Discover Plants

Review

Toxicity, bioaccumulation and mitigating strategies of heavy metals stress on morpho-physiology of spinach

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Abstract
The purpose of this review was to look into the different ways that heavy metal stress affects spinach, and how hazardous they are to soil, people's health, and plant ecosystems. Heavy metals in soil are caused by anthropogenic and industrial activity, and when they accumulate in food chains, they pose a major risk to human health. This paper presents an overview of heavy metals' negative impacts on soil fertility, plant physiology, and human health. Using spinach as a model plant, it is simple to cultivate and maintain, making it a diverse choice for studying how plants respond to stresses such as heavy metals. They describe how heavy metal stress affects spinach morphology and physiology, including absorption, detoxification, and translocation throughout the plant system. Understanding these procedures is critical when assessing the potential risks associated with the accumulation of hazardous components in spinach's edible parts. This review investigates the impact of heavy metal stress on the nutritional quality and yield of spinach after metal exposure. It is critical to investigate numerous strategies for reducing heavy metal stress in spinach, including soil remediation approaches, phytoremediation capabilities, and genetic procedures aimed to increase plant resistance to metals. The goal of this overview is to shed light on the mechanisms underlying the effects of heavy metals on spinach and to propose strategies to alleviate them, thereby protecting agricultural sustainability and public health (Fig. 1).

Keywords Heavy metals stress · MB (metal binding detoxification) detoxification · Mitigation strategies · Phytoremediation · Soil amendment · Micronutrients · Spinach

1 Introduction

Spinacia oleracea is a broad, green, leafy vegetable that belongs to the Caryophyllales group. It has a large surface area, somewhat high growth rates, and moderately higher rates of heavy metal absorption because of its adaptation ability. Recently investigated their growth and toxicity responses to heavy metal contaminations [1]. Because of their poisonous nature, heavy metals like Cu, Co, Cd, Ni, Fe, Hg, Cr, and Pb effects human health. For example, arsenic is a hazardous metallic element existing in many water supplies, air, and geological formations. Its toxicity is well-established, and chronic exposure can have several detrimental effects on health [2]. Heavy metals occur in soil as a result of both natural and human activities, such as mining, industrial waste, and agricultural practices, heavy metals constitute a serious hazard to the environment. Heavy metals, in contrast to organic contaminants, are resistant to chemical and biological

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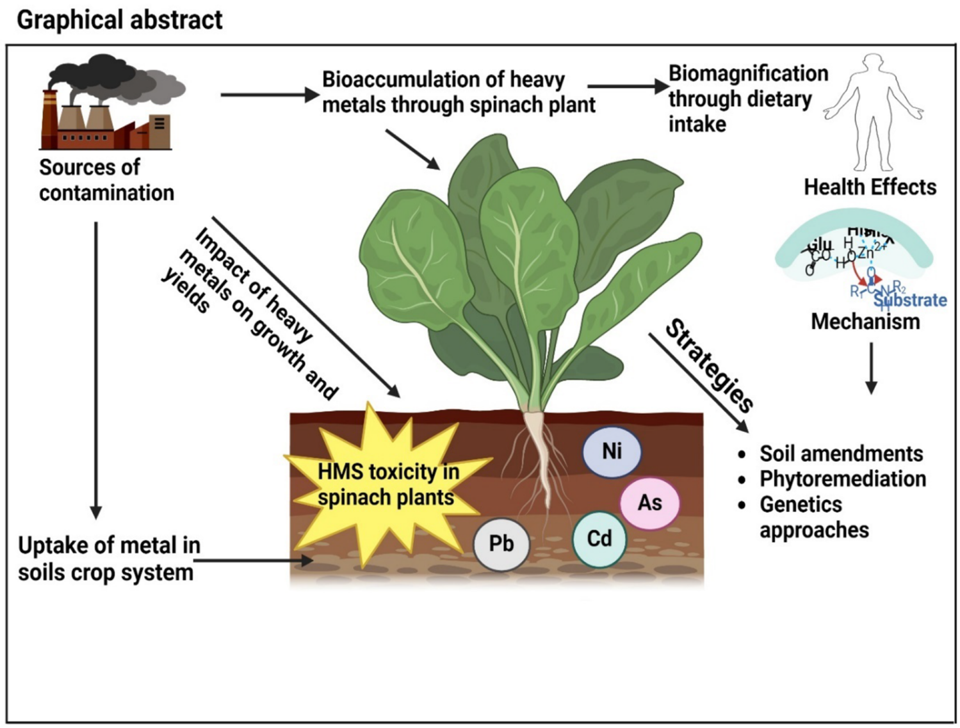

Fig. 1 The figure describes this review and examines the consequences of heavy metal stress on spinach, including how it affects plant physiology, soil fertility, and human health. It also evaluates methods to lessen these impacts, such as soil remediation and genetic modifications

decomposition, which causes them to persist and accumulate in soil over time [3]. These metals can accumulate in the body over time, leading to toxicity and adverse health effects are common problems including kidney damage, brain disorders, heart diseases, respiratory issues, developmental irregularities, and even cancer. The severity of the impact depends on the level and duration of exposure, as well as individual susceptibility [4]. HM can contaminate surface or groundwater and get absorbed by plants or emitted as gases into the troposphere. They can form semi-permanent bonds with soil components like clay, posing long-term health risks. The adverse effects of heavy metals stress on both the environment and human well-being [5]. Using chemical pesticides and fertilizers exposed to raise the risk of soil impurity with heavy metals. Crops grown in such polluted soil can absorb these metals into their tissues. These carriages pose a threat to food safety and human health as consuming crops with high levels of HMs can exert deleterious health, impacts [6].

Elevated concentrations of heavy metals can lead to adverse effects such as decreased plant growth, reduced crop yields, alterations in nutrient uptake, increased plant stress, and potential toxicity not only to plants but also to animals and humans by consuming these plants. When plants absorb heavy metals, these elements can move up the food chain. As they accumulate in the bodies of animals and humans through consumption, they pose health risks. This bioaccumulation of heavy metals from plants to higher trophic levels might lead to adverse health effects for animals and humans [7]. Heavy metal stress in soil poses multifaceted threats to human health, plant growth, and the environment (Fig. 2). To overcome heavy metal toxicity, various fertilizer practices and remediation strategies [8]. Bioaccumulation of heavy metals HMs in soil can harm plant growth, development, and the ability of legumes to fix nitrogen [9]. Soil naturally contains elements like Cd, Cr, As, and Hg in amounts that surpass what plant roots can selectively absorb [10]. Heavy metal contamination directly affects soil quality and root formation. Metals like mercury are absorbed by roots and the amount absorbed varies based on each metal's ionic potential [11]. Utilizing microorganisms to transform heavy metals into less toxic forms is known as microbial remediation. Numerous mechanisms, including biosorption, bioaccumulation, volatilization, bio-leaching, and biomineralization, are included in this process [12]. Heat shock proteins, sometimes referred to as stress proteins, function as protein chaperones to facilitate correct protein folding, which helps to reduce the effects of heavy metal stress. They are essential for protecting and rebuilding proteins under duress. In response to Cadmium (Cd) stress, *Arabidopsis* plants create AtPcrs, Cys-rich proteins in the membrane, which increases the expression of genes encoding metal-binding proteins [13]. Numerous plasma membrane transporters are present in plant cell membranes and are essential for controlling the absorption and equilibrium of metal ions. These transporters regulate the metal ions' entry and exit from plant cells, preserving the proper amounts [14]. The chief objective of this article is to gather primary data regarding the "Toxicity and bioaccumulation of heavy metals stress on morpho-physiology of spinach under mitigating strategies". To examine the effect of heavy metals on human, soil, and plant health. To assess the importance of spinach in HM stress. To explore the impact of heavy metals on

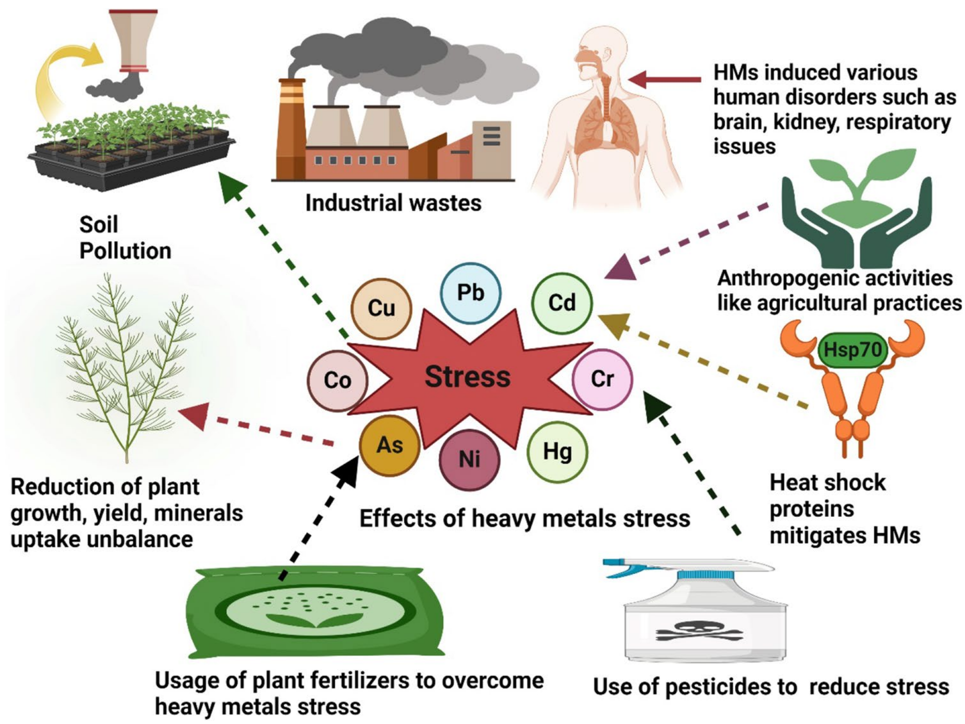

Fig. 2 The visual explanation represents fertilizers and agricultural methods that lower metal toxicity and enhance soil health which, can help decrease heavy metal stress in the soil near dumpsites

the morphological and physiological attributes of spinach plants. To investigate detoxification and binding of HM stress in spinach. To described the effect of heavy metal stress on the nutritional value of spinach, and the accretion of toxic elements in the eatable parts of spinach. To study the role of mitigation strategies for reducing heavy metal stress.

2 Importance of spinach plant

Spinach helps as an important plant because it is a fast-growing crop adaptable to cooler climates. Regular intake of spinach can reduce the risks of chronic ailments such as heart disease and specific cancers, because of its antioxidants and nutritional characteristics [15]. Spinach contains vitamins (vitamins A, C, and E) and minerals (manganese, magnesium, calcium, iron,). It is rich in folic acid, and consuming just a cup of spinach leaves (approximately 25 g) can provide adult humans with percentages of vitamins A (16%), K (15.1%), C (17.5%), and folic acid (24.5%) [16]. Spinach has various antioxidant characteristics, extracts derived from spinach have shown effectiveness in stopping lipid peroxidation in the skin and mitigating metabolic injury in the kidney and liver. This suggests that spinach may have potential protective properties against oxidative stress and related diseases in these organs [17]. There is compelling evidence showing that spinach and its extracts exhibit anticancer and antioxidant effects in cell models of HepG2 and HT-29 [18]. This extract makes it simple to access the many antioxidant compounds and enzymes that occur in spinach by eliminating the cell walls. The process concludes with freeze-drying the subsequent spinach digest, resulting in a lyophilized spinach protoplast extract, which is used as a supplement or ingredient in various products to harness the antioxidant benefits of spinach in a more concentrated and accessible form [19]. Spinach is crucial to providing nutrient-rich addition to diets because of its high content of essential vitamins and minerals (Table 1). It assists as an important source of nutrients, including iron, calcium, vitamins A and C, contributing significantly to overall dietary health.

3 Impacts of heavy metals stress on spinach morphology

Spinach is a type of leafy green vegetable that exhibits a remarkable capacity for biomass production. When compared to other crops, spinach can accumulate substantial amounts of heavy metals [20]. Heavy metals can prevent the growth of spinach plants by affecting various chlorosis, and leaf discoloration [21]. Studies have shown that wastewater irrigation, especially from industries like tanneries containing high levels of chromium (Cr), can lead to an accretion of Cr in spinach plants. This accumulation significantly hinders the plant's development and biomass production. The presence

Table 1 The nutritional values and other vitamins content, mic of Malabar spinach [66]

S. No	Nutrients	Quantity (per 100 g)
1	Water	93 g
2	Energy	19 kcal
3	Proteins	1.8 g
4	Fat	0.3 g
5	Calcium	109 mg
6	Phosphorous	52 mg
7	Iron	1.2 g
8	Magnesium	65 mg
9	Potassium	510 mg
10	Sodium	24 mg
11	Zinc	0.43 mg
12	Vitamin A	8000 IU
13	Vitamin B1	0.05 mg
14	Vitamin B2	0.16 mg
15	Vitamin B3	0.50 mg
16	Vitamin C	102 mg

of Cr in tannery sewage irrigation water results an adverse effects on spinach growth and leads to reduced biomass [22]. Plants raised in extremely Cu-rich soil consequently experience several drawbacks impacts of heavy metals, on the growth attributes of the spinach change nutrient distribution and nutrient absorption, as well as growth retardation, and decreased yield. However, plants produced defensive mechanisms against heavy metals stress and produced Reactive oxygen species, and enhanced oxygen scavenging activity that exerts changes in cell membrane structure, and cell permeability and limits spinach growth [23].

4 Effects of heavy metals on spinach physiology

Numerous research has been conducted on *S. oleracea*, to analyze how it responds to various heavy metals in terms of growth performance and stress responses [24]. Cadmium stress induces a range of abnormalities in plants, affecting both their morphophysiological and biochemical aspects at different levels [25]. Cadmium hinders plant growth by reducing the levels of photosynthetic pigments and the action of antioxidant enzymes, while simultaneously elevating concentrations of malondialdehyde and ROS [26]. An excessive amount of cadmium has inhibitory effects on root and shoot length. Chlorophyll absorption, nutrition uptake, and ultrastructural changes are all impacted by it, Co, Ni, Cu, Zn, and Cd were found to hinder effects on photosynthesis, photosystems 1 and 11, and trigger oxidative impairment in spinach. Each metal resulted in lipid peroxidation and alterations in the antioxidant defense system. Many research investigations have explored the effects of high levels of metallic elements on spinach, specifically concerning their influence on the process of photosynthesis [27].

It exposed that enhanced exposure to UV-B radiation alongside the presence of heavy metal elements like cadmium and Nickel led to a reduction in chlorophyll pigments, ascorbic acid levels, and catalase activity within spinach [28]. Research showed that exposure to lead stress prompted oxidative stress specifically within spinach chloroplasts, resulting in a reduction of chlorophyll content. These collective studies emphasize the opposing impacts of heavy metal stress on spinach, particularly concerning its chlorophyll concentrations [29]. Heavy metals disrupt mitochondrial structure and function, affecting the electron transport chain (ETC) and reducing ATP production potentially impacting the stomatal functioning in spinach. However, HMs imbalance the physiological processes such as photosynthesis, minerals nutrient uptake (iron, calcium, magnesium) and water absorption [30]. Heavy metal stress on spinach results in stunted growth, altered leaf structure, and reduced chlorophyll content (Fig. 3). These observations imply compromised morphophysiological attributes, characterized by inhibited photosynthesis and damaged respiratory processes. Addressing heavy metal toxicity is crucial to protect spinach health and overall crop productivity.

5 Mechanism of heavy metals uptake in spinach

Cadmium stress reduces shoot and root length and the overall fresh and dry weight of spinach [31]. Cadmium negatively impacts spinach by disrupting chlorophyll levels, nutrient absorption and altering the plant's structure at a microscopic level. Spinach absorbs heavy metals like cadmium in multiple steps through its roots, primarily via root hairs using passive diffusion or active transport mechanisms from the soil solution [32]. Essential metals like Mn, Mg, Cu, and Pb are crucial for plant health but can be harmful in excess or in deficiency, impacting plant productivity. Clay minerals or organic matter in soil undergo ion exchange with heavy metal ions. Spinach roots release protons (H^+), displacing metals in the soil through this process [33].

5.1 a. Absorption and translocation

Spinach absorbs heavy metals like zinc, manganese, copper, lead, and cadmium in two basic ways. Diffusion and active transportation channels, quiet diffusion occurs when soil metal concentrations exceed those in plant roots, allowing ions to enter root cells. Active transport refers to particular proteins (transporters) in root cell membranes that aid in the absorption of certain heavy metal ions. Not all spinach includes significant levels of toxins cultivation practices and environmental exposure influence toxin levels. Crops in extremely contaminated locations, such as those with high heavy metal concentrations, may collect more hazardous compounds, including rich green-colored crops like spinach [34]

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Over 86% of composts from Municipal Solid Waste in India exceeded permissible heavy metal limits, posing risks like kidney damage and nervous system disorders when used for crop production because of potential bioaccumulation of contaminants [36]. Research over the past decade focused on stabilizing heavy metals in soil using methods like adhesion,

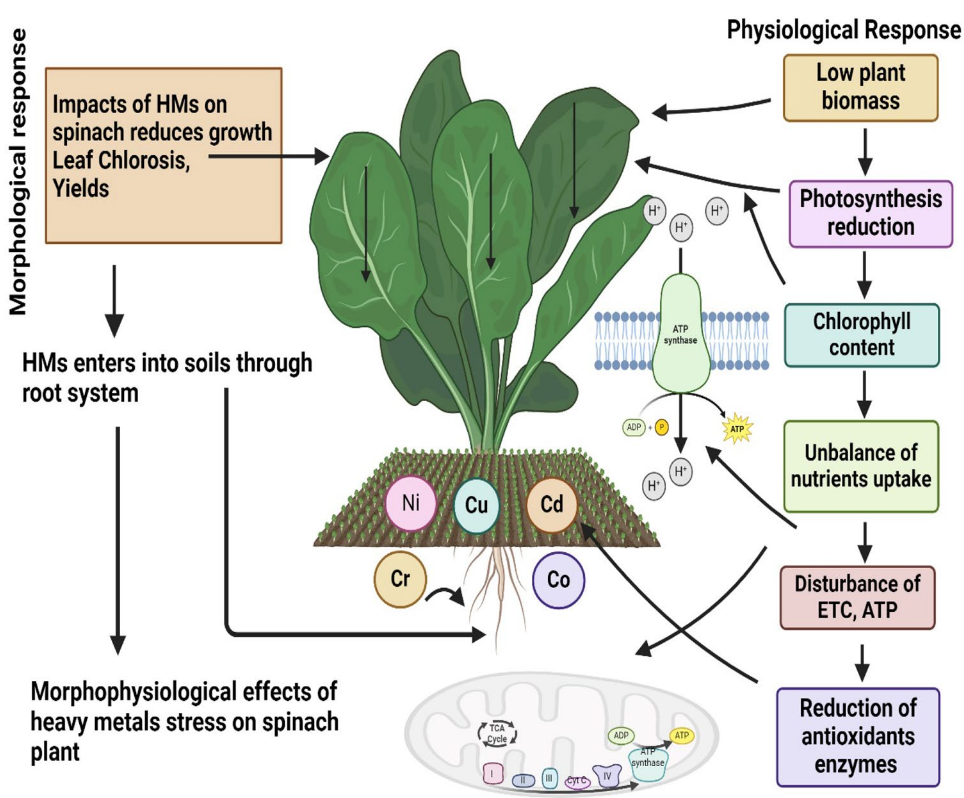

Fig. 3 This diagram illustrates that the heavy metal stress on spinach causes altered leaf structure, stunted growth, and decreased respiration rate, and reduced chlorophyll content

such as compounding, or combined precipitation with amendments. Organic materials like manures, biosolids and fertilizers rich in biological matter have shown effectiveness in reducing contaminant mobility in multi-metal-polluted soils. Materials improve soil health by introducing carbon and essential plant nutrients [37].

5.2 b. Metal binding and detoxification

The metals engage with living systems through binding and redistribution mechanisms. They are essential for biological functions but can be harmful in excess. Balancing their presence is crucial for optimal cellular and organismal health [38]. Metals in biological systems often associate with ligands, like proteins, peptides or small molecules. These ligands possess specific binding sites that coordinate with metal ions through bonding. This interaction stabilizes the metal ions and prevents them from interacting with other molecules [39]. Metalloproteins contain essential metal ions as part of their structure, with specific binding sites allowing for their movement within the protein. Certain plants within the Amaranthaceous family exhibit potential for phytoremediation because of their ability to gather toxic metals in their biomass. Alternanthera Tennelle Colla, a species within this family, has shown the capability to bioaccumulate heavy metals like lead (Cd). Using this plant for phytoremediation of other heavy metals appears promising, based on in vitro investigations (Martins, Vasconcelos [40].

Biotechnological advancements involve leveraging the chemistry of living organisms to develop innovative, environmentally friendly methods for producing common goods. Manipulating cells plays a crucial role in this process. Cadmium cleanup and redistribution, different root components, like main roots and lateral roots have distinct roles and they accumulate cadmium in their cell walls. In understanding this phenomenon, recent research to study Cd subcellular distribution in major roots, lateral roots, and stems of both young and old leaves of two spinach cultivars. This investigation aims to illuminate the reasons behind this unique Cd accumulation process [41].

5.3 c. Phytochelatins, metallothioneins, antioxidants defense system

Heavy metals have recognized to cause various symptoms in plants, including browning of root tips, reserve length of root, decreased biomass, chlorosis, and even death. These metals also impact various metabolic pathways related to water, mineral absorption, respiration, and chlorophyll. To counter the negative impacts of heavy metals, plants employ normal defense mechanisms. Among these defenses, some are enzymatic and others are non-enzymatic. These natural substances such as PAs, work together with MT and PC to alleviate the harsh conditions caused by these metals [42].

Metallothionein's are small sized polypeptides abundant in cysteine that respond to heavy metal stress by altering their gene expression in reaction to various forms of oxidative stress. These metallothionein comprise cysteine-rich domains at their N- and C-terminals, primarily binding heavy metal ions like Cu, Zn, and Cd Phytochelatins' role in heavy metals in plants is significant and glutathione (GSH) is a widely present non-enzymatic antioxidant and made up of three amino acids-Glu, Coys, and Gly-forming a tripeptide γ-Glu-Cies-Gly. Its composition of hydrophilic amino acids enables it to dissolve water [43].

GSH is a widely discussed antioxidant compound recognized for easing oxidative stress induced by various environmental factors, such as heavy metals stress, salinity, drought, and high temperatures. Plants boast strong antioxidant defenses using both enzymes and other compounds to rid the system of harmful free radicals. These defense mechanisms are highly efficient in neutralizing these damaging molecules and safeguarding the plant's health [44]. A diagram explains heavy metal uptake in spinach, highlighting active transport, cell absorption, and potential toxicity (Fig. 4). It visually presents cellular defense strategies, emphasizing mechanisms that mitigate harmful effects and safeguard flexibility against heavy metals in the spinach plant.

6 Impact of heavy metals stress on spinach yield and quality

Although hazardous ions like Cd, Ni, and Hg have harmful effects on soils and human health, spinach plant absorption reduces the presence of heavy metals in the environment. The main goal is to comprehend how these metals interact to change soil conditions and how plants, particularly spinach, absorb them. Heavy metal accretion can have an adverse effect on the quality and growth of spinach [45]. Heavy metal stress can significantly impact spinach yield. When exposed to maximum levels of heavy metals like lead, cadmium, magnesium, or arsenic, spinach plants can experience inhibited growth, reduced photosynthesis, and reduced nutrient uptake. This stress often leads to decreased yield smaller leaves,

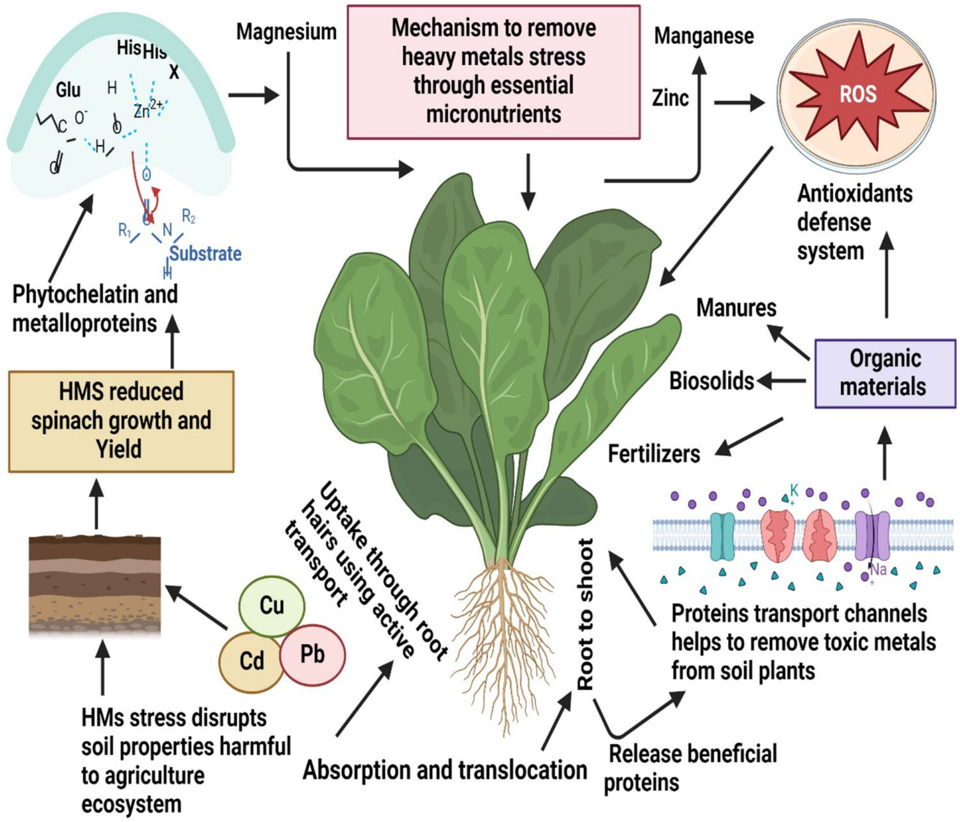

Fig. 4 A diagram illustrates heavy metal uptake through active transport in spinach, showing cell absorption and potential toxicity. It also depicts cellular defense strategies that mitigate harmful effects, enhancing resilience against heavy metal stress

and overall poor plant health [46]. Heavy metals like Cd and Pb negatively impact plant growth by affecting leaves and roots by disrupting enzymatic activity, ultimately reducing plant yield. Plants absorb various heavy metals from the soil or precipitation, but specific minerals like Mn, Mg, Fe are crucial in balanced amounts for optimal growth. For instance, manganese aids in respiration by breaking down water molecules while deficiencies in magnesium cause oxidative damage and cause leaf yellowing. Zinc is essential for plant survival, but excessive amounts hinder growth by reducing chlorophyll, leading to bleaching in plants. Maintaining proper ratios of these essential metals is critical for plant growth and development [47].

7 Impacts of heavy metals stress on nutritional value

The ratio of nutrients to harmful heavy metals impacts metal absorption by plants. Higher nutrient levels can reduce metal uptake, while ample nutrients support crop growth and increase plant absorption sites. This interplay between metal absorption and growth rates influences metal concentrations in plants Reduced nutrient uptake caused by metals like mercury can hinder plants' absorption of essential nutrients, potentially leading to lower levels of crucial vitamins and minerals such as iron, calcium, magnesium, and vitamins A and C in spinach [48]. Metals extracted from soil accumulate more in spinach, particularly in its edible leaves, posing health risks when revealed to higher concentration [49]. Heavy metal stress affects nutrition and reduce the levels of essential micronutrients like calcium, manganese, magnesium, iron, and other minerals such as vitamins A, C, and K, which are profuse in spinach. It has anti-allergic and anti-cancer abilities [50]. The quantity of airborne nutrients influences the behavior of harmful metals in plants. Increased nutrients support plant growth and can dilute the concentration of harmful metals in plant tissues, potentially reducing their toxic effects. Competition between beneficial and toxic metal ions within the plant for binding sites, such as cell walls and membranes, may impact of hazardous metals. This interaction can affect the movement speed of complex substances within the plant [51].

8 Accumulation of toxic elements in edible parts

Spinach contains the highest concentration of heavy metals in its leaves. It may collect larger amounts of heavy metals from the soil surrounding its roots and transform them into substances that are dangerous to consume [52]. PTEs (Potentially toxic elements) possess distinct traits like non-biodegradability and the ability to accumulate in various crop parts, entering the food chain and posing health risks. They negatively impact neurological, enzymatic, endocrine, immune, bone, and circulatory systems. They can induce liver, kidney, and lung diseases, and cancer [53]. The seriousness of this issue depends on heavy metals (chemical speciation), their availability and harmful impacts, the makeup of wastewater sludge, application rates, crop varieties, and handling techniques. These harmful substances, if taken up and stored by crops, can infiltrate the food chain, posing risks to human health. Elevated levels of heavy metals in plants restrict uptake and diminish sunlight exposure, reducing photosynthesis. Heightened salt concentrations raise soil water retention pressures, impeding plant root water absorption [28]. The occurrence of heavy metals in soil disrupts plant growth and soil ecosystems. Regional variations in heavy metal accumulation in spinach and vegetables, driven by soil pollution, present significant toxicity risks for human health (Table 2**.**)

9 Strategies to mitigate heavy metals stress in spinach

HM-RB (Heavy metals Bio remediators), Probable bio remediators of *Spinacia oleracea* plant under contaminants stress few techniques are designated below.

10 Soil remediation techniques

The spinach ability to absorb these metals, this study aimed to find a profitable and simple solution to limit HM, movement in soil because of wastewater irrigation and reduce their absorption by plants. To achieve this target, polyacrylamide Superabsorbent Polymer (SAP) and a mixture of SAP with plantain tree covering biochar have used as soil modifications [54]. These amendments have shown promise in farming and contamination control. The research sought to understand their impact on decreasing HM (heavy metals), absorption by spinach plants watered with artificial effluent comprising Cd, Cr Cu, Pb, and Zn. Investigating how these amendments affect the flexibility of these metals in soil is crucial for developing safer agricultural practices involving wastewater use [55]. Soil microorganisms play an important role in supporting plant development by forming symbiotic relationships with roots which can help to ease stress caused by these metals. One way soil bacteria contribute to is this through the synthesis of indole acetic acid (IAA), a plant hormone known to aid in root development. Studies have exposed that when plants exposed to heavy metal stress, IAA produced by soil bacteria can have a positive effect on plant growth. Some research shows that IAA increases the length of additional roots and influences root architecture in plants like *Arabidopsis.* Plant Growth-Promoting Bacteria (PGPB) have involved in enhancing both root and shoot biomass under these stress conditions. Overall, the synthesis of IAA by soil bacteria and PGPB seem to play a significant role in alleviating the negative effects of heavy metals, on plants, promoting root, growth and aiding in overall plant development in contaminated environments [56].

11 Phytoremediation potential of spinach

It has been shown that spinach can collect and retain heavy metals from contaminated soils such as copper, zinc, lead, and cadmium. Spinach takes these metals from the soil and incorporates them into its roots and leaves using a process known as phytoextraction. Because metals may be removed from the environment by harvesting spinach plants on a regular basis, it is advantageous for areas where heavy metal contamination is a problem [57]. Phytoremediation, a technique that uses their natural mechanisms to remove heavy metal stress in spinach plant. These plants effectively tackle various pollutants such as metals, pesticides, explosives, and oil. This method is helpful because of its reliance on plants most of the remediation work, reducing the need for extensive equipment and labor. It eliminates the necessity for activities like soil excavation or groundwater pumping, conserving energy in the

Table 2 Stress from heavy metals on spinach and other plants varies depending on the area

S. No	Heavy metal	Vegetables	Area	References	Remarks
01	Pb and Cd	*Spinacia oleracea, Solanum lycopersicum*	Amba nalla in Amravati city, Maharashtra	[67]	The tomato exceeds the allowable limit
02	Cr, Ni, Cu, Pb, and Cd	*Lactuca virosa, Lactuca sativa, and Ipomoea aquatica*	Guangzhou, South China	[68]	The evaluation revealed that soil samples indicated the greatest risk due to Cd (cadmium) and Pb (lead) levels
03	Fe, Zn, Cu, Pb, Cd, Mn, and Cr	*Spinacia oleracea L., Brassica oleracea L. var. capitata Linn., Brassica oleracea L.,*	J.P. Cement (Rewa)	[69]	The pollution levels are notably high in the vicinity of cement factories in Rewa, India
04	As, Cd, Cr, Pb, Ni, and Hg	*Spinacia oleracea L., Brassica rapa subspec. pekinensis, Brassica oleracea L. var. capitata,*	Zhejiang, China	[70]	The levels of Cd (cadmium) and Pb (lead) surpassed the maximum allowable concentrations (MACs) established by the Chinese Health Ministry
05	Cd, Pb, Zn, and Cu	*Spinacia oleracea L., Cucurbita moschata Duch,*	New South Wales, Australia	[71]	The maximum limits are set higher than the standards outlined by Australia
06	Fe, As, Cr, Mn, Cu, Zn, Pb, Cd, and Hg	*Solanum lycopersicum, Solanum melongena, spinach, and Coriandrum sativum*	Coal Burning Basin, Korba, India	[72]	The highest HRI value of metals, i.e., As, Mn, Cu, Cd, Pb, and Hg with the spinach was observed due to higher Cd and Pb contents

cleanup process [58]. Phytoremediation comprises various methods, including phytoextraction (plants absorb toxic metals from soil), phytodegradation (plants through metabolic activities breakdown pollutants), hemofiltration (plant roots used to filter and remove pollutants) Phyto stabilization (The utilization of plants to immobilize and contain contaminants in the soil) and phytovolatilization (The process in which plants absorb contaminants from the soil or water and release them into the atmosphere in a gaseous form) [59]. Phytoextraction involves the use of plants with high metal accumulation capabilities to draw contaminants from the polluted environment and concentrate them in their aboveground tissues, which are later harvested. If economically viable, metal enriched plant residues can be exploited for metal recovery rather than being disposed of as perilous waste. This technology harnesses the power of plants to cleanse contaminated sites, showing promise in environmental and ecosystem restoration efforts [60].

Some plants possess inherent abilities to sustain HM, aiding in environmental cleanup via phytoremediation. This method has gained significance over the last two decades because of its effectiveness and capability. While over 500 plant species are acknowledged as hyper-accumulators capable of HM, uptake, many are unsuitable for phytoextraction due to slow growth and limited biomass [61]. Hyperaccumulators help with heavy metal removal via phytoremediation and soil amendments (Table 3). Bioaccumulation studies expose Cd uptake in vegetables, highlighting the capability of these treatments for the operative and sustainable remedy of HM, contaminated soils.

12 Genetic approaches for metal tolerance

To maintain healthy plant growth and safeguard dependent organisms, it's crucial to eliminate collected contaminants. Preventing these persistent substances from entering ecosystems is essential for environmental stewardship and ensuring ecosystem integrity [62].

Phytoremediation offers an affordable, eco-friendly, and non-disruptive method to remove inert metals and pollutants from contaminated environments. Advances in molecular genetics and transgenic techniques have significantly enhanced our understanding of phytoremediation mechanisms. Recent discoveries, like gene overexpression for metal handling and enzyme degradation of hazardous compounds, have opened up fresh possibilities for this technique [63].

The ability of spinach to manage and gather heavy metals can be enhanced through genetic methods, allowing its cultivation in polluted or high-metal environments. By introducing genes responsible for metal-chelating peptides or proteins like Phytochelatins or metallothionein, it's possible to enhance the sequestration and retention of harmful metals within spinach cells. These peptides prevent metals from interacting with biological elements by binding to them, forming stable complexes [64].

Biotechnological advancements, including transgenic methods, have bolstered crop plants' ability to withstand heavy metal stress. However, the external application of organic amendments (OAs) provides a practical, cost-effective, and environmentally friendly natural solution to counter damage caused by both natural and artificial factors. OAs contribute to enhanced morphological traits such as biomass, growth, root length, and leaf area, ultimately boosting crop yield. They increase the level of crucial components like algae and pigments involved in photosynthesis, alleviating the impact of HMs on stressed plants and acting either as primary or supplementary chemicals [65]. Figure 5 represents strategies, including genetic approaches and phytoremediation aiming to mitigate heavy metal stress toxicity in spinach plants. These visuals highlight diverse methods employed to enhance resilience and decrease the harmful impacts of heavy metal exposure.

Table 3 Hyperaccumulators are applied to remove heavy metals from contaminated soils by phytoremediation, soil amendments, and vegetable bioaccumulation of HMS, absorption

Hyperaccumulators, Soil amendments	Heavy Metal	References
Spinacia oleracea L	Cu, Ni, Zn, Pb, Cr	[73]
Brassica oleracea, Raphanus sativus	Zn, Cd, Ni, Cu	[74]
Cucumis sativus L	Pb	[75]
Spinach	Cd in plant tissues	[76]
Rice grain and rice straw uptake Cd, and Cu	Green waste compost	[77]
Exchangeable pakchoi and spinach	Poultry manure Compost	[78]
Tobacco plant	Cow manure	[79]

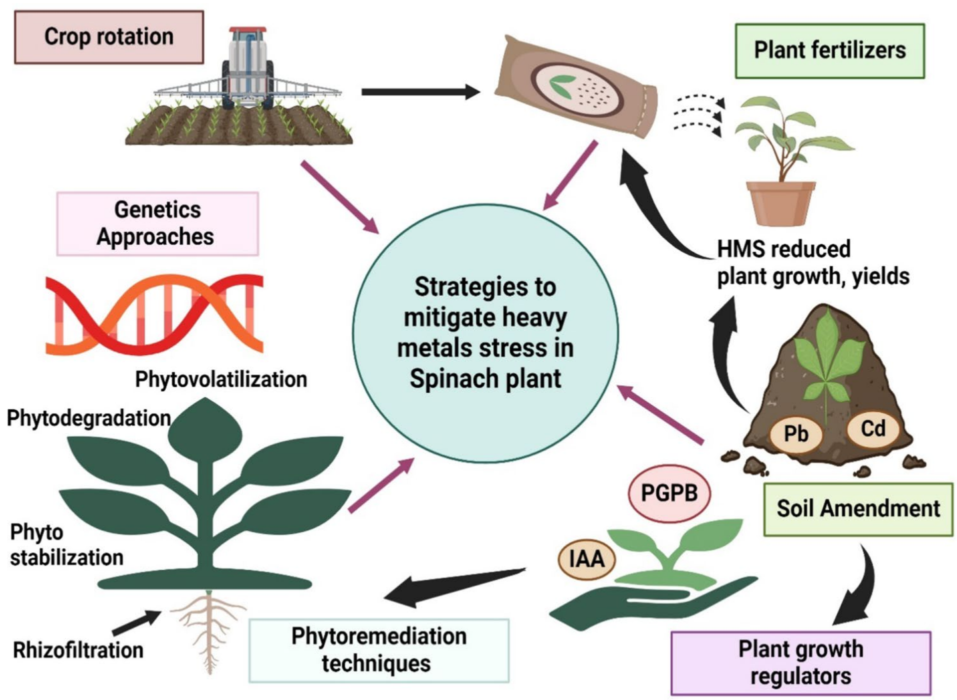

Fig. 5 This diagram illustrates strategies like phytoremediation and genetic approaches to mitigate the toxicity of heavy metal in spinach plant

13 Future prospects

In the future, there is a need for increased research attention directed towards comprehending the intricate mechanisms governing microbial interactions and the mobilization of heavy metals (HMs) within plants. Investigate and develop novel strategies beyond the current mitigating methods for heavy metal stress in spinach. This could involve advanced genetic modifications, innovative soil treatments, or alternative plant-based approaches. Explore the interactive effects of multiple heavy metals on spinach physiology. Investigate how combinations of different metals impact the effectiveness modifying strategies. Collaborations across disciplines such as biology, chemistry, environmental science, and agriculture inscribe heavy metal stress and mitigation in spinach can have broader ecological and societal implications. This involves a thorough investigation into the diverse pathways through which HMs are transported from roots to above-ground components via the xylem. However, the knowledge of soil chemists, breeders, engineers, microbiologists and plant biologists is required for this interdisciplinary project. The goal is equally challenging contamination in the environment, a serious issue that endangers people's health significantly. By exploring these avenues, the research can contribute significantly to addressing the challenges posed by heavy metal stress on spinach while paving the way for sustainable and practical solutions in agriculture and environmental management.

14 Conclusions

Contamination by heavy metals, presents serious risks to agricultural sustainability and human health, especially for important green vegetables like spinach. This study emphasizes the critical necessity to address contamination by highlighting the effects of heavy metal on the morphology, physiology, and production of spinach. Heavy metals bioaccumulate in spinach, which has an impact on soil health and plant health. Developing protection methods requires an understanding of the mechanisms behind heavy metal uptake, translocation, and detoxification in spinach. Concerns about food safety are raised by the discovery of heavy metals, in spinach's edible sections. Soil remediation, spinach phytoremediation potential, and genetic modifications for metal tolerance are promising approaches. To lessen the negative effects of heavy metals pollution on agriculture, human health, and spinach cultivation, integrated methods are crucial.

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Declarations

Ethics approval and consent to participate All authors have read and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Author.

Consent for publication All authors declare that they consent for publication in the discover plant.

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