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Combined effects of heavy metal toxicity

and salinity on wheat: Challenges and mitigation strategies

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*Wheat (*Triticum aestivum*), a staple crop nourish nearly 40% of the global population, is increasingly threatened by soil salinity and heavy metal contamination. These stresses, often occurring together, impair photosynthesis, disrupt nutrient uptake, and enhance oxidative damage, leading to reduced yield and grain quality. Heavy metals such as lead (Pb), cadmium (Cd), arsenic (As), and chromium (Cr) accumulate in plant tissues and pose serious food safety concerns. Salinity further aggravates the problem by inducing osmotic stress. This article summarizes the combined effects of salinity and heavy metal toxicity on wheat growth and phenology, and outlines detoxification mechanisms including sequestration, chelation, and antioxidant defense. Sustainable mitigation strategies, such as plant growth-promoting rhizobacteria (PGPR), phytoremediation, bioremediation, organic amendments, and salt/metal-tolerant varieties offer effective solutions. Integrating agronomic, biological, and molecular approaches is essential to sustain wheat productivity and ensure food security under these dual stresses.*

Keywords: Bioremediation, Detoxification, Heavy metal, Plant growth-promoting rhizobacteria, Salinity stress, Wheat

WHEAT (*Triticum spp.*), a staple cereal crop from the Poaceae family, provides food and nutrition to nearly 40% of the global population and contributes approximately 20% of the world's daily calorie and protein intake. It is vital to global food security, especially in developing nations, and supports the livelihoods of over 80 million smallholder farmers. India ranks second globally in wheat production, contributing about 11.9% of global output and cultivating approximately 12% of the total wheat-growing area.

Among the growing challenges in wheat cultivation, heavy metal (HM) contamination and soil salinity pose serious threats to sustainable crop production. Heavy metals such as lead (Pb), cadmium (Cd), arsenic (As), copper (Cu), and nickel (Ni) are introduced into agricultural soils through anthropogenic sources including industrial discharge, mining activities, the use of fertilizers, sewage sludge, and contaminated irrigation water. These toxic elements can accumulate in plant tissues, disrupt plant growth and metabolic functions, and pose significant risks to human and animal health via the food chain. Soil salinity, often co-occurring with HM contamination, is another major constraint to crop productivity, particularly in arid and semi-arid regions. According to FAO (2022), salinity affects up to 50% of irrigated lands in some regions and is expected to worsen due to climate change. Salt stress impairs plant functions by causing ionic and osmotic stress, oxidative damage, membrane disruption, and metabolic imbalances—ultimately reducing growth and yield. Combined exposure to heavy metals and salinity exacerbates the generation of reactive oxygen species (ROS), leading to oxidative stress, DNA damage, protein denaturation, and lipid peroxidation. The elevated uptake of toxic metals by plants not only reduces agricultural output but also compromises food safety. Essential trace metals like zinc (Zn) and copper (Cu), though vital for physiological functions, can become toxic when their concentrations exceed optimal levels.

Plants act as conduits for the transfer of heavy metals from soil to higher trophic levels, emphasizing the need for accurate monitoring of metal concentrations in soils and crops. Such assessments are critical for evaluating potential health risks and guiding mitigation strategies. Recent studies have investigated concentrations of metals like Cu, Zn, Ni, and Cr in both soils and wheat grains, underlining the urgent need for integrated approaches to manage these dual stresses.

Defence strategies against heavy metal toxicity: Detoxification mechanisms and adaptation strategies

Heavy metal toxicity poses significant environmental and health challenges, affecting ecosystems, wildlife, and human populations. Metals such as lead (Pb), mercury (Hg), arsenic (As), and cadmium (Cd) can cause severe health problems, including organ damage, neurological disorders, and cancer. To mitigate these harmful effects, both natural detoxification processes and adaptive strategies have evolved in humans and animals, including chelation, enzymatic detoxification, bioaccumulation, and environmental adaptations. Ongoing research in chelation therapy and bioremediation remains essential for managing heavy metal contamination.

Cereal crops, which are highly vulnerable to heavy metal toxicity, have developed various defense mechanisms to mitigate the harmful effects of toxic metals like Cd, Pb, and Hg, safeguarding agricultural productivity and food safety. These mechanisms include chelation, vacuolar sequestration, and the binding of metals with organic compounds, limiting metal absorption and preventing their accumulation in vital plant tissues. Additionally, root exudates play a crucial role in modifying metal availability in the soil, reducing uptake, and mitigating toxicity. Cereal crops also demonstrate adaptive responses through genetic selection and breeding for enhanced metal tolerance. Key detoxification and adaptation strategies include metal transporters, metallothioneins, cell wall binding, rhizosphere interactions, and vacuolar sequestration. These mechanisms can function independently or synergistically, enabling plants to adapt and thrive in heavy metal-contaminated environments. The specific response varies depending on the cereal species and environmental conditions.

Bioremediation of heavy metal toxicity: A general perspective

Several physical and chemical techniques such as coagulation, chemical precipitation, ion exchange, nanofiltration, reverse osmosis, soil washing, and excavation have been employed to remediate heavy metal-contaminated soils. However, these methods are often costly, labour-intensive, disruptive to the soil ecosystem, and impractical for large-scale application. In contrast, bioremediation has emerged as a sustainable and eco-friendly alternative. It involves modifying environmental conditions to enhance the activity of microorganisms that can degrade or immobilize pollutants, thereby restoring soil health. Bioremediation is broadly classified into: *In situ* bioremediation (treatment of contaminants directly at the polluted site; it is cost-effective and less invasive) and *Ex situ* bioremediation (removal of contaminated soil for treatment elsewhere; generally more expensive and environmentally taxing).

Due to lower cost and minimal environmental disruption, *in situ* bioremediation is the preferred approach for managing heavy metal-contaminated soils. Common microbiological strategies for metal remediation include bioaccumulation (uptake of metals by microbial cells), biosorption (passive binding of metals to microbial cell surfaces), biotransformation (conversion of toxic metals into less harmful forms), bioleaching (microbial mobilization of metals from solids into solution) and biovolatilization (transformation of metals into volatile forms). These biological processes offer promising potential for restoring soil productivity and ensuring environmental safety in contaminated agricultural lands.

Major heavy metals, source, symptoms and mitigation strategy

Heavy metal contamination in soil is a growing concern for wheat production, as it affects plant physiology, reduces yield, and leads to bioaccumulation in grains, posing health risks. Below is an in-depth look at major toxic heavy metals and their effects on wheat.

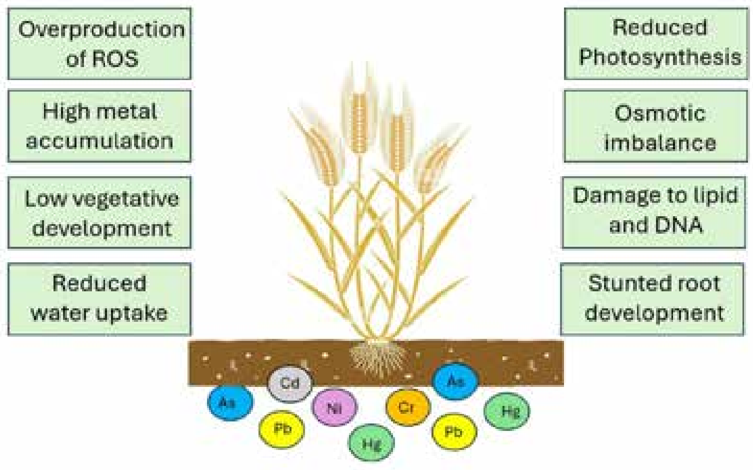

Fig : Negative impacts of heavy metal toxicity on wheat

PGPR associated growth improvement in wheat under metal stress

The effectiveness of plant growth-promoting rhizobacteria (PGPR) in mitigating heavy metal stress in wheat depends on their metal tolerance, colonization ability, and functional traits. Beyond their typical plant growth-promoting functions, PGPR play a crucial role in alleviating metal-induced toxicity, thereby enhancing wheat growth and productivity in contaminated soils. In various studies, PGPR inoculation has led to notable improvements in wheat grown under heavy metal stress:

Table 1. Brief outline of heavy metals, their source, effect and mitigation strategies in wheat

Heavy Metal	Source	Effect on Wheat	Mitigation Strategies
Lead (Pb)	-Industrial emissions, mining, vehicle exhaust - Lead-containing pesticides and contaminated fertilizers - Sewage sludge and wastewater irrigation	-Inhibits root elongation and damages cell structure - Reduces chlorophyll content, causing chlorosis - Disrupts water balance, affecting metabolism - Decreases grain quality and accumulates in kernels	-Phytoremediation using Pb-accumulating plants (e.g., sunflower, mustard) - Organic amendments (e.g., manure, biochar) to immobilize Pb - Calcium and phosphorus fertilizers to reduce Pb bioavailability
Cadmium (Cd)	-Industrial waste, phosphate fertilizers, metal mining - Contaminated irrigation water, sewage sludge	-Interferes with water and nutrient uptake - Reduces chlorophyll synthesis, affecting photosynthesis - Stunts root and shoot growth - Accumulates in grains, posing health risks	-Soil amendments (biochar, organic matter, lime) to reduce Cd mobility - Growing Cd-tolerant wheat varieties - Crop rotation with Cd hyperaccumulators (e.g., Brassica species)
Arsenic (As)	-Industrial effluents, mining, contaminated groundwater - Pesticides and herbicides containing arsenic	-Alters metabolic pathways and enzyme activities - Causes root browning and stunted growth - Reduces seed germination and chlorophyll content - Increases grain arsenic concentration, making wheat unsafe	-Silicon and iron-based fertilizers to reduce uptake - Growing wheat varieties with low arsenic accumulation - Avoiding arsenic-contaminated irrigation water
Mercury (Hg)	-Industrial pollution, coal combustion, mercury-containing pesticides - Wastewater from chemical industries	-Disrupts cellular functions by binding to proteins and enzymes - Causes oxidative stress, leading to DNA damage - Reduces seed germination and plant growth - Accumulates in plant tissues, entering the food chain	-Bioaugmentation using mercury-resistant bacteria - Organic amendments to immobilize Hg in soil - Avoiding mercury-containing fertilizers and pesticides
Chromium (Cr)	-Tannery waste, textile dyes, industrial emissions - Electroplating industry waste, polluted irrigation water	-Inhibits root development and disrupts metabolism - Reduces photosynthesis by affecting chlorophyll biosynthesis - Causes oxidative stress, leading to early senescence - Affects protein and enzyme function, reducing yield	-Organic matter and biochar to reduce Cr bioavailability - Cr-resistant microbes to promote plant growth - Avoiding wastewater irrigation from tanneries
Nickel (Ni)	-Industrial activities, electroplating, mining - Sewage sludge, fertilizers, contaminated water	-Toxic at high concentrations, causing leaf chlorosis and necrosis - Interferes with iron uptake, leading to nutrient deficiencies - Inhibits seed germination and weakens plant defenses - Reduces protein synthesis and grain quality	-Organic amendments (compost, farmyard manure) to reduce Ni toxicity - Soil pH adjustment using lime to reduce Ni solubility - Crop rotation with Ni-accumulating plants (e.g. Alyssum species)

- ***Cadmium (Cd) stress****:* Inoculation with *Pseudomonas* strains SNA5 and PBB1 improved germination, root and shoot length, and overall growth.
- ***Chromium (Cr) stress****:* *Pseudomonas fluorescens* Q14 and *Bacillus thuringiensis* KAP5, possessing ACC deaminase and phosphate-solubilizing traits, enhance root (208%) and shoot (67%) growth, as well as dry biomass of roots (140%) and shoots (71%).
- ***Zinc (Zn) stress****:* *Pseudomonas aeruginosa* increased photosynthetic pigment content, improved growth parameters, and reduced oxidative stress indicators such as malondialdehyde (MDA) and antioxidant enzyme activity.
- ***Lead (Pb) stress****:* *Azotobacter* and *Azospirillum* strains enhanced membrane stability and grain yield while reducing MDA, proline, and hydrogen peroxide (H_2O_2) levels.
- ***Copper (Cu) stress****:* *Bacillus* sp. USTB-O, an IAA-producing strain, improved growth, reduced proline accumulation, and strengthened antioxidant defenses.
- ***General metal stress****:* Inoculation with *Azotobacter chroococcum* and other PGPR strains consistently reduced oxidative stress markers. *Bacillus subtilis* SU47 and *Arthrobacter* sp. SU18 were also effective in lowering antioxidant enzyme activity, indicating stress alleviation.
- ***Arsenic (As) stress****:* *Pseudomonas gessardii* and *Brevundimonas intermedia* increased dry biomass and reduced oxidative stress. Similarly, *Planomicrobium chinense* and *Bacillus cereus* lowered antioxidant enzyme activity under metal stress.

These findings demonstrate the potential of PGPR as a sustainable and eco-friendly strategy to enhance wheat growth and yield under heavy metal stress while simultaneously mitigating toxicity through improved physiological and biochemical responses.

Mitigation strategies for salinity in wheat

Salinity stress poses a major challenge to wheat cultivation, affecting plant growth, water uptake, and yield. Effective mitigation strategies include the development and use of salt-tolerant wheat varieties through traditional breeding and genetic engineering. Agronomic practices such as proper irrigation management, use of gypsum or organic amendments, and crop rotation help reduce salt accumulation in the root zone. The application of plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi can enhance stress tolerance by improving nutrient uptake and reducing oxidative damage. Additionally, seed priming with osmoprotectants and foliar sprays of antioxidants or micronutrients can strengthen the plant's defense mechanisms, promoting better growth and yield under saline conditions.

Future prospects

Emerging strategies for combating heavy metal stress in wheat include advances in bioremediation, genetic engineering, and sustainable agronomic practices. Research is focusing on plant-microbe partnerships, including metal-tolerant rhizobacteria and mycorrhizal fungi, to enhance metal detoxification. Breeding and genetic modification aim to develop wheat varieties with enhanced tolerance and reduced metal uptake. Innovative tools such as nanotechnology, biochar, and organic soil amendments are proving effective in immobilizing metals and restoring soil health. Precision agriculture through targeted nutrient management and real-time soil monitoring further supports resilient wheat cultivation in contaminated areas. Combined with strong environmental regulations and ongoing research, these integrated approaches offer a path toward safe, productive, and sustainable wheat farming in heavy metal-affected regions.

SUMMARY

Heavy metal toxicity and salinity severely impacts wheat growth, physiology, and yield by inducing oxidative stress, impairing photosynthesis, and disrupting nutrient uptake. Toxic metals like cadmium (Cd), lead (Pb), mercury (Hg), nickel (Ni), chromium (Cr), and arsenic (As) accumulate in plant tissues, posing significant risks to human and animal health through the food chain. Mitigation strategies such as the application of plant growth-promoting rhizobacteria (PGPR), microbial bioremediation, phytoremediation, and the use of melanin-producing organisms offer effective and sustainable solutions. Additionally, the interaction between cadmium and zinc plays a critical role in determining the nutritional quality of wheat and warrants further study.

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