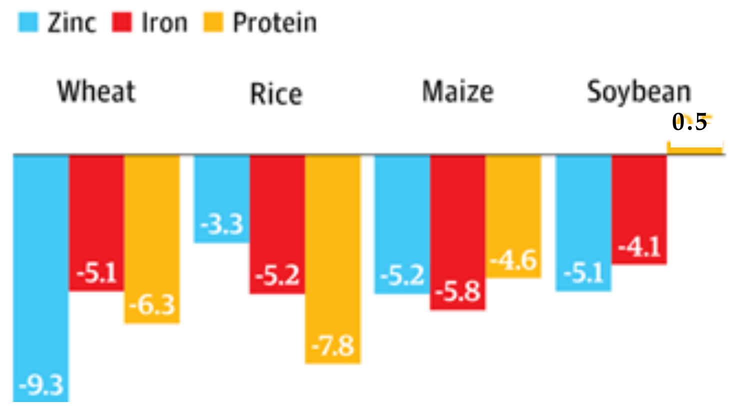

Figure 3. Per cent reduction of nutrients from the staple food crops in an expected level of CO_2 by 2050 (Source: Myers et al., 2014)

across three continents, highlighting how elevated CO could further aggravate the health challenges already faced by billions suffering from malnutrition (Myers et al., 2014).

Zinc and Fe deficiencies represent major global health challenges, affecting over two billion people and contributing to the loss of about 63 million life-years annually. A large portion of those affected rely heavily on C3 grains and legumes as their main dietary sources of Zn and Fe. Research has shown that, under elevated atmospheric CO_2 levels expected by the mid-21st century, these crops tend to accumulate lower concentrations of Zn and Fe when cultivated under field conditions. By 2050, the projected rise in CO_2 may lead to decline in Zn, Fe, and protein content in staple crops such as wheat, rice, maize, and soybean (**Figure 3**).

Micronutrients in Biotic Stress Management

Structural Barriers

Micronutrients play a vital role in reinforcing structural barriers that protect plants from biotic stresses, including pathogen attacks, by enhancing plant architecture and maintaining their physical resilience. Zinc contributes significantly to cuticle stabilization—the protective waxy layer covering the plant surface that serves as a physical barrier against pathogens. It also helps to maintain the integrity and function of the cell membrane. Boron is essential for the formation and stabilization of pectin, a key structural component of the plant cell wall. By cross-linking pectin molecules, B strengthens the cell wall, making it less susceptible to enzymatic breakdown by pathogens, thereby limiting pathogen invasion.

Figure 4 illustrates strengthening the plant cell wall and providing defence against pathogen invasion by Zn, B and Cu.

Defence Signalling

Recent studies emphasize the distinct roles of Zn and B in modulating plant defence signaling against pathogens. Zinc has been shown to induce pathogenesis-related proteins and regulate Zn-finger transcription factors, which serve as key regulators of both abiotic and biotic stress tolerance, thereby offering new insights into the regulatory modules of plant immunity (Huang et al., 2024). Whereas, B has been reported to prime systemic acquired resistance pathways, as demonstrated in *Brassica napus* against *Sclerotinia sclerotiorum* (Cale et al., 2024).

Antimicrobial Properties

Antimicrobial properties describe a substance's capacity to suppress the growth of microorganisms, such as bacteria, fungi, viruses, and parasites. The antimicrobial activity of Cu arises from its redox potential, which disrupts microbial cell membranes, damages proteins and DNA, and promotes the formation of ROS. Through these combined actions, Cu effectively inhibits bacterial and fungal growth. For this reason, it is frequently incorporated into

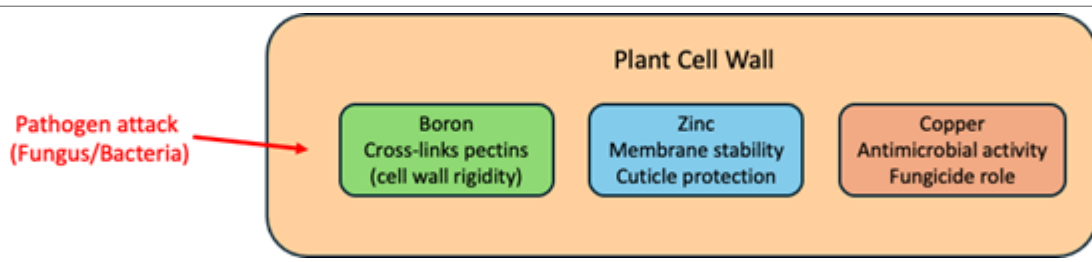

Figure 4. Micronutrient roles in reinforcing cell walls and limiting pathogen invasion (Source: William, 2012)

fungicidal formulations to manage plant diseases like downy mildew.

Interaction with Beneficial Microbes

Zinc enrichment of plant growth-promoting bacteria (PGPB) has been shown to greatly improve their effectiveness in controlling bacterial leaf blight in rice (Sharma et al., 2020). Research further highlights the connectivity between Zn nutrition and PGPB in tropical farming systems (Jalal et al., 2024). This synergistic interaction supports plant growth and resilience by enhancing PGPB functions such as Zn solubilization, phytohormone production, and the activation of systemic resistance against pathogens.

Mechanisms of Micronutrient Mediated Stress Tolerance

Micronutrients play a vital role in lowering ion toxicity, maintaining water balance, enhancing the uptake and assimilation of minerals, regulating gas exchange processes, and alleviating oxidative stress in plants. Adequate levels of these micronutrients enable plants to develop stronger resistance against abiotic stress conditions.

Enzymatic Regulations Micronutrients have definite role of cofactors in SOD, CAT, and ascorbate peroxidase (APX). These enzymes rely on specific micronutrients and play a vital role in scavenging reactive oxygen species. They transform toxic molecules such as reactive oxygen species (O^-_2) and H_2O_2 into harmless products like water and oxygen, thereby shielding plants from oxidative damage during stressful conditions (Ying et al., 2025).

Hormonal Modulation: Zinc plays a key role in the synthesis and function of the growth hormone auxin. Iron influences ethylene, a gaseous plant hormone that regulates both growth and stress responses. Boron interacts with abscisic acid, the main hormone involved in stress regulation, thereby improving drought resistance. These hormone–nutrient interactions are vital for plants to withstand water stress, as reported by Hassan et al. (2020).

Gene Expression: Micronutrients are integral to the regulation of transcription factors, such as zinc-finger proteins, as well as genes associated with stress responses. Among these, zinc-finger transcription factors have been shown to enhance abiotic stress tolerance and improve crop productivity. Consequently, these genes represent valuable candidates for genetic modification, as substantiated by recent studies (Huang et al., 2022).

Signal Transduction: The crosstalk between micronutrients and phytohormones strengthens plants' integrated stress responses by enabling synchronized signaling and gene regulation to cope up with environmental challenges. In a similar way, Wang et al. (2025) stated that micronutrients together with signaling molecules such as melatonin can modulate abscisic acid and gibberellin levels, thereby influencing processes like seed dormancy and stomatal closure during adverse conditions.

Practical Implications and Future Perspectives

- Soil/foliar applications are commonly employed strategies to enhance micronutrient use efficiency. Optimizing these application methods is crucial for improving nutrient uptake and minimizing losses, particularly for essential elements such as Zn, which plays a fundamental role in chlorophyll biosynthesis and enzyme activation (Nadeem and Farooq, 2019).
- Seed priming/coating can improve tolerance to stress during the initial stages of growth. Smart seed coatings are being designed to release beneficial compounds when triggered by environmental factors such as drought or salinity, thereby offering precise protection during early plant development as reported by Patyal et al. (2025).

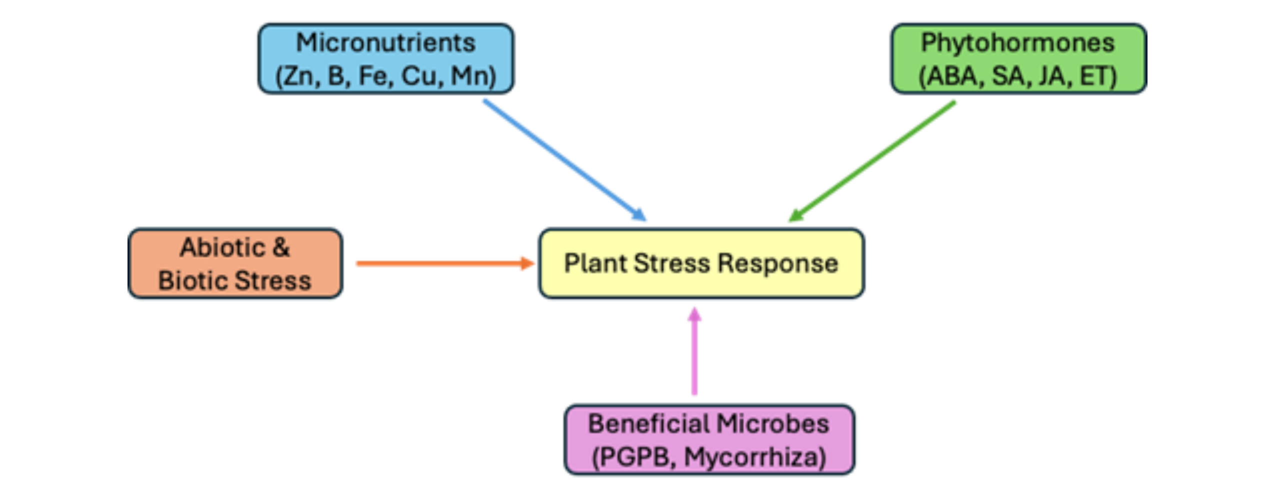

Figure 5. Crosstalk between micronutrients, hormones and microbes in stress management

- Nano fertilisers provide precise nutrient delivery while lowering environmental losses (Yadav et al., 2023). Further studies are needed to evaluate their long-term effectiveness and ecological safety under field conditions, ensuring they support sustainable farming by reducing nutrient leaching and water contamination.
- Integrated nutrient management combined with bio-fertilisers enhances nutrient uptake and crop resilience. Strengthening these integrated systems by harnessing microbial communities and organic matter can support resilient cropping systems, promote efficient nutrient cycling, and lessen dependence on mineral inputs (Amanullah et al., 2023).

Conclusions and Way Forward

Micronutrients are indispensable for enhancing plant tolerance to stress, functioning across physiological, biochemical, and molecular pathways. Adequate and balanced application improves resistance to both abiotic and biotic stresses, positioning micronutrients as a cornerstone of climate-resilient agriculture. Advances in breeding for nutrient-use efficiency, transcriptomic research, and the development of nano-fertilisers are expected to further strengthen micronutrient-based strategies for sustainable crop production. Nevertheless, widespread deficiencies of micronutrients in crops and humans represent a major global concern that requires urgent intervention. A sustainable approach involves the integration of micronutrients into balanced fertilisation regimes through holistic nutrient management practices. Such strategies not only safeguard soil health but also ensure food and nutrition security. Furthermore, concerted efforts of all stakeholders with a favourable and conducive policy environment encouraging the balanced plant nutrition are inevitable.

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