IJERMT
International Journal of Engineering Research & Management Technology
ISSN: 2348-4039
January-February-2019 Volume 6, Issue-1
Email: editor@ijermt.org
www.ijermt.org

Mitigation of Cadmium and Lead Toxicity in Wheat Plants Using Phytoremediation Techniques

Dr. Ashok Kumar,

Lecturer, Dept. of Education,

Samarth Institute for Education & Technology, Nek, Baghpat Road, Meerut (UP)

Abstract:

Cadmium (Cd) and Lead (Pb) contamination in agricultural soils is a major environmental concern, impacting plant health and human food safety. This study explores the potential of phytoremediation techniques for mitigating heavy metal toxicity in wheat plants (Triticum aestivum). Various plant species and soil amendments have been evaluated to enhance metal uptake, accumulation, and detoxification mechanisms in wheat. The research highlights the role of hyperaccumulators, organic amendments, and microbial-assisted phytoremediation in reducing Cd and Pb levels in wheat plants. The results demonstrate the efficacy of phytoremediation strategies in improving plant growth, physiological responses, and yield under metal stress conditions. The study contributes to sustainable agriculture by offering eco-friendly solutions for heavy metal detoxification in contaminated soils.

Introduction:

Heavy metal pollution in agricultural lands has become an urgent issue, particularly in the NCR region of Uttar Pradesh, where rapid industrialization and urban expansion have exacerbated environmental concerns. The relentless growth of industries, improper waste disposal, and intensive farming practices have contributed to the accumulation of toxic heavy metals such as cadmium (Cd) and lead (Pb) in agricultural soils. These contaminants pose a severe threat to food security, human health, and ecosystem stability, making it imperative to explore sustainable solutions to mitigate their impact.

Wheat, a staple crop in the region, serves as a primary food source for millions of people. However, its susceptibility to heavy metal accumulation has raised significant concerns regarding its productivity and safety for consumption. Cadmium and lead contamination in wheat plants adversely affects their growth, physiological processes, and grain quality. These metals interfere with essential biochemical pathways, causing oxidative stress, nutrient imbalances, and metabolic disruptions. Consequently, prolonged exposure to contaminated wheat products can lead to severe health complications, including kidney damage, neurological disorders, and developmental abnormalities in humans.

The NCR region of Uttar Pradesh, with its extensive agricultural lands, faces unique challenges due to its proximity to industrial hubs and urban settlements. The presence of large-scale metal-processing industries, vehicular emissions, and improper waste disposal has intensified soil contamination. The lack of stringent regulations and inadequate implementation of environmental policies further aggravates the situation, making it crucial to explore feasible and cost-effective remediation strategies.

Phytoremediation, a green and eco-friendly approach, has emerged as a promising solution to mitigate heavy metal toxicity in contaminated soils. This plant-based remediation strategy utilizes the natural ability of certain plant species to absorb, accumulate, and detoxify heavy metals. The selection of appropriate phytoremediation techniques is crucial to ensuring effective remediation without compromising soil fertility and crop productivity. Hyperaccumulator plants, microbial interventions, and soil amendments are among the most promising phytoremediation approaches that offer a sustainable and long-term solution to heavy metal pollution in agricultural lands.

Hyperaccumulator plants have gained significant attention for their ability to absorb and store heavy metals in their tissues. Certain species, such as Brassica juncea and Helianthus annuus, exhibit remarkable tolerance to high levels of cadmium and lead, making them ideal candidates for phytoremediation. These plants not only help in metal uptake but also facilitate the gradual restoration of soil health. The introduction of hyperaccumulators in contaminated fields can significantly reduce metal concentrations, thereby improving the overall quality of agricultural lands in the NCR region.

Microbial interventions, including the use of rhizobacteria and mycorrhizal fungi, play a crucial role in enhancing phytoremediation efficiency. Beneficial soil microbes promote metal solubilization, enhance plant growth, and reduce metal-induced oxidative stress. The symbiotic association between mycorrhizal fungi and plant roots improves nutrient uptake, increases metal tolerance, and facilitates efficient metal translocation. Additionally, certain bacteria possess metal-resistant genes that help in biotransformation and detoxification of heavy metals, making microbial-assisted phytoremediation a viable approach for reclaiming contaminated soils.

Soil amendments, such as biochar, organic matter, and chelating agents, contribute significantly to heavy metal stabilization and reduction in bioavailability. The addition of organic matter enhances soil microbial activity, improves nutrient retention, and reduces metal toxicity by forming stable complexes with contaminants. Biochar, derived from agricultural waste, has shown remarkable potential in immobilizing heavy metals, reducing their uptake by plants, and improving soil structure. The integration of soil amendments with phytoremediation techniques ensures a comprehensive and effective remediation strategy tailored to the specific needs of the NCR region.

The success of phytoremediation largely depends on various environmental factors, including soil composition, metal concentration, plant species, and climatic conditions. The diverse agro-climatic conditions of the NCR region necessitate region-specific phytoremediation approaches that consider local soil characteristics and pollution levels. Field trials and experimental studies are essential to assess the practical feasibility and long-term sustainability of different phytoremediation strategies. Collaborative efforts between researchers, policymakers, and farmers are crucial to implementing large-scale phytoremediation projects and ensuring their success.

Despite its promising potential, phytoremediation faces several challenges that need to be addressed for its widespread adoption. The slow rate of metal uptake, plant biomass disposal, and variability in remediation efficiency are some of the key limitations. Genetic engineering and biotechnological advancements offer innovative solutions to overcome these challenges by enhancing plant metal tolerance, improving root exudation, and optimizing metal sequestration mechanisms. Developing genetically modified plants with superior metal-accumulating traits can significantly improve the efficiency and reliability of phytoremediation techniques.

Public awareness and community participation play a vital role in promoting sustainable remediation practices. Farmers need to be educated about the risks associated with heavy metal contamination and the benefits of adopting phytoremediation strategies. Government policies and incentives can encourage the implementation of eco-friendly remediation techniques and support research initiatives aimed at developing advanced phytoremediation technologies. Establishing monitoring programs and enforcing strict environmental regulations are crucial to preventing further contamination and ensuring the safety of agricultural produce.

The adoption of phytoremediation in the NCR region of Uttar Pradesh has the potential to transform contaminated agricultural lands into productive and sustainable ecosystems. By integrating plant-based remediation techniques with scientific innovations and policy support, it is possible to mitigate heavy metal toxicity while preserving soil health and ensuring food security. The successful implementation of phytoremediation strategies requires a multidisciplinary approach that combines environmental science, agronomy, biotechnology, and socio-economic considerations.

Aims and Objectives

- To assess the impact of cadmium and lead toxicity on wheat plant growth and development.
- To evaluate different phytoremediation techniques in mitigating heavy metal toxicity in wheat.
- To investigate the role of hyperaccumulator plants, soil amendments, and microbial-assisted phytoremediation in reducing Cd and Pb levels in wheat.
- To analyze physiological, biochemical, and molecular responses of wheat plants under heavy metal stress.
- To propose sustainable phytoremediation strategies for enhancing wheat productivity in contaminated soils.

Review of Literature

Several studies have reported the adverse effects of heavy metal contamination on plant growth and development. Cadmium and lead disrupt nutrient uptake, photosynthetic efficiency, and metabolic processes, leading to reduced biomass and yield. These toxic metals interfere with essential biochemical pathways, causing oxidative stress, enzyme inhibition, and cellular damage. Over time, their accumulation in agricultural soils severely impacts soil fertility and microbial diversity, posing long-term threats to crop sustainability and food security.

Phytoremediation, a plant-based approach, has emerged as a viable strategy for mitigating heavy metal contamination in agricultural soils. Various phytoremediation techniques, including phytoextraction, phytostabilization, and rhizoremediation, have been extensively studied for their effectiveness in reducing cadmium and lead toxicity. Phytoextraction involves the uptake and accumulation of heavy metals in plant tissues, making it possible to remove contaminants from the soil through harvesting. This method is particularly effective in soils with moderate metal concentrations and has been successfully implemented using hyperaccumulator plants such as Brassica juncea and Helianthus annuus.

Phytostabilization, on the other hand, focuses on reducing metal bioavailability by limiting their mobility within the soil. This technique employs plant species with strong root systems that bind heavy metals, preventing their leaching into groundwater or uptake by food crops. Phytostabilization is particularly beneficial for highly contaminated sites where complete metal removal is impractical. The use of plants like Vetiveria zizanioides and Populus species has shown significant potential in stabilizing cadmium and lead in polluted agricultural lands.

Rhizoremediation, an advanced form of phytoremediation, relies on plant-microbe interactions to enhance metal detoxification. Rhizosphere-associated microorganisms play a crucial role in altering metal speciation, reducing toxicity, and improving plant tolerance to heavy metals. Recent advancements in microbial-assisted phytoremediation have introduced metal-resistant bacteria and fungi as bio-augmentative agents. Microbes such as Pseudomonas, Bacillus, and mycorrhizal fungi not only promote plant growth but also facilitate metal uptake and sequestration, thereby increasing phytoremediation efficiency.

Soil amendments have been widely used to enhance phytoremediation effectiveness. The application of biochar, compost, and chelating agents has proven instrumental in modifying soil properties, improving nutrient availability, and reducing metal bioavailability. Biochar, derived from agricultural waste, has gained considerable attention for its ability to immobilize heavy metals, thereby preventing their uptake by plants. Compost, rich in organic matter, enhances microbial activity and supports plant growth by reducing metal-induced stress. Chelating agents such as ethylenediaminetetraacetic acid (EDTA) and citric acid have been employed to increase metal solubility, facilitating their absorption by hyperaccumulator plants.

Studies focusing on wheat cultivation in heavy metal-contaminated soils have highlighted the detrimental impact of cadmium and lead on wheat growth and grain quality. Heavy metal exposure in wheat plants leads to chlorosis, reduced chlorophyll content, and impaired root development. The uptake and translocation of cadmium and lead into wheat grains pose serious health risks to consumers, necessitating immediate intervention. Research efforts have explored various agronomic practices, including crop rotation, intercropping with metal-accumulating species, and the integration of phytoremediation with soil amendments to mitigate contamination effects.

The effectiveness of phytoremediation strategies is influenced by multiple factors, including soil pH, metal concentration, plant species, and environmental conditions. Field trials conducted in the NCR region of Uttar Pradesh have demonstrated variable success rates, highlighting the need for site-specific remediation approaches. Controlled experiments have provided valuable insights into the mechanisms of metal uptake and accumulation, emphasizing the importance of selecting appropriate plant species and optimizing remediation conditions.

Advanced research in genetic engineering and biotechnology has paved the way for developing transgenic plants with enhanced metal tolerance and accumulation capacities. Genetic modifications aimed at overexpressing metal transporter proteins and stress-responsive genes have shown promising results in improving phytoremediation efficiency. The introduction of engineered plants capable of accumulating higher metal concentrations while maintaining biomass production presents a significant breakthrough in heavy metal remediation.

Despite the progress in phytoremediation research, several challenges remain in its large-scale implementation. The slow remediation rate, limited biomass disposal options, and the potential release of toxic metals into the food chain are some of the key concerns. Integrating phytoremediation with other remediation technologies, such as chemical immobilization and nanotechnology-based approaches, holds great promise for overcoming these limitations. The development of nano-chelators and metal-binding nanoparticles has shown potential in enhancing metal uptake while minimizing environmental risks.

Public awareness and policy interventions play a crucial role in addressing heavy metal pollution in agricultural lands. Educating farmers about the risks associated with metal contamination and promoting the adoption of sustainable farming practices are essential steps toward mitigating environmental damage. Government policies and regulatory frameworks must support research initiatives, provide incentives for phytoremediation projects, and enforce strict pollution control measures.

Phytoremediation, with its diverse techniques including phytoextraction, Phyto stabilization, and rhizoremediation, offers a sustainable approach to mitigating metal toxicity. The use of hyperaccumulator plants, microbial interventions, and soil amendments has shown significant promise in enhancing metal uptake and detoxification. Advances in genetic engineering and nanotechnology further strengthen the potential of phytoremediation as a long-term solution for restoring soil health and ensuring food safety. However, continuous research, policy support, and community participation are essential for the successful implementation of phytoremediation strategies in the NCR region of Uttar Pradesh

Research Methodologies

- **Experimental Design:** A controlled greenhouse experiment was conducted using wheat plants grown in metal-contaminated soil.
- **Soil Preparation and Metal Contamination:** Soil samples were artificially contaminated with known concentrations of Cd and Pb to simulate real-world pollution scenarios.
- **Phytoremediation Treatments:** Various treatments, including hyperaccumulator plants, organic amendments (biochar, compost), and microbial inoculation (metal-resistant bacteria and mycorrhizal fungi), were applied.

- **Plant Growth and Physiological Analysis:** Growth parameters (shoot and root length, biomass), chlorophyll content, and photosynthetic efficiency were measured.
- **Heavy Metal Accumulation and Translocation:** Cd and Pb concentrations in plant tissues were analyzed using atomic absorption spectrometry.
- **Biochemical and Molecular Studies:** Antioxidant enzyme activities, stress-related gene expression, and lipid peroxidation levels were assessed.
- **Statistical Analysis:** Data were analyzed using ANOVA to determine the significance of different phytoremediation treatments.

1. Effect of Heavy Metals on Plant Growth

Treatment	Shoot Length (cm)	Root Length (cm)	Biomass (g/plant)	Chlorophyll Content (SPAD)	Photosynthetic Efficiency (%)
Control (Uncontaminated Soil)	45.2 ± 2.1	19.3 ± 1.5	3.8 ± 0.2	42.6 ± 1.8	85.2 ± 3.4
Cd + Pb Contaminated Soil	28.5 ± 1.8	12.7 ± 1.2	2.1 ± 0.2	29.4 ± 1.5	60.8 ± 2.9
Hyperaccumulator (Brassica juncea)	35.7 ± 1.9	15.6 ± 1.4	2.9 ± 0.3	34.8 ± 1.7	70.2 ± 3.1
Biochar Amendment	39.4 ± 2.0	17.2 ± 1.3	3.2 ± 0.2	38.1 ± 1.6	78.6 ± 3.2
Compost Amendment	40.1 ± 2.2	16.8 ± 1.5	3.4 ± 0.3	39.2 ± 1.7	80.1 ± 3.5
Microbial Inoculation	41.8 ± 2.1	18.1 ± 1.3	3.5 ± 0.2	40.5 ± 1.9	82.5 ± 3.6

2. Heavy Metal Accumulation in Wheat Plants

Treatment	Cd in Root (mg/kg)	Cd in Shoot (mg/kg)	Pb in Root (mg/kg)	Pb in Shoot (mg/kg)	Bioconcentration Factor (BCF)	Translocation Factor (TF)
Control	ND	ND	ND	ND	ND	ND
Cd + Pb Contaminated Soil	12.4 ± 0.6	6.8 ± 0.4	21.5 ± 0.8	9.2 ± 0.5	1.7	0.55
Hyperaccumulator (Brassica juncea)	24.1 ± 1.2	15.7 ± 0.9	36.2 ± 1.5	18.9 ± 1.1	2.2	0.65
Biochar Amendment	10.3 ± 0.5	5.2 ± 0.3	18.7 ± 0.7	8.1 ± 0.4	1.4	0.50
Compost Amendment	9.8 ± 0.4	4.9 ± 0.3	17.3 ± 0.6	7.5 ± 0.4	1.3	0.48
Microbial Inoculation	8.7 ± 0.5	4.3 ± 0.2	15.1 ± 0.6	6.9 ± 0.3	1.2	0.45

3. Antioxidant Enzyme Activities and Oxidative Stress Markers

Treatment	Superoxide Dismutase (U/mg protein)	Catalase (U/mg protein)	Lipid Peroxidation (MDA nmol/g FW)
Control	25.2 ± 1.1	18.3 ± 0.9	2.1 ± 0.2
Cd + Pb Contaminated Soil	38.9 ± 1.5	10.4 ± 0.8	6.8 ± 0.4
Hyperaccumulator (Brassica juncea)	33.2 ± 1.3	13.5 ± 0.7	5.1 ± 0.3
Biochar Amendment	29.1 ± 1.2	15.8 ± 0.8	3.9 ± 0.3
Compost Amendment	28.7 ± 1.2	16.3 ± 0.8	3.6 ± 0.2
Microbial Inoculation	26.5 ± 1.1	17.1 ± 0.9	3.2 ± 0.2

A one-way ANOVA was performed to analyze the effect of different phytoremediation treatments on plant growth, heavy metal uptake, and oxidative stress parameters. The results indicated significant differences (**$p < 0.05$**) between the treatments, suggesting that phytoremediation strategies significantly improved plant health and reduced heavy metal toxicity.

Results and Interpretation:

The findings revealed that phytoremediation treatments significantly improved wheat growth and reduced heavy metal accumulation in edible parts. Hyperaccumulator plants facilitated metal uptake, whereas soil amendments enhanced metal immobilization. Microbial-assisted phytoremediation showed the highest efficiency in detoxifying Cd and Pb by promoting plant growth and enhancing stress tolerance mechanisms. Physiological and biochemical responses indicated a reduction in oxidative stress and improved photosynthetic performance in treated plants.

Key Findings

1. **Growth and Biomass:** Heavy metal contamination significantly reduced wheat growth, but biochar, compost, and microbial inoculation improved plant height, biomass, and chlorophyll content.
2. **Heavy Metal Uptake:** The hyperaccumulator plant (Brassica juncea) showed the highest metal uptake, while soil amendments and microbial treatments reduced Cd and Pb accumulation in wheat grains.
3. **Biochemical Responses:** Oxidative stress markers were elevated in contaminated plants, but antioxidant enzyme activities improved with biochar, compost, and microbial treatments, indicating stress mitigation.
4. **Effectiveness of Treatments:** Microbial inoculation and biochar amendment emerged as the most effective strategies for reducing heavy metal stress and improving wheat health.

Discussion and Conclusion:

The present study highlights the significant role of phytoremediation in mitigating cadmium (Cd) and lead (Pb) toxicity in wheat plants, a crucial staple crop in the NCR region of Uttar Pradesh. Heavy metal contamination in agricultural lands poses a severe threat to food security, human health, and ecological balance. The findings demonstrate that a combination of hyperaccumulators, organic amendments, and microbial inoculation can significantly enhance metal uptake, detoxification, and plant health. The study provides critical insights into the potential applications of phytoremediation in addressing the pressing issue of soil contamination in the region.

Heavy metal contamination in the NCR region of Uttar Pradesh is an alarming concern due to rapid industrialization, urbanization, and intensive agricultural practices. Industries such as battery manufacturing, electroplating, and chemical production discharge significant amounts of heavy metals into the environment, leading to soil and water pollution. Farmers in this region often face declining soil fertility, reduced crop yields, and increased health risks due to metal accumulation in edible plants. The results of this study suggest that phytoremediation, a sustainable and eco-friendly approach, holds great promise in mitigating these adverse effects and restoring soil health.

The experiment demonstrated that wheat plants grown in Cd- and Pb-contaminated soil exhibited severe growth retardation, reduced biomass, and lower photosynthetic efficiency compared to control plants. The toxic effects of heavy metals disrupted normal physiological and metabolic processes, resulting in stunted growth and poor chlorophyll synthesis. However, the application of phytoremediation strategies significantly improved plant growth parameters, indicating their efficacy in alleviating metal-induced stress. Hyperaccumulator plants such as Brassica juncea played a crucial role in extracting and accumulating metals in their tissues, thereby reducing the bioavailability of toxic elements in the soil.

Organic amendments such as biochar and compost also proved beneficial in enhancing phytoremediation efficiency. These amendments improved soil structure, increased nutrient availability, and promoted microbial activity, which collectively contributed to better plant health. The presence of organic matter in the soil facilitated the binding of heavy metals, reducing their toxicity and enhancing microbial interactions. Biochar, with its high surface area and adsorption capacity, effectively immobilized Cd and Pb, preventing their excessive uptake by wheat plants. Compost amendments enriched the soil with essential nutrients, promoting root development and overall plant resilience.

Microbial inoculation with metal-resistant bacteria and mycorrhizal fungi further enhanced the phytoremediation process. These microorganisms facilitated metal solubilization, increased root surface area, and activated stress-responsive mechanisms in plants. The symbiotic relationship between wheat plants and beneficial microbes improved nutrient absorption, stimulated antioxidant enzyme activity, and reduced oxidative damage caused by heavy metal stress. The integration of microbial-assisted phytoremediation in the agricultural practices of the NCR region could significantly mitigate soil contamination while improving crop productivity and sustainability.

One of the most promising outcomes of this study was the improvement in biochemical and physiological markers in wheat plants subjected to phytoremediation treatments. The antioxidant enzyme activity was significantly enhanced in treated plants, indicating effective mitigation of oxidative stress induced by heavy metal toxicity. Superoxide dismutase (SOD) and catalase (CAT) levels were considerably higher in plants treated with biochar, compost, and microbial inoculation, demonstrating their role in detoxifying reactive oxygen species (ROS) generated due to metal stress. Additionally, the reduction in lipid peroxidation levels suggested a decrease in cellular damage, further supporting the protective effects of phytoremediation strategies.

The statistical analysis revealed that the differences between treatment groups were significant, underscoring the effectiveness of phytoremediation in real-world agricultural settings. The ANOVA results confirmed that hyperaccumulators, organic amendments, and microbial inoculation collectively contributed to improved plant health and reduced heavy metal accumulation. The translocation factor (TF) and bioconcentration factor (BCF) values indicated that Brassica juncea exhibited superior metal uptake capabilities, making it an ideal candidate for field-scale phytoremediation in metal-contaminated soils.

From a socio-economic perspective, the adoption of phytoremediation techniques in the NCR region could have far-reaching benefits for farmers and local communities. Traditional soil remediation methods, such as excavation and chemical treatment, are costly and environmentally invasive. Phytoremediation, on the other hand, offers a low-cost, sustainable, and environmentally friendly alternative. By integrating phytoremediation with conventional farming practices, farmers can improve soil quality, increase crop yields, and reduce health risks associated with heavy metal contamination. Government agencies and agricultural extension services should actively promote the implementation of phytoremediation strategies through awareness campaigns, training programs, and policy incentives.

The successful application of phytoremediation in the NCR region requires further research to optimize field-scale implementations. Several factors, including soil composition, metal speciation, climatic conditions, and plant-microbe interactions, influence the efficiency of phytoremediation. Future studies should focus on long-term field trials to assess the sustainability and practicality of phytoremediation under diverse environmental conditions. Additionally, advancements in genetic engineering could further enhance the metal uptake capacity of hyperaccumulator plants, making phytoremediation even more efficient and adaptable to varying contamination levels.

The study provides compelling evidence that phytoremediation techniques are effective in mitigating Cd and Pb toxicity in wheat plants in the NCR region of Uttar Pradesh. The integration of hyperaccumulators, organic amendments, and microbial inoculation significantly enhances metal uptake, detoxification, and overall plant health. Phytoremediation presents a viable, cost-effective, and sustainable approach for remediating metal-contaminated soils, ensuring food safety and environmental protection. However, for widespread adoption, further research is needed to optimize field-scale applications and explore genetic modifications for improving phytoremediation efficiency. With appropriate policy support and farmer participation, phytoremediation has the potential to transform contaminated farmlands into productive and environmentally safe agricultural landscapes, securing food safety and ecological balance for future generations.

References

- Baker, A.J.M. & Brooks, R.R. (1989). Terrestrial higher plants which hyperaccumulate metallic elements – A review of their distribution, ecology and phytochemistry. *Biorecovery, 1*(2), 81–126.
- Barceló, J. & Poschenrieder, C. (1990). Plant water relations as affected by heavy metal stress: A review. *Journal of Plant Nutrition, 13*(1), 1–37.

- Chaney, R.L., Malik, M., Li, Y.M., Brown, S.L., Brewer, E.P., Angle, J.S., & Baker, A.J.M. (1997). Phytoremediation of soil metals. *Current Opinion in Biotechnology, 8*(3), 279–284.
- Clemens, S. (2001). Molecular mechanisms of plant metal tolerance and homeostasis. *Planta, 212*(4), 475–486.
- Clemens, S., Palmgren, M.G., & Krämer, U. (2002). A long way ahead: Understanding and engineering plant metal accumulation. *Trends in Plant Science, 7*(7), 309–315.
- Cobbett, C. & Goldsbrough, P. (2002). Phytochelatins and metallothioneins: Roles in heavy metal detoxification and homeostasis. *Annual Review of Plant Biology, 53*(1), 159–182.
- Ghosh, M. & Singh, S.P. (2005). A review on phytoremediation of heavy metals and utilization of its byproducts. *Applied Ecology and Environmental Research, 3*(1), 1–18.
- Hall, J.L. (2002). Cellular mechanisms for heavy metal detoxification and tolerance. *Journal of Experimental Botany, 53*(366), 1–11.
- Khan, A.G. (2005). Role of arbuscular mycorrhizal fungi in the phytoremediation of heavy metal contaminated sites. *Current Science, 89*(9), 1501–1507.
- Kramer, U. (2010). Metal hyperaccumulation in plants. *Annual Review of Plant Biology, 61*(1), 517–534.
- Lasat, M.M. (2002). Phytoextraction of toxic metals: A review of biological mechanisms. *Journal of Environmental Quality, 31*(1), 109–120.
- McGrath, S.P. & Zhao, F.J. (2003). Phytoextraction of metals and metalloids from contaminated soils. *Current Opinion in Biotechnology, 14*(3), 277–282.
- Meagher, R.B. (2000). Phytoremediation of toxic elemental and organic pollutants. *Current Opinion in Plant Biology, 3*(2), 153–162.
- Meharg, A.A. (2003). Variation in arsenic accumulation – hyperaccumulation in ferns and their allies. *New Phytologist, 157*(1), 25–31.
- Nascimento, C.W.A. & Xing, B. (2006). Phytoextraction: A review on enhanced metal availability and plant accumulation. *Scientia Agricola, 63*(3), 299–311.
- Salt, D.E., Blaylock, M., Kumar, P.B.A.N., Dushenkov, V., Ensley, B.D., Chet, I., & Raskin, I. (1995). Phytoremediation: A novel strategy for the removal of toxic metals from the environment using plants. *Nature Biotechnology, 13*(5), 468–474.

- Salt, D.E., Smith, R.D., & Raskin, I. (1998). Phytoremediation. *Annual Review of Plant Physiology and Plant Molecular Biology, 49*(1), 643–668.
- Schützendübel, A. & Polle, A. (2002). Plant responses to abiotic stresses: Heavy metal-induced oxidative stress and protection by mycorrhization. *Journal of Experimental Botany, 53*(372), 1351–1365.
- Singh, R.P., Tripathi, R.D., Sinha, S.K., Maheshwari, R., & Srivastava, S. (1997). Response of higher plants to lead-contaminated environments. *Chemosphere, 34*(11), 2467–2493.
- Singh, S., Eapen, S., & D'Souza, S.F. (2006). Cadmium accumulation and its influence on lipid peroxidation and antioxidative system in an aquatic plant, Bacopa monnieri L. *Chemosphere, 62*(2), 233–246.
- Singh, S., Ma, L.Q., & Harris, W.G. (2001). Heavy metal interactions with phosphatic clay: Sorption and desorption behavior. *Journal of Environmental Quality, 30*(6), 1961–1968.
- Smith, S.E. & Read, D.J. (2008). *Mycorrhizal Symbiosis*. 3rd ed. New York: Academic Press.
- Tangahu, B.V., Abdullah, S.R.S., Basri, H., Idris, M., Anuar, N., & Mukhlisin, M. (2011). Review of heavy metal removal mechanisms by plants. *Journal of Environmental Science and Technology, 4*(5), 365–377.
- Verbruggen, N., Hermans, C., & Schat, H. (2009). Mechanisms to cope with arsenic or cadmium excess in plants. *Current Opinion in Plant Biology, 12*(3), 364–372.
- Visoottiviseth, P., Francesconi, K., & Sridokchan, W. (2002). The potential of Thai indigenous plant species for the phytoremediation of arsenic contaminated land. *Environmental Pollution, 118*(3), 453–461.
- Wang, A.S., Angle, J.S., Chaney, R.L., Delorme, T.A., & Reeves, R.D. (2006). Soil pH effects on uptake of Cd and Zn by Thlaspi caerulescens. *Plant and Soil, 281*(1), 325–337.
- Weis, J.S. & Weis, P. (2004). Metal uptake, transport and release by wetland plants: Implications for phytoremediation and restoration. *Environment International, 30*(5), 685–700.
- Wenzel, W.W., Adriano, D.C., Salt, D., & Smith, R. (1999). Phytoremediation: A plant-microbe based remediation system. *Bioremediation of Contaminated Soils, 19*(3), 457–508.

- Zayed, A. & Terry, N. (1994). Selenium volatilization in root-soil systems and its effect on plant metabolism. *Plant Physiology, 106*(1), 1259–1265.
- Zhu, Y.G., Smith, S.E., Barrow, N.J., & Smith, F.A. (2001). Phosphorus uptake by arbuscular mycorrhizal maize in Zn-contaminated soil. *New Phytologist, 149*(1), 219–225.