

Bioremediation of Cadmium through Hyperaccumulating Plants: Mechanisms, Molecular Pathways and Future Prospects

Raj K. Pandey¹, Pragati Pandey¹, Shail Pande² and Tulika Mishra^{3*}

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ABSTRACT

Cadmium (Cd) is a toxic heavy metal that significantly endangers both environmental and human health. Its presence in soil and water can have devastating effects on ecosystems, and it can accumulate in the food chain, leading to serious health problems for humans. Fortunately, nature offers a powerful and elegant solution to this problem: phytoremediation. Phytoremediation is an eco-friendly and cost-efficient strategy that employs plants to extract, neutralize, or immobilize environmental contaminants. Unlike conventional remediation techniques, it offers a sustainable solution for pollutant removal. Certain plant species are capable of absorbing cadmium from the soil through their root systems. Some of these plant species, termed 'hyperaccumulators,' exhibit an exceptional capacity to sequester elevated levels of cadmium within their biomass, predominantly localizing the metal in foliar and stem tissues. These plants act as green sponges, effectively extracting the metal from the soil. Once absorbed, cadmium is transported throughout the plant via the vascular system. In some cases, plants can efficiently translocate cadmium from their roots to their shoots, making it easier to remove the metal from the contaminated site by harvesting the plant biomass. Plants can also stabilise cadmium in the soil by reducing its bioavailability. This can be achieved through various mechanisms, such as the release of organic acids that bind to cadmium, preventing it from leaching into groundwater or being taken up by other organisms.

Keywords: Cadmium, Hyperaccumulator, Phytoremediation, Metal, Toxicity.

Highlights:

Impacts of Cadmium on plants and animals.

Threshold level of cadmium in soil and some plants.

Different plants useful for the phytoremediation of Cadmium.

Different mechanisms of Cd phytoremediation and Cadmium sequestration.

Advancing bioengineering, nanotechnology, for sustainable bio remediation.

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INTRODUCTION

Cadmium (Cd) contamination is a significant threat to plant well-being and productivity, affecting various physiological and biochemical processes. As a non-essential heavy metal, Cd readily enters the soil through industrial activities, agricultural practices, and atmospheric deposition, leading to its uptake by plants. The consequences of Cd accumulation within plant tissues are far-reaching, resulting in a cascade of harmful effects. Regulatory thresholds for cadmium as a heavy metal contaminant are established under the Food Safety and Standards (Contaminants, Toxins, and Residues) framework (Table 1).

Cd disrupts the uptake and transport of essential nutrients, such as zinc and iron, leading to nutrient deficiencies and impaired growth. Cadmium inhibits cell division and elongation, resulting in decreased root and shoot biomass. It also interferes with the synthesis and signaling of plant hormones, which regulate growth and development. Cd also inhibits chlorophyll synthesis, resulting in leaf yellowing and reduced photosynthetic capacity (Zhang *et al.*, 2024). This metal has also been shown to cause damage to the components of the photosynthetic apparatus, such as photosystem II, leading to decreased carbon fixation (Kupper *et al.*, 2007). Cd affects

¹Research Assistant, Department of Botany, D.D.U Gorakhpur University, India

²Professor and Principal DAVPG College, Gorakhpur, India

³Assistant Professor, D.D.U Gorakhpur University, Gorakhpur, India

***Corresponding author:** Tulika Mishra, Assistant Professor, D.D.U Gorakhpur University, Gorakhpur, India, Email: tulika.mishra.2000@gmail.com

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the opening and closing of stomata, which are essential for gas exchange during photosynthesis. As per WHO guidelines 2011, Cd level safe for drinking water is 0.003 mg L⁻¹. According to United States Environmental Protection Agency, as well as the European Union (UNEP 2010), up to 5 µg L⁻¹ of cadmium is tolerable. Cadmium exposure can lead to the generation of reactive oxygen species (ROS) within cells, causing oxidative stress. ROS (such as H₂O₂ and O₂⁻) have the potential to harm cellular structure. These superoxides can attack lipids in cell

Table 1 : FSSAI limits (maximum) for cadmium (Cd) in food items (2020)

Food Category	Proposed Cadmium Limit (mg/kg / ppm)
Cereals, Pulses, Legumes	0.10 ppm
Leafy Vegetables	0.20 ppm
Other Vegetables / Potatoes / Roots	0.05 ppm
Fruits	0.05 ppm
Infant milk substitute & infant foods	0.10 ppm
Turmeric (whole and powder)	0.10ppm
Other foods (general category)	1.50 ppm

membranes, leading to membrane damage and dysfunction. (Keunen *et al.*, 2011). ROS can also damage proteins and DNA, disrupt cellular processes, causing mutations. Cd competes with essential nutrients for uptake and transport, leading to nutrient deficiencies. Cadmium also disrupts water absorption and translocation processes, inducing physiological water stress and subsequent wilting. Additionally, its detrimental impact on root architecture further compromises the uptake of essential water and mineral nutrients. Cd can bind to different enzymes and inhibit the activity of various enzymes involved in plant metabolism. It can interfere with protein synthesis, leading to the production of abnormal proteins and can affect the synthesis and breakdown of carbohydrates, leading to imbalances in energy production.

Cd toxicity disrupts diverse biochemical and physiological mechanisms underpinning plant function and adaptability, with the extent of damage varying according to the tolerance of plants to Cd. Even at low concentrations, Cd can interfere with the absorption of macronutrients and micronutrients (Rochayati *et al.*, 2011). Cadmium toxicity is also damaging to fundamental plant processes, leading to reduced growth, decreased yield, and impaired plant health. The bioaccumulation of cadmium in consumable plant tissues presents a serious threat to human health via trophic transfer within the food chain. Due to increased industrialization, mining, smelting, electroplating, agriculture,

and anthropogenic activities, different parts of the world are polluted, especially through the different concentrations of heavy metals and their compounds. Of all those heavy metals, cadmium is a highly toxic heavy metal, approximately having toxicity levels 2-20 times higher than other heavy metals to most organisms, including plants and animals (Sall *et al.*, 2020). Natural concentration of Cd in soil is around 0.36 mg kg⁻¹ (Kubier *et al.*, 2019). The Food and Agriculture Organisation (FAO) of the United Nations recommends the following permissible limits for cadmium in soil. Maximum allowable concentration is 3 mgkg⁻¹ (dry weight) for soils used for agricultural purposes. (WHO/FAO, 2007). There are different carcinogenic, mutagenic and teratogenic effects of Cd if the concentration of Cd goes above the threshold limit (Nordberg and Costa, 2021).

Phytoremediation is an environmentally friendly “Green approach” that utilizes plants to clean up heavy metal-contaminated soils, including those polluted with cadmium (Cd). Certain plant species can uptake Cd from the soil through their roots and translocate it to their shoots in a process known as ‘Phytoextraction.’ Others may immobilize the metal in the rhizosphere through ‘Phytostabilization,’ thereby reducing its mobility and bioavailability. In aquatic environments, ‘Rhizofiltration’ allows roots to absorb or adsorb Cd from polluted water. Plants also employ various physiological and biochemical mechanisms to tolerate and detoxify Cd, such as chelation by ‘Phytochelatin’s and metallothionein’s, sequestration into vacuoles, and activation of antioxidant enzymes like superoxide dismutase and catalase to counteract oxidative stress (Fig-1). Additionally, the release of root exudates such as organic acids can increase Cd solubility, enhancing its uptake from Soil (Khan *et al.*, 2016). The success of phytoremediation depends on selecting plant species that are well-suited to the specific environmental conditions and have a high capacity for cadmium uptake and accumulation. Phytoremediation is far more affordable than customary remediation strategies. This process can be utilized to re-establish degraded lands and further improve the soil system.

Conventional remediation techniques, like unearthing and removal, are frequently expensive and problematic. Phytoremediation; the utilization of plants to eliminate metals, offers a manageable and financially viable alternative. Numerous plant taxa have been rigorously documented for their capacity to phytoremediate cadmium-laden soils via mechanisms like hyperaccumulation, rhizofiltration, and metal immobilization. Noteworthy among these are *Medicago sativa* (Ghnaya *et al.*, 2015), *Tagetes erecta* (Li *et al.*, 2015), *Brassica juncea* (Gallego *et al.*, 2012), and *Helianthus annuus* (Li, *et al.*, 2018), renowned for their exceptional Cd uptake and translocation efficiencies. Hydrophytes including *Eichhornia crassipes*, *Lemna minor*, and *Pistia stratiotes* proficiently extract aqueous Cd through rhizofiltration. Herbaceous species like *Zea mays*, *Hibiscus cannabinus*, and *Crotalaria juncea* have also demonstrated substantial Cd bioaccumulation. Emerging prominently are bamboo species—*Bambusa bambos*, *B. vulgaris*, *B. balcooa*, and *Phyllostachys pubescens*; esteemed for their rapid biomass accrual, deep rooting, and pronounced Cd sequestration (Arumugam *et al.*, 2023; Srivastava and Agrawal, 2023; Bian *et al.*, 2023). (Table-2)

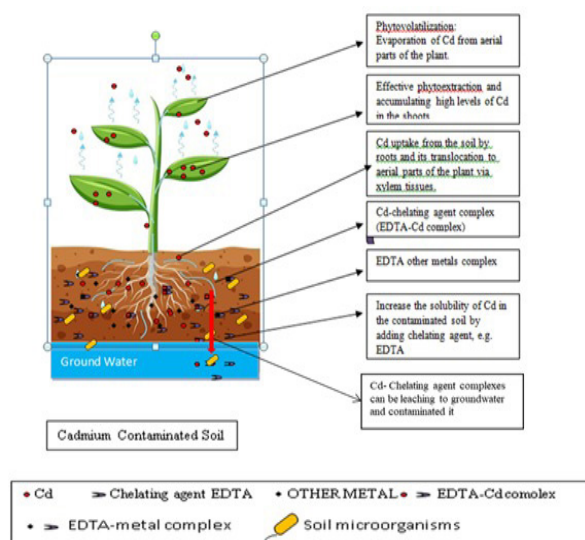
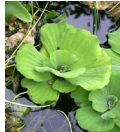
**Fig 1:** Different Methods of Phytoremediation of Cadmium Metal

Table 2 : Plant species with phytoremediation Potential

S. No.	Plants	Plants Part used in Phytoremediation	Mode of Remediation	Reference	Plant Species
1.	Medicago sativa	Major concentration in roots, leaves also show presence	Phytoextraction and Phytostabilization	Ghnaya <i>et al.</i> , 2015	
2.	Tagetes erecta	More in roots than in shoots	Phytoextraction and Phytostabilization	Li <i>et al.</i> , 2015	
3.	Azolla pinnata	Roots and Shoots	Phytoextraction and Phytostabilization	Khilji <i>et al.</i> , 2024	
4.	Hibiscus cannabinus	Roots and Shoots	Hyperaccumulator Cd Tolerant, Phytoextraction	Guo <i>et al.</i> , 2024	
5.	Beta vulgaris	Whole plant	Phytoextraction	Rai, 2010	
6.	Bambusa bambos Bambusa vulgaris Bambusa balcooa	Rhizome root system, More or less whole plant part	Phytoextraction	Arumugam <i>et al.</i> , 2023	
7.	Helianthus annuus	Roots, more or less whole plant	Rhizofiltration	Li <i>et al.</i> , 2018	
8.	Brassica juncea	Roots more or less whole plant	Phytoextraction. Rhizofiltration etc.	Gallego <i>et al.</i> , 2012	
9.	Eichhornia crassipes	Root tissues	Rhizofiltration	Singh and Balomajumder, 2021	
10.	Pistia stratiotes	Leaf	Hyperaccumulator	Li. <i>et. al.</i> , 2022.	
11.	Crotalaria juncea	Mainly in Roots and Shoots	Hyperaccumulator and Stabilizer	Dos <i>et. al.</i> , 2024	

Role of Plants in The Phytoremediation of Heavy Metal Cadmium

Medicago sativa

(Horse feed/alfalfa), has arisen as a promising contender for Cd phytoremediation because of its extraordinary qualities (Wang *et al.*, 2015). Alfalfa is a fast-growing and high-yielding crop, permitting it to gather huge amounts of Cd in its tissues. Alfalfa can accumulate Cd in different plant parts, and it is useful in eliminating it from the contaminant source. Alfalfa can compartmentalize Cd in vacuoles inside its cells, reducing its effect and keeping it from obstructing cell processes (Liu *et al.*, 2017). It can be utilized in a mix with other remediation procedures, like soil corrections or microbial immunisation, to upgrade Cd removal. Its high biomass creation, profound underground root growth, Cd resistance, and amassing limit make it an optimal contender for eliminating Cd from the environment.

Helianthus annuus (sunflower)

has gathered critical consideration for its noteworthy capacity to gather and endure heavy metals, especially cadmium (Chauhan *et al.*, 2020). Sunflowers have a few qualities that make them ideal possibilities for cadmium phytoremediation. Their fast development rate and high biomass creation empower them to ingest significant amounts of cadmium from tainted soil (Huang *et al.*, 2020). Their broad underground root growth helps in boosting the absorption of the metal from the soil, and from there it is translocated to shoots and leaves, actually sequestering it from the contaminant source (Meyer *et al.*, 2022). Sunflowers can chelate cadmium, restricting it to natural atoms inside their cells. It can likewise compartmentalise cadmium in unambiguous tissues or organelles, further limiting its harmful impacts (Borges *et al.*, 2022).

Tagetes erecta

(sunflower), is another promising plant species against cadmium pollution (Khan *et al.*, 2021). This ornamental plant shows quick development and broad underground root growth making it a potential species for phytoremediation. Studies have shown that *T. erecta* has a momentous capacity to ingest and collect cadmium from contaminated soil. The plant's metabolic pathways really help in wiping out the metal and keeping it from draining into groundwater or being taken up by different plants. It absorbs this metal in its tissues, especially the roots and shoots. The immobilisation of cadmium in the soil, helps in diminishing its bioavailability and forestalling its spread. The utilisation of its root exudates to adjust the soil micro-climate, making cadmium less open to different life forms (Kabata, 2000). This beautiful plant species can not only add aesthetic value to the land area but also help in soil remedial process. (Wang *et al.*, 2021). Further research is needed to optimise the conditions for *T. erecta*'s growth and cadmium uptake, as well as to develop strategies for the safe disposal of cadmium-laden plant material (Rahman *et al.*, 2017).

Brassica juncea

employs several mechanisms to tolerate and accumulate cadmium. Its extensive root system efficiently absorbs cadmium

from the soil, while specialized transporter proteins (BjYSL7, BjCET1, BjCET2, BjCET3, and BjCET4) facilitate its uptake into the plant's vascular system (You *et al.*, 2024). Once inside the plant, cadmium is transported to various tissues, including leaves and stems, where it is sequestered in vacuoles, preventing it from interfering with cellular processes. Additionally, *B. juncea* produces chelating agents, such as phytochelatin, which bind to cadmium and further reduce its toxicity. The efficiency of uptake of cadmium by *Brassica juncea* can be affected by several aspects, including, organic matter, pH of the soil and the existence of other metals (Fe²⁺, Zn²⁺, Sb³⁺, and Pb²⁺). Optimal soil conditions and the use of other techniques like chelating agents may increase cadmium availability and uptake by the plants. Furthermore, genetic engineering approaches have been explored to further improve the cadmium accumulation capacity of *B. juncea* (Zhou, 2017).

Several Bamboo species have shown significant potential in cadmium (Cd) phytoremediation due to their rapid growth, extensive root systems, and high biomass yield. Species such as *Bambusa arundinacea*, *Dendrocalamus strictus*, *Phyllostachys edulis*, *Bambusa balcooa*, and *Bambusa vulgaris* (Arumugam *et al.*, 2023) exhibit varying mechanisms like phytoextraction and phytostabilization, depending on their ability to uptake, translocate, or immobilize Cd. These mechanisms include root uptake through Ca²⁺ and Zn²⁺ channels, sequestration by Phytochelatin and metallothioneins, binding of Cd to cell walls, and modulation of the rhizosphere through organic acid exudation. Bamboo also enhances soil health by improving microbial activity and organic matter content. The detoxification process is further supported by an upregulation of antioxidant enzymes and metal transporter genes; particularly HMA (Heavy Metal ATPases), ZIP (Zinc/Iron-regulated transporter-like Protein), NRAMP (Natural Resistance-Associated Macrophage Protein) family genes and ABC (ATP-Binding Cassette) transporter Proteins. They facilitate in bamboo's Cd tolerance and accumulation mechanisms. Under Cd-stress *Dendrocalamus brandisii*, revealed active participation of metal transporter systems in the plant's adaptive response to Cd toxicity (Yurong *et al.*, 2024). It was also found to influence the structure of the rhizosphere microbial community, suggesting a coordinated plant-microbe interaction that could enhance stress tolerance and remediation potential (Abdu *et al.*, 2017). Overall, bamboo offers a dual benefit: effective remediation of Cd-contaminated soils and generation of non-edible biomass for sustainable utilization, making it a promising candidate for eco-friendly and scalable phytoremediation strategies, particularly in polluted agro-ecosystems like those in the Indo-Gangetic plains.

Mechanism of Cd-uptake

Cadmium (Cd) transport and storage in plant cells involve several key protein families that regulate its uptake, translocation, sequestration, and detoxification across root, shoot, and leaf tissues. In roots, ZIP (ZRT-IRT-like Protein) transporters and NRAMP (Natural Resistance-Associated Macrophage Proteins) facilitate Cd uptake from the soil into root cells. Once inside, Heavy Metal ATPases (HMAs) like HMA2 and HMA4 are critical for loading Cd into the xylem for transport from roots to shoots and leaves. In the shoots and leaves, tonoplast-localized transporters such as Cation/H⁺ antiporters (CAXs) and ATP-binding cassette

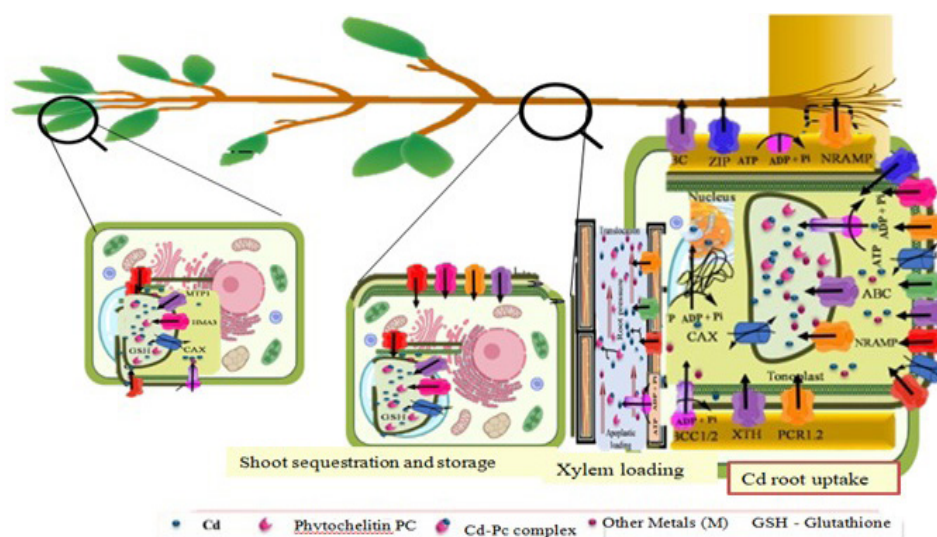


Fig2 : Major transport proteins involved in Cadmium removal and storage in cells of roots, shoots and Leaves.

(ABC) transporters, particularly ABCC1 and ABCC2, play a key role in sequestering Cd into vacuoles, thereby reducing its toxicity. Additionally, metal chelators such as phytochelatins and metallothioneins assist in binding and stabilizing Cd in cellular compartments (Tao and Lu., 2022; Baruah et al., 2023). Together, these transport proteins coordinate a complex defense system that helps plants manage Cd stress by controlling its distribution and reducing its harmful effects. Once Cd accumulates in aerial parts, plants cannot naturally remove it externally. Therefore, the practical method to eliminate Cd from the plant system is through harvesting the contaminated biomass (leaves and shoots) and safely disposing of or processing it. This can include methods like incineration, composting under controlled conditions, or phytomining (recovering metals from plant ash). Effective removal depends on regular harvesting before leaf senescence, as falling leaves can reintroduce Cd into the soil. Thus, combining physiological detoxification with proper agronomic management is key to successful Cd removal from plant shoots and leaves (Fig-2).

Remediation of cadmium (Cd) using plants offers great potential to restore and heal our Earth and has shown many positive results. From many studies, it is clear that Cd harms plant functions, but in response, plants activate their defense systems through various physiological and metabolic changes. For successful soil restoration, it is important to understand and use the natural ability of certain plants to absorb and store high amounts of Cd. This helps in controlling and reducing Cd levels in the soil. By using combined approaches like genomics, proteomics, and metabolomics (multi-omics), we can improve how plants grow and function even in soils with low metal content. This will also support the process of extracting Cd from the soil through plants (phytoextraction). Omics-based approaches can be employed to deepen our understanding of how Arbuscular mycorrhizal fungi (AMF) and plant growth-promoting bacteria (PGPBs) play a pivotal role in enhancing cadmium phytoremediation by modulating a range of genetic, metabolic, and hormonal pathways. Investigating these genetic

mechanisms holds the potential to not only optimize the phytoremediation capabilities of crops but also boost their productivity in cadmium-contaminated environments.

Influence of Cadmium on Flora and Mankind

Plants under cadmium stress induce phytochelatin synthesis, stunted growth, leaf epinasty, and chlorosis (Das *et al.*, 2014). Besides inhibiting nitrate assimilation, it alters different cell transport processes and the ultrastructure of chloroplasts, causing a reduction in photosynthetic rate and leaf transpiration. The root tip and the root uptake of Cd can follow the apoplastic or symplastic pathway (Gallego *et al.*, 2012; Dalcorsio *et al.*, 2008). Cd toxicity reduces the activity of the electron transport system resulting in inhibition of the photochemical reaction of plant (Jinadasa *et al.*, 2016).

Cd adversely affects human health, like renal failure (Templeton *et al.*, 2010). Cadmium interaction with male body causes decreases the sperm count thus, it can cause infertility in human males. (Benoff *et al.*, 2009). The acute exposures of cadmium can cause cough, dryness, irritation of the nose and throat, chest pain, pulmonary oedema and pneumonitis (Roy *et al.*, 2013). In humans, long-term contact with cadmium (Cd) can cause cancer. It promotes the transformation of normal epithelial cells into malignant ones and disrupts critical biological processes by inhibiting the synthesis of DNA, RNA, and proteins. These effects highlight severe long-term health risks like Cadmium carcinogenesis.

Conclusion and Future Prospects

Cd contamination is a major environmental concern as it is non-biodegradable and toxic. This contamination has adverse effects on ecosystems, including harmful impacts on soil microorganisms, disruption of biogeochemical cycles, reduced enzymatic activities, and interference with plant growth, such as decreased water uptake. Phytoremediation presents a promising approach to remediate cadmium-contaminated environments. While phytoremediation has its limitations, it is a valuable tool

in environmental remediation techniques, and further research and development can enhance its effectiveness and expand its applications.

Phytoremediation of cadmium (Cd) faces several challenges. One major issue is the limited availability of Cd in soil due to its strong binding with soil particles, reducing plant uptake. Some plants that can accumulate Cd have low biomass, while high-biomass species may not absorb enough Cd efficiently. High Cd levels can be toxic to plants, limiting their growth. There's also a risk of Cd entering the food chain. Safe disposal of Cd-rich plant biomass also remains a concern. The prospects of cadmium remediation with hyperaccumulator plants are increasingly promising, especially with the integration of advanced genetic techniques like CRISPR-cas9. Through genetic modification, plants can be engineered to enhance their ability to absorb, transport, and detoxify cadmium more efficiently. CRISPR-cas9 technology allows precise alterations to the plant genome, potentially increasing cadmium tolerance and uptake without compromising plant health. Combined with other phytoremediation techniques, these advances hold the potential for large-scale, sustainable, and cost-effective cleanup of cadmium-polluted environments, offering a green solution to heavy metal contamination.

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Authors Contribution

The corresponding author, Dr. Tulika Mishra is working in the area of Phytoremediation and Medicinal plants, with an experience of about 21 years, and has published many research and review articles which are oriented towards pharmacology and Bio-remediation. She has conceptualized the study and edited the work. Mr. Raj K. Pandey and Ms. Pragati Pandey are pursuing their Ph.D. degree under the guidance of the corresponding author from the Department of Botany, D.D.U Gorakhpur University, Gorakhpur (U.P.), India, and their areas of thrust are also related to Phytoremediation and Medicinal Plants, and Prof. Shail Pande is a collaborator for this research and helped in the Review of Literature writing.

CONFLICT OF INTEREST

There is no conflict of interest.

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