Essential Insights for Effective Environmental Management and Human Well-being: Strategies for Remediation in Soil-Plant-Environment Systems

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Abstract

This concise review addresses the growing concerns surrounding cadmium, a toxic heavy metal with widespread presence and adverse effects on human health and the environment. It explores various aspects of cadmium, encompassing its natural abundance, uses, and global contamination of environmental sites. The investigation includes examining maximum allowable levels and offering insights into regulatory frameworks. The review further explores cadmium's complex speciation and bioavailability in soil, considering factors such as redox potential, pH, organic matter, and microorganisms. Additionally, it discusses the impacts of cadmium on plant growth, development, and nutrition, emphasizing defense mechanisms like hyperaccumulation. The comprehensive overview extends to diverse remediation technologies, critically evaluating their efficacy in mitigating cadmium pollution. This holistic exploration aims to provide essential insights for effective environmental management and human well-being.

Keywords: Environmental Management, Human Welfare, Cadmium, Redox Potential.

Introduction

The global surge in urbanization and industrialization has brought forth formidable environmental challenges, marked by the escalating release of potentially harmful substances into our

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surroundings. Pollutants from industrial activities, urban runoff, agricultural practices, improper waste management, and mining activities threaten ecosystems, human health, and the delicate balance of the natural environment. Simultaneously, the agricultural sector, a cornerstone for global sustenance, grapples with water scarcity issues. Climate change, population growth, over-extraction of groundwater, and inefficient water management practices contribute to the growing challenge of securing adequate water for irrigation, prompting farmers to explore alternative resources (Chowdhary et al., 2020).

Amidst these challenges, industrial wastewater emerges as a potential solution for agricultural water supply. Seen as a cost-effective alternative, industrial effluent, a byproduct of industrial operations, could provide essential nutrients such as nitrogen, phosphorous, and potassium, reducing reliance on artificial fertilizers and supporting sustainable agriculture. However, the use of industrial wastewater for irrigation comes with its own set of challenges. The quality of wastewater depends on industrial operations, and contaminants like heavy metals, organic compounds, and salts can adversely impact soil and crop health. Safe and effective use necessitates proper treatment, monitoring, and compliance with regulations related to public health and environmental protection (Raj & Maiti, 2020).

Moreover, it is vital to recognize that industrial wastewater may contain various pollutants, including heavy metals like cadmium. Cadmium, known for its high toxicity and mobility, poses significant risks to human health and the environment. Its accumulation in soil, often stemming from human activities like using fertilizers and industrial waste deposition, raises concerns about the contamination of crops and potential adverse effects on those who consume them. Addressing the challenge of cadmium contamination is paramount to ensuring the well-being of ecosystems and human populations alike (Rani et al., 2014).

Cadmium Minerals and Natural Abundance

Cadmium, classified as a chalcophile element, is not commonly found in its natural state. In sulfur minerals, particularly sphalerite (ZnS), it often serves as a replacement for other details like zinc (Zn), lead (Pb), copper (Cu), and mercury (Hg). Additionally, albeit to a lesser extent, cadmium can replace zinc in various raw minerals, including smithsonite (ZnCO3), as shown in Table 1. Greenockite and Hawleyite (CdS) are the most widespread minerals containing cadmium (Cd). The presence of cadmium-containing minerals varies significantly on a global scale. Table 2 highlights two of the frequently encountered minerals, including cadmium (Jenkins *et al.* 2002).

Cadmium and Sources

Cadmium is extensively utilized across various industries, with applications ranging from electroplating and solder manufacturing to its use in electromotive force cells, Ni-Cd batteries, and the production of cadmium rods for neutron absorption in nuclear fission regulation. Its versatility extends to diverse fields. It plays a crucial role in manufacturing television image tubes, particularly in black-and-white picture tubes, and contributes to color picture tubes with green and blue phosphors for visual effects. Despite its natural occurrence in the Earth's crust, with concentrations ranging from 0.1 to 0.5 parts per million (ppm), the release of cadmium into the environment is exacerbated by both natural processes, such as forest fires and volcanic eruptions, and human activities like metal refining, waste incineration, and the use of phosphate fertilizers (Hembrom et al., 2020).

Cadmium Contaminated Sites Worldwide

In the southern and southeastern regions of the globe, concerns about cadmium contamination have escalated due to the complex interplay of natural forces and human activities, leading to various forms of pollution, particularly the accumulation of heavy metals like cadmium. In Scandinavia, the cadmium concentration is increasing by approximately 0.2% per year, raising alarms about potential environmental and health impacts. This upward trend necessitates careful monitoring and understanding to develop strategies to mitigate the effects of cadmium pollution. In Pakistan, heavy metal pollution is on the rise, driven by urbanization, industrialization, and extensive pesticide and fertilizer use in agriculture. Rapid urbanization contributes to improper waste disposal and the release of pollutants into the environment, while industrial activities and agricultural practices intensify heavy metal contamination in soil, water, and air. The increasing adoption of industrial effluents for irrigation exacerbates the accumulation of harmful metals in agricultural soils. Addressing these issues is crucial to ensure the well-being of ecosystems and human populations in these vulnerable regions (Riaz et al., 2018).

Maximum Allowable Levels of Cadmium in the Soil and Environment

In China, the acceptable upper limit for cadmium concentration in agricultural soils is 0.6 parts per million (ppm). In contrast, in Holland (the Netherlands), the permissible range is broader, varying from 0.8 to 5 milligrams per kilogram (mg/kg). Similarly, the allowed limit in India is 3 to 6 mg/kg. Exceeding these thresholds can lead to cadmium toxicity in microorganisms and plants, impacting soil quality and agricultural production. The concern arises due to the potential entry of cadmium into the food chain, posing health risks when consumed. Industrial activities in paper mills, textile factories, and tanneries contribute to water pollution, releasing contaminants like cadmium into water bodies. Strict waste disposal and wastewater treatment regulations are essential to control cadmium pollution. Monitoring levels, adopting effective waste management, and raising awareness are crucial for environmental preservation and human health. Despite reports of cadmium concentrations exceeding WHO limits, specific occupational exposures, as evidenced in a study by Ahmad et al. (2014), align with safety guidelines, emphasizing the importance of continued vigilance to mitigate potential health risks from prolonged exposure.

Speciation and Bio-availability of Cadmium in Soil

The accessibility of cadmium in biological systems significantly influences its toxic and physiological impact. Soil speciation, involving the distribution and transformation of chemical elements, is crucial for understanding nutrient availability, pollutant mobility, and overall soil quality. In environmental and soil science, "speciation" describes the various chemical forms of elements in the soil matrix. The presence and impact of cadmium depend on its quantity and chemical composition. Different chemical forms of cadmium exhibit varying mobility, reactivity, and bioavailability. Understanding these forms is essential for assessing potential harm, guiding remediation strategies, and informing environmental decisions. Notably, the exchangeable fraction and those associated with Fe–Mn oxides, carbonates, and organic matter are potentially bioavailable, while the residual fraction is considered non-bioavailable, providing insights into the risk associated with cadmium contamination (Tandy et al., 2009; Rodriguez et al., 2009).

Speciation studies indicate notable variability in free cadmium species concentrations, mainly dissolved cadmium, ranging from 0% to 60%, with an average of 20%. Iron and manganese-bound fractions consistently dominated, accounting for a significant portion, while approximately 45% of cadmium is associated with metal oxide fractions, such as iron-manganese oxides and hydroxides. Surprisingly, the organic matter-bound fraction constituted the second largest, making up 39% of the distribution. Conversely, carbonate (13%), residue (2.5%), and exchangeable forms (1%) had minimal significance. Notably, a slight shift in cadmium fractions occurred six weeks after plant seeding, with a decrease in metal oxide-bound cadmium (from 45% to 29%) and increases in carbonate-bound (from 13% to 19%) and exchangeable cadmium (from 1% to 8%) fractions (Gigliotti & Massaccesi, 2013). 6 Various factors, including soil organic matter, pH, redox potential (Eh), and microbial communities, influence cadmium bioavailability, ranking soil redox potential as the second most crucial factor after pH (Sarwar et al., 2010).

Effect of Soil pH on Cd Bioavailability and Speciation in Soil

The primary determinant influencing the bioavailability of cadmium in paddy soils is soil pH. Notably, elevated cadmium bioavailability is often associated with acidic soil conditions, leading to increased cadmium release into the environment (Yu et al., 2016). A direct correlation exists between decreased soil pH and enhanced cadmium bioavailability, as acidic conditions facilitate the transformation of cadmium into more accessible forms, ultimately increasing uptake by living organisms (Li et al., 2014). Recent research on cadmium assimilation by rice crops revealed a significant negative correlation between cadmium levels in rice grains and soil pH, highlighting the robust link between cadmium uptake and soil pH (Rafiq et al., 2014). Experimental data demonstrated a marked reduction in cadmium concentrations within rice grains with a two-unit increase in pH. Prolonged flooding decreased redox potential, elevated soil pH, and diminished cadmium availability. The recurring flooding effect intensified soil pH and negatively charged soil particles, reducing exchangeable cadmium levels (Li et al., 2017). Soil pH significantly influences cadmium inorganic speciation, with $CdCl^+$ dominating and exhibiting an inverse relationship with increasing pH. The solubility of Cd from solid phases consistently decreases with rising pH levels, highlighting the complex role of pH in shaping cadmium speciation and availability (Ren et al., 2015). The application of ammoniacal fertilizer impacts the exchangeable proportion of cadmium, particularly at lower pH levels (Zaccheo & Crippa, 2007).

Effect of Redox Potential on Cd Bioavailability and Speciation in Soil

Soil redox potential is a critical factor influencing the bioavailability of cadmium (Cd) in the environment. The availability of electron acceptors and the environment's overall redox state significantly affect Cd's speciation. Under reducing conditions, Cd tends to form precipitates like $CdCO_3$ and CdS, while under oxidizing conditions, it exists as Cd^{2+} or soluble salts (Sarwar et al., 2010). This interaction between redox potential and Cd's chemical forms plays a crucial role in its uptake by living organisms. However, the impact of soil redox potential extends beyond Cd bioavailability. It influences soil mineral composition, organic matter content, microbial activity, and overall soil characteristics, contributing to the complex dynamics of Cd in the soil environment (Gallego et al., 2012).

In situations characterized by alternating wet and dry conditions, the cycling of iron (Fe) is intricately linked to changes in redox potential, resulting in dynamic processes with consequences such as organic matter decomposition, methane gas generation, and the immobilization of heavy metals like Cd (Jackel et al., 2005; Rinklebe et al., 2016). The dissolution of iron-manganese oxy-hydroxides under reducing conditions enhances Cd bioavailability while oxidizing conditions reduce Cd bioavailability and modify its speciation in the soil (Rinklebe et al., 2016). Research has demonstrated that varying redox potentials significantly affect Cd absorption and translocation in plants, impacting the soluble Cd fraction in soil solutions (Han et al., 2018). Conversely, alternate studies suggest that oxidizing conditions can enhance Cd bioavailability, as observed with increased redox potential leading to a notable escalation in soluble Cd content (Shaheen et al., 2016). These divergent findings highlight the complexity of Cd behavior in response to changing redox conditions.

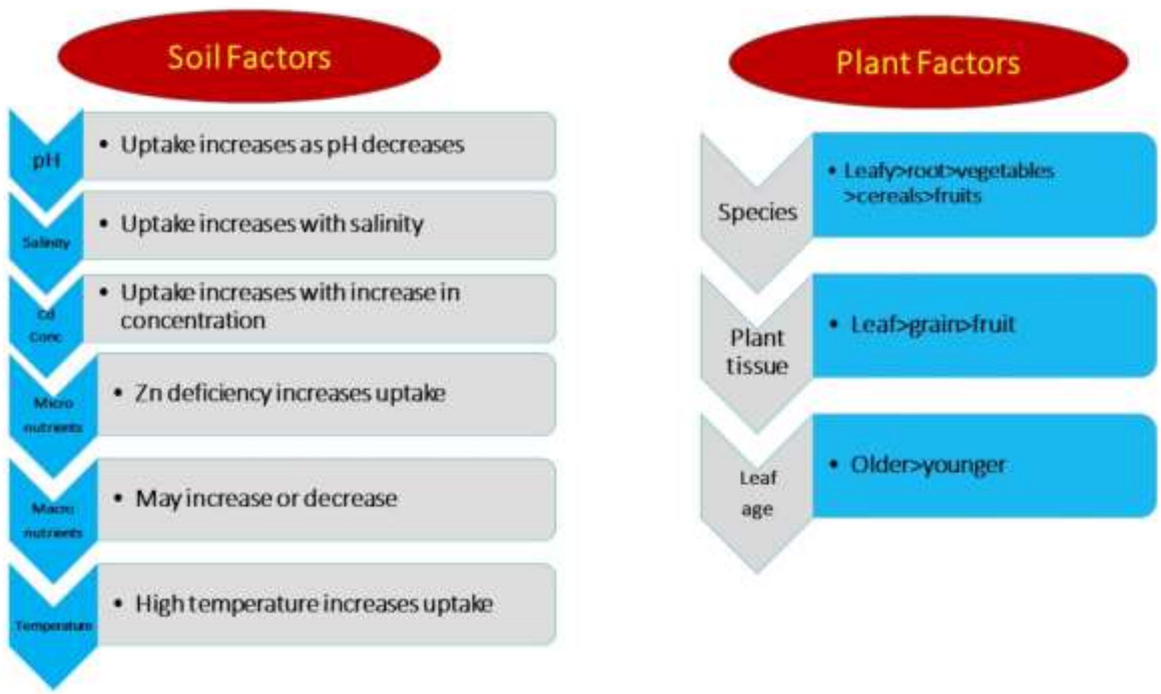
Effect of Microorganisms on Cd Bioavailability and Speciation in Soil

In soil environments, microorganisms play a crucial role in influencing the speciation and bioavailability of cadmium (Cd) through various biological processes, including microbial metabolism, enzymatic activities, and interactions with soil components (Majewska et al., 2007). These interactions can lead to changes in Cd's availability for uptake by plants and other organisms, ultimately impacting Cd's overall cycling and fate in soil ecosystems. Rhizosphere bacteria contribute to phytoremediation processes by altering the bioavailability of metals, releasing chelating agents, participating in biosorption, and influencing soil pH (Rajkumar et al., 2010). Microbially produced Low Molecular Weight Organic Acids (LMWOAs) significantly affect the solubility of Cd in soil, forming stable complexes that depend on pH, Cd form, and the nature of organic acids present (Ryan et al., 2001). Increased excretion of organic acids by microorganisms can enhance the solubility and mobility of Cd in soil, potentially leading to more significant environmental contamination (Li et al., 2010). However, the impact of microorganisms on Cd mobilization can vary under specific conditions and microbial species involved, highlighting the complexity of microbial interactions in soil environments (Braud et al., 2006). Furthermore, compounds synthesized by plant-associated bacteria, such as extracellular polymeric substances (EPS), proteins, and mucopolysaccharides, can form complexes with hazardous heavy metals, reducing their mobility and altering speciation in soil (Guo et al., 2007). Certain microorganisms, including iron/sulfur-oxidizing bacteria and iron-reducing bacteria, can modify the mobility of Cd through oxidation or reduction reactions, impacting the transformations and solubility of Cd in the soil environment (Beolchini et al., 2009).

Effect of Organic Matter on Cd Bioavailability and Speciation in Soil

The interaction between cadmium (Cd) and organic matter in soil is contingent on the quantity and composition of organic material (Hamid et al., 2019). The nature and amount of organic matter significantly influence Cd binding, mobility, and availability in the soil (Hamid et al., 2019). Sewage sludge, a primary anthropogenic source of organic matter, often contains elevated Cd levels due to various sources, including industrial and governmental activities (Hamid et al., 2019). When applied as an agricultural amendment, sewage sludge has the potential to substantially increase Cd content in soils (Hamid et al., 2019). Proper management of organic waste, particularly sewage sludge, is crucial to prevent the accumulation of toxic metals like Cd in the environment (Hamid et al., 2019). Introducing organic amendments into soils has a dual impact on Cd immobilization through adsorption mechanisms, enhancing Cd immobilization and contributing to increased surface charge (Clark et al., 2007). While organic matter decreases the bioavailability of Cd, it instigates transformations affecting Cd speciation in the soil, highlighting the intricate nature of their interactions (Hamid et al., 2019). Organic matter's high cation exchange capacity often reduces Cd bioavailability in soils with higher organic matter content (Sauv et al., 2003). For instance, they are adding chicken manure, which substantially reduced Cd concentrations in wheat grains by approximately 75% (Zhang et al., 2015). The utilization of compost, biogas slurry, and biochar derived from rice husk and composted municipal solid waste has demonstrated significant impacts on reducing Cd bioavailability in the soil-plant system (Ahmad et al., 2014; Bian et al., 2016). Additionally, incorporating cow and pig manure as soil amendments led to reduced Cd concentrations in Eucalyptus plants, highlighting the potential of these amendments to mitigate Cd uptake by plants (Meeinkuirt et al., 2016). In adsorption studies, organic matter substantially increased Cd adsorption in soil, emphasizing its role in enhancing the soil's capacity to immobilize Cd ions (Sauv et al., 2003).

Figure 1



The escalation of active cadmium (Cd) content in soils is influenced by various factors such as organic matter decomposition, transitional product formation, and low oxygen levels, collectively diminishing the soil's Cd retention capacity (Wang et al., 2017). A noteworthy correlation was observed between water-soluble Cd concentrations and soil organic matter, indicating that higher organic matter content resulted in decreased water-soluble Cd concentrations due to increased binding sites in the soil matrix (Beesley et al., 2014). Biochar amendment, particularly when using DTPA extraction, demonstrated a substantial 56% reduction in the bioavailable Cd fraction, showcasing its potential to mitigate Cd availability in soil (Puga et al., 2015). Investigation into rice straw biochar effects revealed an 11% reduction in extractable acid Cd and a significant 37% increase in organically bound Cd, indicating its capacity to influence Cd distribution and forms in soil (Lu et al., 2017). Additionally, the introduction of biochar increased Cd association with carbonates while decreasing exchangeable Cd, suggesting a shift toward less accessible Cd forms in the soil matrix (Meng et al., 2018). Overall, these studies underscore the significant impact of various amendments on Cd speciation and availability in soil environments.

Effect of Cd on Mineral Nutrition

The presence of cadmium (Cd) ions in various plant species has been shown to disrupt essential mineral nutrient uptake, translocation, and provision, impacting overall plant health and growth (Chang et al., 2003; Metwally et al., 2005; Guo et al., 2007; Yang et al., 2007; Astolfi et al., 2005). Exposure to Cd results in reduced uptake of nutrients such as iron, boron, manganese, calcium, potassium, phosphorus, zinc, sulfur, zinc, copper, magnesium, molybdenum, and others, affecting crucial physiological processes (Chang et al., 2003; Metwally et al., 2005; Guo et al., 2007). Additionally, Cd inhibits the activity of enzymes involved in ammonia assimilation and nitrogen fixation in soybean plants, impacting nitrogen-related processes critical for plant growth (Yang et al., 2007). Furthermore, Cd interferes with the H+ ATPase enzyme in maize root cells, hindering the absorption of necessary substances and disrupting ion transport processes (Astolfi et al., 2005). In soil, Cd can undergo precipitation and adsorption reactions, reducing its solubility and availability for plant uptake (Matusik et al., 2008). Elevated Cd concentrations intensify competition between Cd and essential nutrients for transporters within cell membranes, leading to plant nutrient deficiencies (Zhao et al., 2005). In response to high Cd concentrations, plants may employ a defense mechanism by sequestering Cd in non-edible vegetative parts to minimize contamination in edible portions, safeguarding the quality and safety of harvestable parts for consumption (Zhao et al., 2005).

Effect of Cd on Growth, Development, and Photosynthesis of Plants

Prolonged exposure to cadmium (Cd) can lead to various detrimental effects on plant health. These include symptoms such as root browning, decomposition, and the development of mucilaginous roots. Additionally, Cd toxicity may cause reductions in shoot growth and hinder the apical growth of roots. Visible signs of toxicity can manifest as leaf chlorosis (yellowing) and the rolling of leaves. Furthermore, Cd exposure might inhibit the formation of lateral roots, and in severe cases, it can result in the main root's distortion, rigidity, twisting, and browning. These symptoms collectively illustrate the range of negative impacts Cd toxicity can have on plants' overall growth and development (Yadav, 2010). The primary cause of observed cadmium (Cd) toxicity in plants is the disruption of normal cell division and abnormal elongation of cortical cells and epidermal layers in the apical region. This structural disturbance can result in significant changes in leaves, such as alterations in chloroplast ultrastructure and decreased chlorophyll content. These changes can lead to symptoms like chlorosis (yellowing) and, more importantly, a reduction in the efficiency of photosynthesis. This decline in photosynthetic capacity has a cascading effect on the plant's overall growth and vitality, contributing to the overall impact of Cd toxicity on plant health (Miyadate et al., 2011). Rascio et al. (2008) provided insight into the effect of cadmium (Cd) contamination on rice seedlings, revealing inhibited root growth and potential alterations in morphogenesis. Similarly, in pea plants, Cd stress-induced changes in root mitotic processes and elongation potentially lead to chromosomal aberrations in root tips. These observations underscore the impact of Cd stress on cellular processes. Additionally, other abnormalities induced by Cd in plants often encompass irregularities such as fragments, precocious divisions, ligands, stickiness, and the formation of bridges between chromosomes (Rascio et al., 2008). Tables 3 and 4 serve as comprehensive references that compile a wide range of research findings illustrating the effects of cadmium (Cd) on various essential attributes of different plant species. These tables present a condensed summary of the impacts of Cd exposure on parameters such as root growth, morphogenesis, mitotic processes, photosynthesis, chlorophyll content, and other physiological aspects across diverse plant species. Through the data presented in these tables, it becomes evident that numerous research studies consistently point towards a common trend: both short-term and long-term exposure to Cd can harm plant species. Specifically, one significant outcome highlighted across the studies is the inhibition of photosynthesis in various plants, including well-known examples like barley, maize, and peas. This inhibition likely contributes to observable impacts such as reduced growth, altered morphology, changes in root development, and even chromosomal aberrations in some cases. The uniformity of these findings underscores the potential disruptive impact of Cd on essential plant functions, emphasizing the importance of understanding and mitigating its effects to ensure healthy plant growth and agricultural productivity (Popova et al., 2008). *Helianthus annuus* (Sunflower) (Di Cagno et al., 2001), *Thlaspi caerulescens* (Kupper et al., 2007), *Brassica napus* (oilseed rape) (Baryla et al., 2001) and *Vigna radiate* (Mungbean) (Wahid et al., 2008). In the study conducted by Baryla et al. (2001), a noteworthy observation was made regarding the mechanism underlying chlorosis in oilseed rape plants exposed to cadmium (Cd). The research findings indicated that the development of chlorosis in this context was not primarily attributed to a direct interaction between Cd and the chlorophyll biosynthesis mechanism. Instead, the chlorosis was likely linked to reductions in chloroplast density within the plant cells. Furthermore, the study indicated that the impact of Cd on pigment concentration was more pronounced at specific locations within the leaf. Particularly, the decline in pigment concentration was found to be more significant at the leaf surface, especially in the guard cells of stomata, which are responsible for regulating gas exchange, than in the mesophyll cells, which constitute the interior tissue of the leaf. This observation suggests that Cd exposure may have a differential effect on chlorophyll content and distribution within distinct leaf cell types, contributing to the observed chlorosis. Cadmium exposure can disrupt the integrity and functionality of cellular membranes in various organisms, including plants. This disruption occurs due to the toxic effects of cadmium on cellular processes, which in turn affect the composition and properties of membrane lipids and fatty acids. Cadmium interferes with essential cellular processes, such as oxidative stress response, ion homeostasis, and enzyme activity. These disruptions can lead to changes in cell membranes' lipid metabolism and composition. Cadmium exposure has been shown to induce the production of reactive oxygen species (ROS) within cells, which can lead to lipid peroxidation and the degradation of lipids by oxidative damage. This process alters the lipid composition of membranes, affecting their fluidity, permeability, and overall functionality. Moreover, cadmium can influence the activity of enzymes involved in lipid metabolism, such as those responsible for fatty acid synthesis and desaturation. This can change the types and ratios of fatty acids in the membrane lipids. The altered fatty acid composition can further impact the physical properties of membranes, including their stability, rigidity, and ability to function effectively. In plants, the changes in membrane lipids and fatty acids due to cadmium exposure can disrupt various physiological processes, such as nutrient uptake, ion transport, and cell signaling. The specific mechanisms underlying these effects are complex and can involve interactions with other elements and compounds within the cell (Popova et al., 2009).

Table 1: Effect of variable Cd concentrations on the modified antioxidants enzymes of different plant species.

Plant Species	Cd concentration (µM)	Modified Antioxidant Enzymes
Pisumsativum	5	CAT, APOX, GPOX
Triticum durum	1 and 10	CAT, SOD, APOX, GPOX
Pisumsativum	4 and 40	CAT, SOD, APOX, GPOX
Populuscanescens	5 and 50	CAT, SOD, APOX, GR, MDAR

Phragmitesaustralis	50	CAT, SOD, APOX, GR
Glycine max	50, 100 and 200	CAT, SOD, APOX
Helianthus annus	500	CAT, SOD, APOX, GR, DHAR
Oryza sativa	100 and 500	CAT, SOD, GPOX
Arabidopsis thaliana	300 and 500	CAT, SOD, APOX, GPOX, GR
Saccharumofficinarum	2000 and 5000	CAT, SOD, GR
Oryza sativa	5000	CAT, SOD, APOX, GPOX, GR

Table 2: Effect of Cd on the major attributes of plant species

Parameters	**Effects**
Cellular concentrations	Changes in cellular concentrations of essential micronutrients like iron, calcium, manganese, zinc
Root ultrastructure	Inhibition of root elongation, increase in the volume of cortex cells, damage to the epidermis
Carbonic anhydrase	Retards the activity of carbonic anhydrase
Lipid peroxidation	Membrane leakage, change of lipid composition
Fresh weight and dry mass	Decline in root and shoot mass in *Vignaambacensis*
	Diminished the fresh mass in *Vignaradiata*
	Decrease in dry mass in *Cicerarietinum*
Photosynthesis	Inhibition of root Fe(III) reductase
	Diminished chlorophyll and carotenoids content, and increased non-photochemical quenching in *Brassica napus*
	Overall destruction of photosynthetic efficiency
	Destructs photosystems I and II
	Destructs the photosynthetic apparatus particularly the light-harvesting complex II
	Chlorotic leaves, changed ratios of chlorophyll a and b, decreasing net photosynthetic rate
	Hindered stomatal opening in *Syzygiumaromaticum*, *Medicago sativa*, *Glucine max*
	Retards photosynthesis

Cadmium Tolerance in the Plant by Hyperaccumulation Mechanism

The term "hyperaccumulators" denotes plant species with an extraordinary ability to efficiently accumulate high quantities of specific heavy metals (HMs) from the soil. These plants accumulate heavy metals and actively transport them from roots to leaves, contributing to effective environmental detoxification (Rascio & Navari-Izzo, 2011). Hyperaccumulators can store heavy metals at levels significantly higher, often ranging from one hundred to one thousand times more, than non-hyperaccumulating species. Notably, despite accumulating substantial amounts of heavy metals, hyperaccumulators display limited or no signs of phytotoxicity, demonstrating their unique ability to thrive in metal-rich environments without negative consequences (Rascio & Navari-Izzo, 2011). In phytoremediation, where specific plants are used to remediate polluted soils, hyperaccumulators play a crucial role, providing valuable insights into mitigating heavy metal pollution in agricultural settings (Rascio & Navari-Izzo, 2011).

Research has identified around 450 angiosperm species capable of hyperaccumulating heavy metals (Rascio & Navari-Izzo, 2011). These plants employ unique mechanisms for the detoxification of heavy metals, involving chelation and storage in vacuoles. The root cell tonoplast, responsible for controlling substance movement within the cell, likely plays a crucial role in regulating the release of heavy metal ions from vacuoles into the plant's tissues (Lu et al., 2009). Sequestration and detoxification of heavy metals, such as cadmium (Cd), occur in various plant shoot locations, including the epidermis, trichomes, and cuticle, minimizing their negative impact on essential physiological processes. Expelling heavy metals from stomatal cells and forming complexes that render metals less toxic are strategies employed by hyperaccumulating plants, effectively limiting the harmful effects of Cd and other heavy metals while maintaining essential plant functions (Altinozlu et al., 2012).

Remediation Technologies

Bioremediation

Bioremediation involves employing living organisms such as plants, microbes, and their enzymes to eliminate or clean up pollutants from the environment effectively. These biological agents work by entirely breaking down the pollutant through mineralization or converting it into less harmful forms through biotransformation. Numerous bacteria and fungi are recognized for their ability to perform these processes (Beolchini et al., 2009). The success of microbial remediation for heavy metal (HM) contamination at a specific location hinge on various factors. These include the concentration of calcium, the ionic strength of the environment, the interaction of Cd with cell walls, the process of methylation of Cd, the pH of the soil or medium, and the overall concentration of the metal (Iravani & Varma, 2020). The cell walls of a wide range of bacterial species contain functional groups such as sulfhydryl, phosphate, hydroxyl, and carboxyl that can effectively bind to cadmium (Cd). As a result, a significant increase in bacterial biomass could lead to a reduction in the availability of Cd within agricultural regions. It's important to highlight that bacterial Cd adsorption is more noticeable in sandy soils than in clay soils. This approach holds potential as a practical strategy, supported by the demonstrated effectiveness of immobilizing Cd through bacterial mechanisms. Notably, successful immobilization of Cd in agricultural soil has been accomplished using G9 Pseudomonas fluorescens and Tp8 *Bacillus subtilis* bacteria (Sarin & Sarin, 2010). Bacteria capable of sulfate reduction can effectively cause the precipitation of metals as metal sulfides, rendering them promising contenders for decreasing the availability of plant-accessible Cd. Moreover, the utilization of alginate for introducing microbes into soil has showcased its potential in reducing exchangeable Cd. However, careful attention must be given to the regeneration of alginate beads in such practices, as the mineralization of alginate can potentially lead to the unintended release of bound Cd (Nsimba, 2012).

Phytoremediation

Phytoremediation is a distinct approach within bioremediation, where plants are used exclusively to address and reduce the presence of pollutants. This method is effective because plants possess a natural capability to increase the availability of specific pollutants and gather them in their aboveground parts, such as leaves or shoots. These accumulated pollutants can either remain inactive within plant cells or be released into the air as volatile compounds. When pollutants are stored within plant structures, they can later be harvested, offering a means to extract the sequestered contaminants from the environment, thereby contributing to the process of pollutant remediation (Wang et al., 2017). Phytoremediation involving hyperaccumulator plants is an attractive method for eliminating metal pollutants from soil. This is due to the remarkable capacity of hyperaccumulators to endure and accumulate larger quantities of heavy metals (HMs). The choice of plant species is crucial in phytoremediation, as a significant root surface area in contact with the soil is vital for effectively depositing metals. Natural metal hyperaccumulator phenotypes are particularly well-suited for phytoremediation. Plant families such as Poaceae, Brassicaceae, Fabaceae, Plumbaginaceae, Betulaceae, Caryophyllaceae, and Fagaceae have been found to amass substantial amounts of HMs, with Brassicaceae being a prominent example. The desirable traits for plant selection in phytoextraction include high biomass yield and rapid growth rates, contributing to the plant's effectiveness in extracting and accumulating pollutants (Wenzel, 2009). This approach involves using naturally occurring plants that have demonstrated the ability to thrive in environments contaminated with heavy metals. Plants like Ludwigia parviflora, Cyperus rotundus, Marselia quadrifolia, and Cyperus kylinga are well-suited for remediating metal-polluted wetland rice fields. This strategy relies on the synergistic combination of phytoremediation with metal-chelating compounds or the establishment of symbiotic relationships with mycorrhizal fungi. The interaction with mycorrhizal fungi in the context of phytoremediation offers significant advantages. These fungi can chelate Cd within their fungal structures, adsorb Cd to chitin present in their cell walls, and even precipitate Cd as polyphosphate granules in the soil. These mechanisms collectively contribute to effectively removing Cd-contaminated soil (Sebastian & Prasad, 2013).

Amendments Used for Remediation of Cd-Polluted Sites

Several soil amendments have been successfully used for the remediation of Cd. This has included paper mill sludge and Fe/Mn oxide (de Livera et al., 2011), bentonite (Karapinar & Donat, 2009), bringing (Adriano et al., 2004), sewage sludge (Riaz et al., 2018), alkaline organic treatment (Bolan & Duraisamy, 2003), humus and lime (Ok et al., 2011), leaf litter (Adriano et al., 2004), charcoal (Wang et al., 2017), poultry manure (Han et al,. 2018), silicon (Kirkham, 2006), mineral rock phosphate and phosphate (Basta & Tabatabai, 1992), clay minerals (Shirvani et al., 2007), limestone, zeolite, palygorskite, silica slag (Hamid et al., 2019), alkaline organic treatment, K2HPO4 (Adriano et al., 2004), vermicomposting, cattle manure and compost, peat (Ma & Tobin, 2004) and elemental sulfur (de Livera et al., 2011).

Lime, also known as calcium carbonate (CaCO3), is a commonly used amendment for the remediation of Cd-polluted sites due to its potential to immobilize cadmium (Cd) in soil and reduce its mobility and bioavailability. Lime is an alkaline substance that, when added to soil, can increase the pH of the earth. This increase in pH can influence the solubility and mobility of Cd. At higher pH levels, Cd tends to form less soluble and less mobile species, reducing its availability for plant uptake and movement through the soil. The increased pH resulting from lime application can trigger the formation of insoluble Cd compounds, such as Cd(OH)2, CdCO3, and Cd3(PO4)2. These compounds are less likely to leach into groundwater or be taken up by plants, contributing to the immobilization of Cd in the soil. Lime can also influence the cation exchange capacity of soil. Cation exchange involves the reversible interaction of ions between soil particles and the surrounding soil solution. When lime is added to the ground, it can increase the CEC, leading to the binding of Cd ions to the soil particles. This reduces the movement of Cd in the soil and makes it less available for plant uptake. The increase in soil pH due to lime application can also influence the availability of other cations in the ground, such as calcium (Ca) and magnesium (Mg). These cations can compete with Cd ions for binding sites on soil particles. This competition further reduces the mobility and bioavailability of Cd (Huang et al., 2017).

Conclusion

This thorough review delves into the multifaceted dimensions of cadmium, covering its occurrence, sources, environmental contamination, and remediation strategies. The introduction outlines the escalating concerns related to cadmium exposure and its adverse effects on the environment and living organisms. The article systematically explores the natural abundance of cadmium minerals, its prevalence in the Earth's crust, and the diverse industrial, agricultural, and anthropogenic pathways it enters the environment. A critical focus is placed on the global extent of cadmium contamination, emphasizing the need for efficient remediation strategies. The review details regulatory standards for cadmium levels in soil and the environment, highlighting the importance of monitoring and compliance. Understanding cadmium bioavailability and speciation in soil is thoroughly examined, considering factors such as redox potential, soil pH, organic matter, and microorganisms. The article delves into the impact of cadmium on plant growth, development, and nutrition, emphasizing mechanisms of cadmium tolerance in plants. The final segment explores various remediation technologies, focusing on phytoremediation, bioremediation, and soil amendments, offering sustainable alternatives for environmental restoration. In conclusion, this comprehensive synthesis aims to contribute to advancing sustainable practices and policies for a cadmium-safe environment.

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