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Soil-plant Strategies to Enhance Sustainable Agriculture under Metal Stress

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SUSTAINABLE agriculture is hampered by heavy metals (HMs) toxicity, a serious abiotic stress that can seriously impair plant growth and reproduction. HMs such as arsenic, Fe, Mn, Cu, Ni, Co, Cd, Zn, and Hg have long been present in soils due to sewage discharge and industrial waste. While some of these metals are necessary micronutrients that control many routine plant processes, too much of them can be harmful and directly affect senescence, metabolism, physiology, and plant development. Plants are responsible for maintaining the homeostasis of essential metals that they require for survival in addition to protecting themselves from stress. The current review offers a summary of various nutrient management techniques to lessen HMs stress in plants, with an emphasis on ecologically friendly approaches. In order to help plants detoxify and increase their resistance to HM stress, the current review provides comprehensive explanations of how nutrients and fertilizer/biofertilizer react to HMs. To maximize the benefits of these methods, this review highlights the importance of integrating methods from other scientific fields and the need for a better understanding of how metal stress impacts plant physiology and metabolism. A deeper understanding of the role of nano-priming in HM metabolism will help in designing more effective bioremediation strategies to address soil HM contamination.

Keywords: Soil health, Antioxidant enzyme activity, Integrated nutrient management, Sustainable agriculture.

1. Introduction

HMss (HMs) are present in natural soil, but industrialization has contaminated it and increased HM concentrations to levels that are harmful to both plants and animals (Chibuike and Obiora, 2014). HMs can enter terrestrial ecosystems through a variety of processes, including mining, vehicle emissions, improper industrial waste disposal, waste incineration, human activities like the use of agrochemicals, and the weathering cycle of natural rocks. Consequently, this phenomenon encourages the accumulation of HMs (HM) interactions in plant cells and tissues as well as the uptake of HMs by plant roots. Research conducted by Zhuang et al. (2013, 2014) indicates that these pollutants infiltrated the human body via the food chain. Some of the elements that HM needs are manganese (Mn), zinc (Zn), copper (Cu), iron (Fe), cobalt (Co), nickel (Ni), selenium (Se), and molybdenum (Mo). Lead (Pb), cadmium (Cd), mercury (Hg), silver (Ag), arsenic (As), and chromium (Cr) are HMs that are not needed. Essential HMs are important for many biological processes in plants. However, non-essential HMss compete with essential HMs for protein binding sites, which can harm plants and stop them from working properly (Torres et al., 2008). Remediating contaminated soils to reduce bioavailable metal concentrations is crucial for mitigating environmental and health risks. Various strategies have been developed to address this challenge. Soil amendments, such as biochar, hydroxyapatite, manure, and plant ash, have been shown to effectively decrease the bioavailability of metals like cadmium in crops like maize (Wang et al., 2020). Additionally, the application of nanoscale zero-valent iron (nZVI) composites has demonstrated effectiveness in immobilizing HMss and enhancing plant growth in mining-contaminated soils (Mousa et al., 2024). Phytoremediation, utilizing plants like telegraph weed, California buckwheat, and mulefat, has proven successful in reducing HMss such as lead, arsenic, and copper in contaminated brownfield sites. These approaches offer promising solutions for remediating contaminated soils and reducing the bioavailability of harmful metals.

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Nanotechnology is a new approach that is becoming popular in the agricultural sectors of developing countries. Nanoparticles act as cues to activate a range of defense mechanisms in plants when they are exposed to harmful environments. Nanoparticles are a better fertilizer option than ordinary salts because they are lighter, more soluble, and have a larger surface area. Nano biofertilizer is produced by combining biofertilizers with nanoparticles. This approach puts biofertilizers into a nanomaterial that performs well. They help protect the ecosystem from disturbances and govern how nutrients get into the soil. They are better for the environment, cost less, demand less artificial fertilizer, and help plants absorb and use nutrients better. Biofortification of plants to thrive in marginal soils with either low or high metal content is a critical strategy to enhance food security and nutritional quality in challenging agricultural environments. Marginal soils often suffer from nutrient deficiencies or toxic metal concentrations, which can hinder plant growth and reduce crop yields. To address these issues, biofortification techniques aim to increase the nutrient density of crops through various methods (Bhardwaj et al., 2022; Sheoran et al., 2022). One approach is the use of soil amendments and fertilizers to improve nutrient availability. For instance, the application of zinc (Zn) fertilizers has been shown to increase grain Zn concentration in wheat, with foliar application proving more effective than soil application alone (Zhao et al., 2022). Similarly, iron (Fe) biofortification in chickpea has been achieved through the application of Fe-EDDHA fertilizers, enhancing seed Fe content (Jahan et al., 2023). Another strategy involves plant breeding to develop varieties with enhanced nutrient uptake and tolerance to metal stress. This includes selecting or genetically modifying crops to accumulate higher levels of essential nutrients or to exclude toxic metals from edible parts, thereby improving both yield and nutritional quality (Teklu et al., 2023). Additionally, agronomic practices such as inoculation with plant growth-promoting microorganisms can aid in biofortification. These microbes can enhance nutrient uptake, stimulate plant growth, and improve soil health, contributing to better crop performance in marginal soils (Bhardwaj et al., 2022). Collectively, these biofortification strategies offer sustainable solutions to improve crop productivity and nutritional content in marginal soils, addressing both nutrient deficiencies and metal toxicity challenges (Sheoran et al., 2022; Zhao et al., 2022).

Producing safe food in areas affected by metal-contaminated soils requires strategies that minimize the transfer of toxic metals into the edible parts of crops. HMss such as cadmium (Cd), lead (Pb), arsenic (As), and mercury (Hg) can accumulate in soils due to industrial activities, mining, wastewater irrigation, and excessive agrochemical use, posing serious health risks when transferred to humans through the food chain (Shahid et al., 2022; Li et al., 2023). To mitigate this, various approaches have been developed. The use of soil amendments, such as biochar, lime, and phosphate-based compounds, has been shown to immobilize metals, reducing their bioavailability and uptake by plants (Chen et al., 2023; Zhang et al., 2022). Phytoremediation, involving the cultivation of metal-excluding or hyperaccumulator plants in rotation or intercropping systems, can also limit metal accumulation in edible tissues (Ali et al., 2023). Furthermore, agronomic practices such as optimizing irrigation, applying appropriate fertilizers, and inoculating plants with growth-promoting microbes can enhance nutrient uptake while restricting metal absorption (Bhardwaj et al., 2022). Collectively, these strategies are crucial for producing safe, nutritious food while minimizing the health risks associated with metal-contaminated soils (Zhao et al., 2022).In order to increase the yield and nutritional value of plant produce for sustainable agriculture with nanopriming, this review describes the most recent biological techniques/methods for developing nanoscale agricultural materials and other strategies that can successfully handle HMs stress in plants.

2. Methods of Nutrient Management to Reduce the HMs Stress

HMss (HMs) that don't break down in the environment, such mercury (Hg), manganese (Mn), iron (Fe), copper (Cu), zinc (Zn), cobalt (Co), arsenic (As), and nickel, can build up in soil over time because of sewage and industrial waste. Some HMs are thought to be important micronutrients that plants require to grow and work their best. On the other hand, many others can have bad impacts and may directly alter a plant's metabolism, senescence, physiology, and growth (Hafeez et al., 2023). The physiochemical makeup of the soil is the main thing that determines how plants take in and store HMs. HMs are mostly found in plant root cells because cell walls can trap them or casparian strips can block them. An excess of HMs in plant tissues can affect many morphological, physiological, and biochemical processes, which can then affect agricultural productivity (Choudhary et al., 2022). HM messes off a lot of plants' natural operations, like photosynthesis, germination of seeds, moving and storing seed reserves during germination, and plant growth in general. This makes plants less productive. Plants that are close to HMs that are poisonous are more likely to make reactive oxygen species (ROS). This encompasses non-radicals such as hydrogen peroxide (H_2O_2) and singlet oxygen, with radicals including hydroxyl radicals (OH•) and superoxide radicals (O_2•$^-$) (Singh et al., 2021; Tamás et al., 2017). ROS-active metals can create ROS immediately away when they are used in Haber-Weiss/Fenton processes. NADPH oxidases (NOXs) can also make ROS indirectly, or you can stop enzymes by feeding them alternative cations. Plants mainly make reactive oxygen species (ROS) in the endoplasmic reticulum, cell walls, plasma membrane, mitochondria, chloroplasts, and peroxisomes (Raza et al., 2023; Hafeez et al., 2023). Different types of crops can be affected by different HMs, as shown in Table 1.

Table 1. HMs toxicity impacts on crop plants.

HMs	Crop	Toxicity on crop plant	Reference
Co	Tomato	↓in nutritional content of plants.	Sahu and Basti (2021)
	Mung bean	↓in the nutritional content of plants,	Rehman et al. (2023)
	Radish	↓in antioxidant enzyme activity, ↓in the overall leaf area, shoot length and root length, ↓in plant protein, sugar and amino acid content	Mahey et al. (2020)
Cr	Wheat	↓in shoot and root growth.	Mahey et al. (2020); Saud et al. (2022)
	Tomato	↓in plant nutrient acquisition.	Okereafor et al. (2020)
	Onion	Germination process inhibition, ↓in plant biomass.	Saud et al. (2022); Okereafor et al. (2020)
Cu	Bean	Cu accumulation and decreased root development.	Okereafor et al. (2020); Rai et al. (2021)
	Black bindweed	Plant death and ↓in biomass and seed production.	Rehman et al. (2023); Okereafor et al. (2020)
	Rhodes grass	↓in root growth.	Kumar et al. (2021)
Hg	Rice	↓in plant height, ↓in tiller and panicle formation, ↓in yield and bioaccumulation of Hg in shoot and root of seedlings.	Rashid et al. (2023); Okereafor et al. (2020)
	Tomato	↓in germination percentage, ↓in crop length	Okereafor et al. (2020); Kumar et al. (2023)
Zn	Cluster bean	↓in % germination ↓chlorophyll and height	Okereafor et al. (2020)
	Pea	Alteration in photosystem II and growth	Rehman et al. (2023)
	Rye grass	Zinc accumulation, growth and nutrient content reduction ↓in photosynthetic efficiency.	Chibuike and Obiora (2014)
As	Rice	↓in %germination , height and leaf surface area	Okreafor et al. (2020)
	Tomato	↓in yield and weight	Devi, 2024
	Canola	Stunted growth, Chlorosis and wilting	Chibuike and Obiora (2014)
Pb	Maize	↓in germination percentage, Suppressed growth, ↓in plant biomass and ↓in plant protein content	Okreafor et al. (2020); Rehman et al. (2023)
	Portia tree	↓in number of leaves and leaf area, ↓in plant height and plant biomass	Devi, 2024
	Oat	Inhibition of enzyme activity which affects CO_2 fixation	Rashid et al. (2023)
Cd	Wheat	↓in seed germination, ↓in plant nutrient content, ↓in shoot and root length	Okreafor et al. (2020)
	Garlic	↓in shoot growth and Cd accumulation in plant parts	Okreafor et al. (2020)
	Maize	↓in shoot growth and inhibition of root growth	Rehman et al. (2023)

For all living things, eating nutritious food is vital. According to one theory, plants need seventeen different things in order to be happy and healthy. There are two types of these vital nutrients that plants need: macronutrients and micronutrients. Macroscopic nutrients include things like carbon (C), hydrogen (H), oxygen (O), nitrogen (N), potassium (K), phosphorus (P), calcium (Ca), magnesium (Mg), and sulfur (S). The following micronutrients are listed by Sandeep et al. (2019): manganese (Mn), copper (Cu), iron (Fe), zinc (Zn), nickel (Ni), molybdenum (Mo), and boron (B). Despite the fact that plants don't actually need silicon (Si), people believe it to be a good fertilizer. To stay healthy and perform functions like absorbing light with chlorophyll (N, Mg), maintaining the osmotic pressure of stomata (K), and producing energy to store carbohydrates (P), plants require the proper amount of nutrients. If plants are properly nourished, they can cope with HM stress more effectively. Creating new types of nutrients is a major part of this process. The presence of nutrients such as nitrogen (N), potassium (K), calcium (Ca), and magnesium (Mg) improves the activity of antioxidant enzymes such as catalase (CAT), peroxidase (POD), and superoxide dismutase (SOD). Reactive oxygen species (ROS) are reduced by these enzymes (Zulfiqar and Ashraf 2022; Shahid et al., 2014; Sharma et al., 2023). Plants may be able to absorb more water if they contain minerals like calcium and potassium. This aids in the regulation of their stomata and osmotic balance (Kumari et al., 2022). Micronutrients like iron, zinc, and boron help plants cope with stress by accelerating their metabolism, activating their immune systems, and altering various aspects of their bodies. You can manage stress more effectively if you take several minerals at once. The opposite is also true. We still have a lot to learn, but using plant nutrients to deal with HM stressors is an affordable and sustainable way to do this. As shown in Table 2, plants that are highly stressed by HMs react differently to nutrients.

Table 2. The effect of nutrients on plant growth and development and their impact or mechanisms during HMs stress.

Nutrient	Impact on Plant Growth & Development	Strengths in HMs Stress	References
Nitrogen	Essential for amino acids, proteins, chlorophyll and nucleic acids synthesis	Supports protein synthesis and detoxification processes, Conversion of HM speciation from bioavailable to organic bound	Li et al. (2019)
Phosphorus	Vital for energy transfer (ATP), nucleic acids and membrane structures	Root biomass development and energy storage, enhancing resilience to stress.	Bechtaoui et al. (2021); Khan et al. (2023)
Potassium	Regulates osmotic balance, enzyme activation and stomatal opening	Improves water use efficiency, including osmotic adjustment, reduces ROS generation under HM stress	Dhiman et al. (2022)
Calcium	Integral component for cell wall stability, membrane function & signaling	Mitigates HM toxicity, especially cadmium (Cd), by limiting uptake & enhancing cellular stability	Huang et al. (2017)
Magnesium	Central component of chlorophyll and an enzyme activator	Critical for photosynthesis efficiency & enhancing antioxidant defense against oxidative stress induced by HM.	Shen et al. (2016)
Sulfur	Amino acid, vitamin & antioxidant component	Supports detoxification processes & synthesis of essential compounds for coping with HM stress	Cao et al. (2023)
Iron	Essential for chlorophyll synthesis & electron transport in photosynthesis	Significant for maintaining chlorophyll synthesis & mitigating chlorosis under HM stress.	ul Hassan et al. (2017)
Zinc	Co-factor for various enzymes, important for protein synthesis	Increases antioxidant enzyme activity & crucial for coping with oxidative stress from HM	Hassan et al. (2022)
Copper	Involved in photosynthesis, respiration & lignin synthesis	Supports energy production and increases HM stress tolerance	Giannakoula et al. (2021)
Manganese	Activates enzymes in photosynthesis & nitrogen metabolism.	Plays a role in antioxidant defense & mitigates impact of HM on photosynthesis	Kosakivska et al. (2021)
Boron	Required for cell wall structure & membrane functions	Supports cell integrity & reduces susceptibility to HM toxicity especially Cd	Riaz et al. (2021)
Molybdenum	Required for nitrogen fixation & nitrate reduction	Facilitates nitrogen metabolism, enhancing plant growth under HM stress	Li et al. (2021a)
Selenium	Plays an important role in antioxidant defense mechanism	Induces antioxidant systems & mitigates oxidative stress from HM	Arshad et al. (2023)

To grow more crops, you need to grasp how macro and micronutrients work in crop nutrition. It's important to make sure that plants get adequate food because most soils used for growing crops don't have enough of the nutrients they need. There are a lot of techniques to provide crops nutrients, like fertilizers, bio-fertilizers (plant growth-promoting rhizobacteria, or PGPR), farm yard manure (FYM), priming crops with nutrients, and foliar application of nutrients (Kumar et al., 2022; Kaushal et al., 2023). Controlling the nutrients that plants take in is one of the best methods to help them deal with HM stress. Plants can deal with the harmful effects of HMss better when they get the proper amount and mix of nutrients. We spoke about a few different ways to feed plants so they can deal with HM stress.

3. Sustainable Crop Nutrition and Farm Management Practices

3.1. Manures, fertilizers and plant-based fertilizers

Farming makes up a third of the world's GDP. But the number of people on Earth is going up. By 2050, there will be 9.5 billion people living here. Because of this, a lot of people would need food (Kumar et al. 2022a). One of the main reasons why many crops don't grow well is because of biotic and abiotic pressures, a lack of fertile land, urbanization, and climate change. Climate change can also cause the weather to act in ways that aren't usual. To make sure there is enough food and to grow more food in a certain area, the soil's quality, the amount of nutrients in it, the health of the living organisms in it, and the state of the ecosystem are all very important. Plants really need manures, fertilizers, and bio-fertilizers since they help the soil and keep the nutrients in balance. Plants need these two things to deal with stress from HMs (Glaser and Lehr, 2019; Dotaniya et al., 2020). Manure is an organic fertilizer that improves the soil by changing its structure, adding more bacteria, and storing more water. They are made up of animal excrement and plant stuff. There are cheaper ways to provide nutrients to the soil that don't injure plants. Plants can take them in more easily this way. The soil might be better at hanging onto HMs since it has more organic matter in it. This makes it harder for plants to get to and lessens the effects of HM stress (Zhang et al., 2021). But manures might not contain as many nutrients as synthetic fertilizers, and sometimes they have even fewer. Traditional chemical fertilizers, especially nitrogen (N), phosphorous (P), and potassium (K), are very important for modern farming methods and technologies that employ a lot of inputs (Kumar et al. 2022a). This is because they require these nutrients to grow and generate more food for everyone. But if you use too many of these man-made things, they can make the soil worse, take away nutrients, and add HMs. The plants won't grow as much, and the soil won't be as nice for them.

Biofertilizers are living creatures like PGPR that help plants acquire the nutrients they need. This means that they will last a long time and help plants grow. Biofertilizers like Rhizobium, Azospirillum, and Phosphate Solubilizing Bacteria (PSB) help the soil grow better and more organized. They also help plants take in nutrients better (Kaushal et al., 2023). These helpful bacteria can also help plants deal with the stress that metals place on them. For example, they might hang onto HMs, which makes it tougher for plants to get them. A lot of people think that PGPR and mycorrhizal fungi play a large role in how nutrients get into the soil and how stress is lowered. This is why they are so necessary for the soil ecology to work right (Kumar et al., 2021). Using beneficial microorganisms as biofertilizers increases the nutrient content of the soil in three ways: (i) by changing how the plant takes in nutrients and how its roots release them; (ii) by changing how soluble and available nutrients are; and (iii) by making interactions with other soil bacteria better. Microbes mineralize nutrients by acidolysis, oxidoreduction, chelation (or chelating agents that bind HMs and reduce their toxicity), or by releasing compounds such as lactate, catechol, gluconate, citrate, oxalate, and pseudobactin (Kumar et al., 2022a). This characteristic not only makes it easy to gather plants that have HMs in them, but it also protects plants against the bad effects of HMs. Putting plants that take up metals in the soil is part of this effort to clean it. When arbuscular mycorrhizal fungi are on land, they commonly create symbiotic relationships with plants. This helps the fungi take in carbon and makes it easier for the plants to receive water and nutrients (Kaushal et al., 2023). Researchers have found that a lot of bacteria contain traits that help plants flourish. These traits are important for making nutrients like nitrogen, phosphorus, potassium, zinc, and sulfur more available, as well as for managing phytohormones, reducing plant diseases, and relieving stress induced by HMss (Sharma et al., 2023). Inoculating a single beneficial microbe or a consortium thereof has been demonstrated to enhance plant biomass and agricultural yield in both greenhouse and field environments (Kumar et al., 2021). Plants that employ biofertilizers are also stronger at fighting free radicals, which is vital for dealing with the oxidative stress that HMs generate.

Researchers think that using bio-fertilizers to manage nutrients will greatly improve soil quality by adding organic matter, increasing the number of different types of microorganisms, and making chemical fertilizers less necessary (Zhang et al., 2021). Farmers can cultivate crops that are better for the environment and less likely to become sick from things like HM poisoning with this method. In conclusion, substituting bio-fertilizers for conventional fertilizers may enhance agricultural sustainability by alleviating the stress imposed by HMs on plants (Kumar et al., 2021; Kumar et al., 2022a; Kaushal et al., 2023). Utilizing the advantageous interactions between plants and microbes may mitigate the detrimental impacts of HMs on soil ecosystems and plant development, while simultaneously enhancing crop yield. We need to do more research and development to find better ways to mix and use bio-fertilizers so that they operate better on all kinds of farms. The application of manures, composts, and plant-based fertilizers mitigates HMs stress primarily by increasing soil organic matter and cation exchange capacity, which provide binding sites for metals and reduce their solubility. Functional groups such as carboxyl, hydroxyl, and phenolic moieties in organic amendments chelate or adsorb HMss, thereby immobilizing them in less bioavailable forms. Additionally, nutrients released from these fertilizers (e.g., Ca, Mg, Zn, Fe) compete with HMss at root uptake sites, reducing their absorption and translocation (Alkahtani et al., 2021; Elbehiry et al., 2024).

3.2. Nutrient Spraying

Put them on the leaves and let them dissolve in water. That's the finest method to use them. Foliar fertilization is when you sprinkle the proper amount of fertilizer on the leaves of plants that are still growing. Foliar feeding was found to be 6, 4, and 20 times more effective than soil treatment for nitrogen, boron, and zinc, respectively (Krishnashree et al., 2021). Plants can get critical minerals and compounds right away when fertilizers are applied on their leaves. This makes it easier for people to manage with HM stress. This method helps the body quickly absorb nutrients, which is useful when there aren't enough nutrients or when someone has been poisoned by HM. Foliar feeding is a means to provide plants vital nutrients directly, without needing to go through the ground. Plants may be better equipped to deal with the effects of HM stress this way, even if the soil is polluted (Bharti et al., 2018).

Adding minerals like iron, zinc, and magnesium to plant leaves makes it less likely that HMs will get into the plant and move around in it. This is because these minerals start physiological and metabolic processes that remove HM ions from the plant (Ali et al., 2021). For instance, putting micronutrients on the skin can make antioxidant enzymes perform better. These enzymes are very important because they break down ROS that are generated when HM stress happens and stop cells from being harmed by oxidation. Plants need to be healthy when nutrients are spread out on their leaves. This lets them grow and do things even when they are under HM stress (Javed et al., 2021). The type of plant, the time of day, and how the nutrients are mixed all affect how well this treatment works. Part of the aim should be to use foliar fertilizer distribution to control nutrients in a way that decreases HM stress in crops, improves plants, and makes farming more sustainable. Foliar feeding offers the plant nutrients directly, not through the ground. This method works best when the soil doesn't let plants get nutrients or when plants need a quick dosage of nutrients to feel better (Stewart et al., 2021).

Foliar nutrient spraying alleviates HMs stress by bypassing contaminated soils and supplying essential nutrients directly to plant leaves, thus reducing root-mediated uptake of toxic metals. Foliar-applied elements such as Zn, Mn, Ca, and Si strengthen the cell wall, enhance antioxidant enzyme activity, and restrict metal translocation from roots to aerial tissues. This approach also improves osmolyte accumulation and membrane stability, which counteract oxidative stress caused by HMss (Xie et al., 2025).

3.3. Crop Rotation and Intercropping

Crop rotation and intercropping are two highly important aspects of nutrient management systems that assist maintain plants healthy and strong, even when they are stressed out by HMs. These methods can help nutrients travel through the soil faster, lower the number of pests and diseases, and make HMs (HMs) less available to plants (Bian et al., 2021). You can do this by planting several types of plants in the same spot at different periods or all at once. Crop rotation is when you plant different kinds of crops in a row on the same piece of land. It keeps the soil healthy, stops diseases from spreading, and stops erosion. This process could also modify how much HM is in the soil and how it moves. Cui et al. (2012) performed a study examining the impact of crop rotation on cadmium (Cd) uptake in various crops. The findings indicated that alternating between crops with reduced cadmium uptake and those with higher cadmium uptake can maintain cadmium levels in crops at a safe threshold and mitigate the risk of cadmium entering the food chain. Intercropping, which is growing two or more types of crops next to each other, can make the soil better and more productive by promoting favorable interactions between the different types of crops (Rahayu et al., 2022). For instance, legumes could bring nitrogen back into the soil. Putting legumes in with other plants could provide the earth more nitrogen. More nitrogen could assist crops that aren't legumes grow better and could also lower the amount of HMss in plant tissues. Zuo et al. (2023) found that planting legumes and maize together lowered the amount of HMs in the grain. The legumes' roots changed the soil's pH, which caused the microorganisms in the soil work harder. This made it easier for plants to absorb metals that are bad for them. These approaches can help plants deal with the stress that HMs cause by making them harder for plants to get to and improving the soil. These methods demonstrate the significance of employing integrated and sustainable agricultural practices to regulate nutrient dynamics and mitigate the detrimental effects of HMs on crops (Bian et al., 2021). Intercropping and crop rotation can assist the soil get rid of HMs, make the nitrogen cycle better, and add new plants. Putting diverse types of plants in the ground that can take up nutrients and store HMs can benefit the soil.

Crop rotation and intercropping mitigate HMs stress through dilution and phytoremediation effects. Rotating with legumes or hyperaccumulators enhances soil fertility, promotes microbial activity, and gradually decreases available HMss via phytoextraction and immobilization. Intercropping alters rhizosphere chemistry through root exudates (e.g., citric and malic acids) that precipitate or chelate metals, reducing their bioavailability. These practices also redistribute metals into less toxic pools and limit their uptake into edible plant parts (Zhou et al., 2022; Wu et al., 2024; Xu et al., 2023).

3.4. Agricultural Management

Precision agriculture (PA) is a new and very advanced way to control how much food is cultivated. The most important thing is that it works well, lasts a long time, and is useful. This means employing the latest tools, like GPS, remote sensing, and information management systems, to keep an eye on the farming process and make it better. Roy and George (2020), for example, talk about how to use fertilizer. HMss (HMs) can be bad for plants, but PA can help them by making it easier to use targeted nutrient management methods that lessen the bad impacts of HMs in the soil. People who are stressed out by HMss can learn how to use minerals and fertilizers the right way with the help of PA. Monteiro et al. (2021) say that PA systems can locate the areas of a field that are affected by HMs and modify the amount of nutrients they need by employing sensors that are attached to the crops and soil. This management by location makes sure that plants get the proper amount of nutrients so they can handle stress in the best way possible. Plants may be able to get additional HMs if you use too much fertilizer. Research in this area has revealed that PA technology could assist people deal with HM stress. One study, for example, used drones to figure out how much HMs was in the ground from a distance. Then it used what it had learned to figure out where to place soil additives. This method significantly reduced the quantity of metals that crops absorbed by carefully managing the soil's pH and adding organic matter to areas that were most affected by HMs (Venkatramanan and Shah, 2019). Another example is systems that give plants the right amount of water. They send nutrients and water straight to the roots. Plants have a harder time getting nutrients, and HMs may travel through the soil faster (Akhtar et al., 2021). Researchers found that using chelating agents with precise irrigation made the amount of HMs in the soil solution much lower. This made it easier for plants to grow in places that had been contaminated earlier. These examples show how precision farming can help plants handle HM stress better and keep nutrients better. Farmers can grow more crops and keep them fresh for longer with PA technology. This also keeps the food and the environment safe. This plan makes sure that the environment gets the necessary nutrients at the right times and places. This is the best approach for the ecosystem to get the most benefits and the least harm (Arora et al., 2008; Poveda, 2021).

Agricultural management practices such as liming, mulching, and biochar application regulate soil pH, redox potential, and microbial activity, thereby reducing metal solubility and availability. Liming raises soil pH, leading to precipitation of metals into insoluble hydroxides or carbonates. Biochar and organic residues enhance sorption and sequestration of metals while improving soil aeration and microbial detoxification pathways. Controlled irrigation and residue management further restrict the mobilization and transport of soluble HMss (Zhou et al., 2022; Elbehiry et al., 2024).

3.5. Integrated Nutrient Management (INM)

People are beginning to see that the INM system, which employs chemical fertilizers, organic manures, and helpful microbes, could help crops grow better and keep the soil healthy for a long period. Using less chemicals is the first step in this plan to protect the environment. This also helps keep the yields the same (Selim, 2020). Plants can grow better when you apply fertilizers that are both organic and not. This is because they acquire a balanced amount of nutrients, the soil structure gets stronger, and microbes start to operate. This strategy is very significant for lowering the levels of HMs in farm soils, in addition to the benefits of INM. HMs can stay in the soil when factories and chemical fertilizers are used, which can make plants and food unsafe (Selim, 2018). Studies show that the organic parts of INM, especially organic manures, stop plants from taking up HMs from the soil. For instance, adding compost or FYM could make it tougher for plants to get to HMs since they attach to them. This is because the manures have organic matter and humic chemicals in them. These compounds adhere to HMs, hence reducing their mobility (Glaser and Lehr, 2019; Dotaniya et al., 2020).

The microbial portion of INM can also help keep HM under check even more. Some good bacteria can clean up HMs by making them less dangerous or breaking them down into safer forms. This is part of the INM plan. Adding these bacteria to organic and inorganic fertilizers might help crops deal with HMs stress, which makes plants grow better and gives higher yields in places that are already polluted (Selim, 2020). In short, INM is the best way to make farming more sustainable because it manages nutrients and soil fertility and also makes HMs less toxic. This plan is helpful for the environment since it aims to keep farming going without harming the ecology. To enhance agricultural productivity and protect the environment, further research and practical applications of Integrated Nutrient Management (INM) must rigorously evaluate its effectiveness in soils contaminated with HMs and optimize the synergistic use of organic manures, chemical fertilizers, and beneficial microorganisms (Selim, 2020; Selim, 2018).To apply these nitrogen management approaches, you need to know a lot about the plant species, the type of HM stress, and the soil conditions. If you change how you do things to meet the environment, plants can handle a lot more metal stress.

Integrated Nutrient Management mitigates HMs stress by synergistically combining organic and inorganic nutrient sources. Organic fractions immobilize metals through chelation and adsorption, while mineral fertilizers provide essential ions that compete with toxic metals at transporters and root uptake sites. INM also sustains soil microbial consortia capable of biotransforming HMss into less toxic forms, while maintaining optimal soil fertility and nutrient balance that enhances plant resilience against oxidative damage (Zhou et al., 2022; Xu et al., 2023).

4. Impact of HMs on Plant Physiological Performance

Plants that contain HMss are under a lot of stress, which makes it more harder for them to grow, develop, and produce. Table 1 shows how bad even little amounts of HMs may be for plants. The plant's biology and chemistry may be greatly affected, which could make it less healthy and productive. Plants react differently when they are under stress from HMs, such as how they take in water and nutrients (Kumar et al., 2022b). HMs can damage the structure and function of the roots or compete with them for places to absorb nutrients, making it hard for plants to get the nutrients they need. Lead, cadmium, and mercury are examples of HMs that can make it hard for plants to make food. They can lower the amount of chlorophyll, change the shape and function of chloroplasts, and make it harder for electrons to move around. Because of this, photosynthesis doesn't work as well and makes less biomass. Astolfi et al. (2014) say that when barley is stressed by Cd, it stops taking in K and Ca, which are both needed for plants to control their water and start cellular processes. Studies indicate that cadmium (Cd) can lead to a loss of up to 40% of chlorophyll in the leaves of wheat (Triticum aestivum). As a result, plant development and photosynthesis are slower (Abedi and Mijori, 2020). HMs can take up transport sites or make them hard to reach, which can stop critical nutrients from moving around and being absorbed. This could change the balance of nutrients, which could change how plants grow and develop. Plants that were exposed to Pb took up 15% less calcium and 25% less potassium than plants that were not exposed. Consequently, the quantity and quality of the fruit were modified (Jia et al., 2019).

Plants that come into contact with HMs may also suffer from oxidative stress, which is caused by having too many reactive oxygen species. These chemicals can damage DNA, proteins, and lipids in cells, which can impact how well plants grow and how healthy they are. Plants need enzymes like SOD, CAT, and POD to protect themselves against ROS. Research shows that stress caused by HMs can make these antioxidant activities stronger (Riyazuddin et al., 2021), even though HMs can reverse this effect. HM stress also makes photosynthesis less effective, which is another important function of the body. Metals can hurt the portions of plants that produce photosynthesis, slow down the enzymes in the Calvin cycle, and stop the plant from making chlorophyll. Ali et al. (2022) found that wheat that had been exposed to Pb and Cd had much reduced chlorophyll levels and photosynthetic efficiency. Consequently, the plants generated diminished biomass. Rice plants (*Oryza sativa*) suffered a lot of oxidative damage when they were exposed to arsenic (As). Taking antioxidants like selenium (Se) can help lower some of this stress. Kalita et al. (2018) showed a 50% jump in lipid peroxidation levels, which is an example of this.

HMs can also change plant growth regulators and signaling molecules, which can change how plants grow and develop. When you're stressed, your body makes hormones like ethylene. These hormones can change how plants respond to too much HMs. Masood et al. (2013) say that ethylene is very important for controlling how plants react to cadmium stress, which stops them from taking in nutrients and growing roots. HMs can stop the growth of roots, shoots, flowers, fruits, and crops when they build up in plant tissues. The severity of these impacts depends on the type of plant, how long it has been exposed, and the type and amount of HMs. He et al. (2023) found that lettuce (Lactuca sativa) planted in soil with cadmium contamination had 20% less biomass and roots that were 30% shorter than those grown in soil without contamination. HMs can also modify how genes work, which can start certain processes that assist the body get rid of metals and deal with stress. Plants may have genes that make phytochelatins and metallothioneins, which are active metal chelators. These chelators make HMs less dangerous by sticking to them. Cobbett and Goldsbrough (2002) looked at how phytochelatins protect plants from the detrimental effects of Cd by binding to and storing it. Plants may take in and lose water at different rates when they are under HM stress. This might make it harder for them to handle drought stress and use water more efficiently. As a result, plants may become even more stressed, which makes it harder for them to grow and live. Researchers discovered that chromium (Cr) stress diminished the transpiration rate of sunflower (Helianthus annuus) plants by 40%. Consequently, there was a reduction in biomass production and a decrease in water efficiency (Farid et al., 2020). Plants can use different ways to protect themselves when they are among too many HMs. Some of these processes are putting metals into vacuoles, making proteins that cling to metals (such phytochelatins and metallothioneins), and turning on antioxidant enzymes like SOD and CAT (Figure 1). Barley (Hordeum vulgare) synthesized up to thrice more phytochelatin in response to cadmium stress. Consequently, the plant exhibited enhanced capability to remove Cd and demonstrated a reduced likelihood of translocating it to its shoots (Özyiğit et al., 2021).

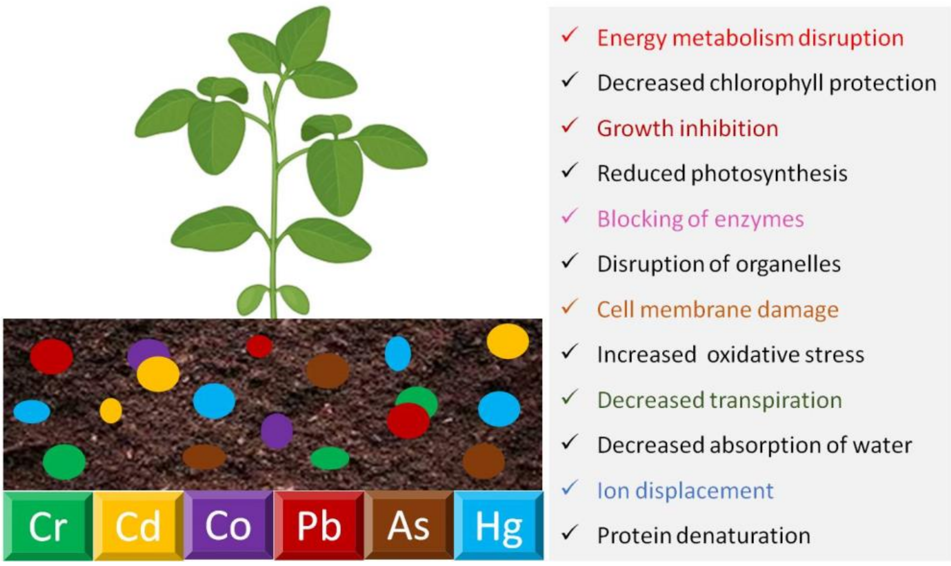

Fig. 1. Illustration of toxic impact of various HMss on crop plants.

5. Plant Metabolism Affected by HMs Stress

Knowing how HM stress affects crop plants' metabolism is essential to creating strategies to improve plant growth and crop yield in contaminated areas. Even in trace amounts, non-essential elements known as HMss (HMs), like Cd, Pb, As, Hg, and Cr, can be harmful to plants and interfere with a number of metabolic functions (Kumar and Aery, 2016). In this review, the mechanisms of HM-induced growth limitation in plants are investigated, with special focus on the disruption of membrane integrity, nutritional imbalances, ROS generation, and disruption of enzyme activity.

5.1. Interference with Enzymatic Functions

Studies have indicated that HMs such as Cd, Pb, and Hg hinder the activity of essential enzymes in plants, leading to stunted growth and development. For example, it is commonly known that Cd reduces carbon fixation and photosynthetic efficiency by inhibiting Rubisco, an enzyme necessary for photosynthesis (Hafeez et al., 2023). Similar to this, Pb's interference with the electron transport chain (ETC) illustrates how HMs hinder cellular respiration, which in turn hinders ATP synthesis and plant metabolism in general. The impact of Cd on nutrient absorption enzymes and how these disruptions result in growth impairment were demonstrated by Astolfi et al. (2014) in their work on barley. It is commonly known that As and Cr disrupt mitochondrial functions, leading to decreased respiration rates and an energy imbalance (Ghori et al., 2019).

5.2. Generation of Reactive Oxygen Species

Another important process influencing plant metabolism is the induction of ROS by HMs. Under HM stress, these extremely reactive substances, such as hydrogen peroxide and superoxide radicals, can surpass a plant's antioxidant defenses, resulting in oxidative damage. In response, plants activate their defense mechanisms against free radicals, which include non-enzymatic antioxidants like ascorbate and glutathione (GSH) and enzymatic antioxidants like SOD, CAT, and POD (Mehta et al., 2020). ROS are neutralized by these antioxidants, but the plant's antioxidant stores may be depleted due to the increased demand, which could impact metabolism as a whole. According to research, SODs—enzymes that catalyze the dismutation of superoxide radicals—are essential for shielding plants from oxidative stress brought on by HMs (Shahid et al., 2014; Sahu and Basti, 2021). Researchers found that SOD activity increased under drought stress (Alam et al., 2021), which highlights the role antioxidant defenses play in reducing HM toxicity in plants.

5.3. Inequalities in Nutrients

Nutrient imbalances resulting from competition between HMs and vital nutrients for uptake by plant roots can exacerbate the effects of HM stress. Nutrient deficiencies may result from HMs' competition with vital nutrients for uptake sites on the root membrane (Hafeez et al., 2023). Additionally, HMs can interfere with the internal movement and metabolic use of nutrients, impacting important functions like the fixation and assimilation of nitrogen and the metabolism of potassium and phosphorus. One of the best examples is the competition between Cd and Zn, where the preferential uptake of Cd causes a Zn deficiency that impacts multiple plant processes (Ghori et al., 2019). Similar to this, Pb's competition with Ca shows how HMs can cause essential nutrient deficiencies, which can affect plant growth and metabolism (Kalaivanan and Ganeshamurthy, 2016). Numerous investigations shed light on the molecular processes that underlie these competitive relationships and how they affect the health of plants (Hafeez et al., 2023; Shahid et al., 2014; Mehta et al., 2020).

5.4. Membrane integrity disruption

Crucial physiological functions may be impacted by HM stress, which can weaken the cellular membranes' structural integrity and functionality. One important factor causing increased membrane permeability and loss of selective barrier function is lipid peroxidation, which is brought on by ROS produced in response to HM accumulation (Zanganeh et al. 2021). This disturbance may hinder the absorption of vital nutrients and water, thereby hindering the growth of plants. Antioxidant enzymes have been shown to be important in maintaining membrane integrity during HM stress (Zhang et al., 2017). Secondary metabolites, which are essential for defense, signaling, and stress response, can also be influenced by HM stress. Metals like Cd can increase the synthesis of metallothioneins and phytochelatins, which chelate HMs and lessen their toxicity. Furthermore, stress can boost the production of phenolic compounds with antioxidant qualities, such as flavonoids (Malik et al., 2019).

HMs have a complex effect on crop plant metabolism, including oxidative stress, membrane integrity degradation, nutrient imbalances, and disruption of enzymatic activity. The negative impacts of HMs such as Cd, Pb, As, Cu, Zn, Ni, Cr, Mn, and Al on crop plants are highlighted in this overview. These effects include, but are not limited to, DNA damage, decreased photosynthesis, and decreased growth and yield (Table 3 and Fig. 2).

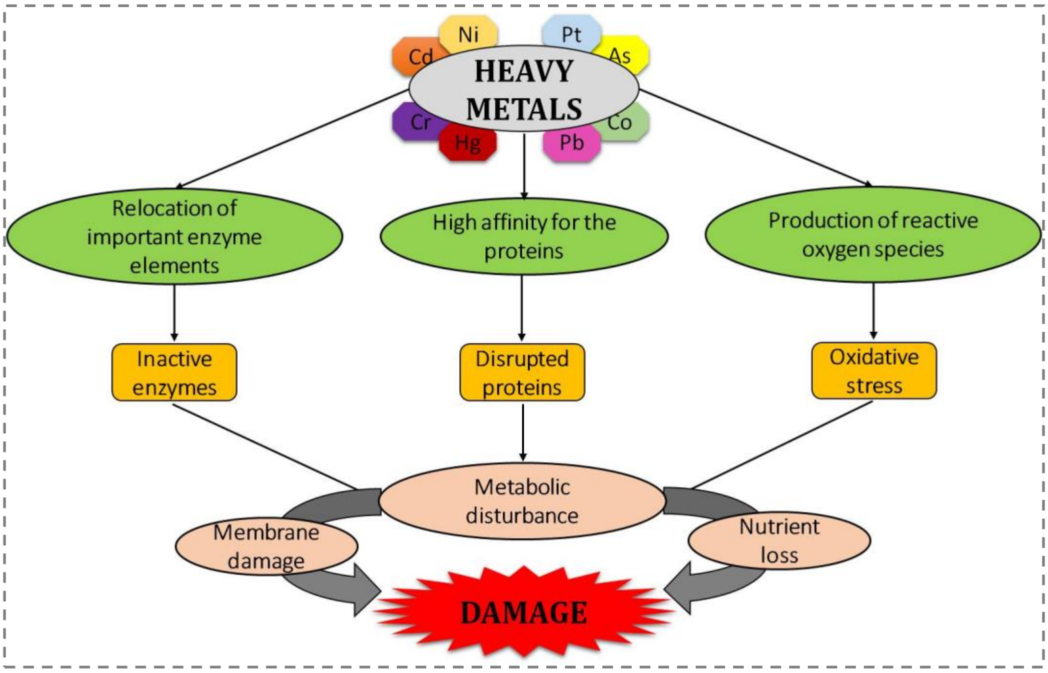

Fig. 2. Mechanism of action mediated by HMs

Table 3 This table summarizes the impacts of different HMs on crop plants.

HM	Plant Species	Observed Physiological Effects, Metabolism and Yield	References
Cd	*Nicotiana tabacum*	DNA damage and increase in lipid peroxidation	Ghori et al., 2019
	Triticum aestivum	Reduction in biomass, nitrogen and phosphorus content	Hafeez et al., 2023
	Brassica juncea	Decrease in photosynthesis rate, RuBisCO activity, increase in lipid peroxidation and H_2O_2 content	Wang et al., 2019
	Brassica juncea	Decrease in dry weight, leaf area, photosynthesis rate, chlorophyll content and seed yield	Riaz et al., 2021
Pb	*Helianthus annuus*	Inhibition in seed germination, biomass, leaf area, chlorophyll and growth	Hafeez et al., 2023
	Triticum aestivum	Reduction in seed germination and biomass	Navabpour et al., 2020
Cu	*Brassica juncea*	Decrease in seed germination, growth, reduction in root and shoot length	Choudhary et al., 2022
Zn	*Zea mays*	Increase in lipid peroxidation activities	Kumar et al., 2022
Ni	*Brassica juncea*	Reduction in photosynthesis, chlorophyll content, stomatal conductance, nitrogen content andenzyme activities	Ghori et al., 2019
Cr	*Cyamopsis tetragonobola*	Decrease in enzyme activity like nitrate reductase and nitrogenase	Ghori et al., 2019
Mn	*Cucumis sativus*	Chlorosis, necrosis and inhibition of growth	Hafeez et al., 2023

6. Nano-Priming against HMs Stress

Farmers employ nanotechnology for a lot of different reasons. The first use of nanotechnology in farming was to make biosensors. Synthetic nanomaterials are employed right now to help plants develop faster and protect them from things that can hurt them, both living and nonliving. The successful use of nanosystems like hydrogels, nanoclays, and nanozeolites has made the soil better (Prajapati et al., 2020). Numerous inorganic adsorbents can assist nanoscale systems. Redox interactions with metallic nanoparticles (NPs) can help clean up or break down soil that has been polluted. Researchers have demonstrated that nanoformulations of insecticides are efficacious in agricultural applications. Lee and Kasote (2024) explain that this is why it's a good idea to control and limit how nanomaterials are used in farming. Farmers have started adopting nano-priming, which is the practice of using nanoparticles to get seeds ready, because it is simple and works well. "Nano-priming" means putting tiny particles on seeds before they grow. Researchers have shown that this starts a number of physiological processes in plants that help them deal with different types of stress, such as HMs. Plants have been able to fight off illnesses, deal with stress, grow more, and germinate seeds thanks to nano-priming procedures. This method is also easier to use than putting nanomaterials on the skin (Fraceto et al., 2016). It has also been underlined how important nano-priming methods are for making farming and the environment safer. Cadmium, cobalt, lead, chromium, manganese, aluminum, zinc, and other HMs can build up in the soil and harm plants. The nano-priming method is one way to lower the toxicity of HMs. ZnO NPs protected plants from stress by lowering the amount of Co they took in and making ultra-cellular structures and photosynthetic apparatus more stable (Salam et al., 2022).Cadmium inhibits the germination of rice seeds and the development of seedlings. Cadmium (Cd) toxicity has been linked to increased generation of reactive oxygen species (ROS) and starch immobilization, which may modify protein profiles and physiological activities (Li et al., 2021b; Khan et al., 2021).

Better Growth and Germination: Nano-priming seeds helped enzymes perform better, absorb more water, and obtain more nutrients, which made them germinate and grow faster (Singhal et al., 2023). In some cases, this is quite crucial since too much metal stress can make regular biological processes not perform right. Nano-primed indicates that plants have nanoparticles on them. This gets their antioxidant defense systems going and makes them manufacture more antioxidant enzymes like SOD, peroxidase, and catalase. These enzymes assist minimize oxidative damage by getting rid of ROS that are generated when HM is under stress (Imtiaz et al., 2023).

How metals enter the body: Some nanoparticles can change how HMs move through soil or make them hard to get to (Benerjee et al., 2023; Ulhassan et al., 2023). This could make some portions of plants that are weak less poisonous and less prone to hold HMs. Taking care of the stress response: Nanopriming could change how some genes in plants that help them deal with stress work. This enhances the plant's inherent capacity to manage HMs stress by activating genes that facilitate stress response and deactivating genes that predispose it to stress (Sun et al., 2023; Rexlin et al., 2022).

More study and field experiments are needed to properly understand how nano-priming works, enhance the procedures, and make sure they are safe and healthy for the environment for use in farming. The overview paper discusses about numerous ways to control nutrients to reduce HMs stress in plants, how HMs affect plant metabolism, and the fascinating manner that nano-priming protects plants. The citations in the review indicate how difficult it is for plants to deal with high metal stress and how new concepts are being employed to make it less of a problem. The most important thing is to be aware of what you eat. This protects plants against HM toxicity and helps them grow faster and make more. Changes in how well plants photosynthesize, how well they take in nutrients, and how healthy they are generally show how significant these treatments are, since HMs are hazardous for plant metabolism. Using nanotechnology, "nano-priming" is a new approach to assist plants deal with stress from HMs. This might make farming better for the environment and more productive. These findings underscore the necessity for additional study and development in these domains. As the world's population expands and environmental problems get worse, we need more and more creative solutions to maintain crops healthy and food safe. Nano-priming techniques, nutrient management strategies, and a better understanding of how HMs affect plants on a biochemical level all work together to make sure that agriculture can continue even when HMs are present. Future research ought to focus on refining these tactics and assessing their suitability for diverse crops and environmental circumstances to provide the groundwork.

7. Role of Plants in Phytoremediation of HMs

Plants play a central role in phytoremediation of HMs through their ability to uptake, translocate, sequester, and detoxify toxic elements from contaminated soils and water. They mitigate HM stress via two main strategies: avoidance and tolerance. In the avoidance mechanism, plants limit metal entry through root surface adsorption, cell wall binding, and rhizosphere modifications such as exudation of organic acids and amino acids that alter pH and redox conditions, thereby immobilizing or precipitating metals into less bioavailable forms (Ali et al., 2013; Zhang et al., 2024). Once inside plant tissues, tolerance mechanisms involve chelation of metals with phytochelatins, metallothioneins, and organic acids, followed by sequestration into vacuoles or less metabolically active organs to prevent toxicity (Sharma et al., 2022). Additionally, plants activate antioxidant defense systems, including enzymes like superoxide dismutase, catalase, and peroxidases, to counteract the oxidative stress caused by HM-induced reactive oxygen species (Gupta et al., 2020). Based on these processes, different phytoremediation strategies are recognized: phytoextraction (uptake and accumulation of metals in harvestable biomass), phytostabilization (immobilization in roots and soil to reduce mobility), rhizofiltration (absorption from water by roots), and phytovolatilization (conversion and release of volatile metal forms such as arsenic or mercury) (Ashraf et al., 2019; Singh et al., 2023). Several species, such as *Brassica juncea*, *Pteris* *vittata*, *Helianthus annuus*, and *Lemna minor*, are well-known for their phytoremediation potential due to traits like high biomass, extensive roots, fast growth, and strong tolerance to HMs (Ali et al., 2013; Faizan et al., 2024). Despite limitations such as slow remediation rates, shallow root zone effectiveness, and the need for safe biomass disposal, phytoremediation remains an eco-friendly, cost-effective, and sustainable approach for managing HM-contaminated sites. Recent research emphasizes the role of genetic engineering, soil amendments, and plant–microbe interactions in enhancing phytoremediation efficiency, offering promising directions for future application (Zhang et al., 2024; Gupta et al., 2020).

8. Conclusion

In brief, when plants are stressed by HMs, their growth, development, and production change in a number of sophisticated ways. We need to know how these responses function so that we can create crops more resistant to HMs and make sure they can flourish in contaminated places. Scientists are still attempting to find out how plants handle stress from HMs. This will help them grow crops that are less likely to get sick and find better ways to clean up dirt that has been polluted.

List of abbreviations:
As: Arsenic
B: Boron
CAT: Catalase
H_2O_2: Hydrogen peroxide
HMs: Havey metal

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