Phytoremediation of Contaminated Tannery Wasteland Soil with Metal-Tolerant Plants: A Literature Review

Suvashree Basu[1]*, Suchhanda Ghosh[2], Poornima Sharma[3]

[1]Research Scholar in Mansarovar Global University, Department of Botany, Sehore, Madhya Pradesh, India

[1]State Aided College Teacher, Department of Botany, Barrackpore Rastraguru Surendranath College, Barrackpore, West Bengal, India.
Corresponding Author Email: *suvashreebasu[at]gmail.com*

[2]Assistant Professor of Botany, Shri Shikshayatan College, Kolkata, West Bengal, India

[3]Associate Professor, Department of Botany, Faculty of Science, Mansarovar Global University, Sehore, Madhya Pradesh, India

Abstract: ***Tannery wastelands are often contaminated with toxic heavy metals, posing significant environmental and health risks. Phytoremediation, a cost - effective and eco - friendly remediation approach, utilizes metal - tolerant plants to remove, stabilize, and degrade contaminants. This review explores the extent of heavy metal contamination in tannery soils and the mechanisms underlying phytoremediation, including phytoextraction, phytostabilization, and rhizofiltration. A range of metal - tolerant plant species such as*** **Ricinus communis, Brassica juncea,** ***Lantana camara, Gotalaria juncea, Parthenium hysterophorus, Hyptis suaveolense, Solanum nigrum, Cymbopogon flexuosus, Phragmites australis and*** **Vetiveria zizanioides** ***have demonstrated potential in remediating tannery - contaminated soils. However, phytoremediation faces challenges related to slow remediation rates, metal bioavailability, and biomass disposal. Future research should focus on enhancing remediation efficiency through genetic engineering, microbial - assisted approaches, and soil amendments. Integrating phytoremediation with sustainable land management practices can further improve its effectiveness. This study highlights the importance of phytoremediation in restoring degraded tannery sites and promoting environmental sustainability.***

Keywords: Phytoremediation, Heavy Metal Contamination, Tannery Wastelands, Metal - Tolerant Plants, Soil Remediation, Environmental Sustainability.

1. Introduction

Tannery industries contribute significantly to global economic growth, particularly in leather production and trade. However, they are also notorious for their adverse environmental impacts, primarily due to the discharge of hazardous chemicals, including heavy metals, into the surrounding ecosystems [1]. Tannery waste, especially in the form of effluents and sludge, is rich in chromium (Cr), lead (Pb), cadmium (Cd), nickel (Ni), arsenic (As), and other toxic elements, which lead to severe soil and water contamination. Heavy metal pollution in tannery wastelands presents a persistent environmental hazard, affecting soil fertility, plant growth, microbial diversity, and ultimately human health through bioaccumulation in the food chain [2].

Conventional remediation techniques, such as excavation, soil washing, and chemical stabilization, are often expensive, labor - intensive, and environmentally disruptive. As a sustainable alternative, phytoremediation has gained significant attention in recent years. Phytoremediation is a green, cost - effective, and environmentally friendly strategy that utilizes plants to remove, stabilize, or detoxify heavy metals from contaminated soils [3]. This technique exploits the natural ability of certain plant species to tolerate and accumulate heavy metals, thereby rehabilitating degraded lands while maintaining ecosystem balance [4].

Phytoremediation encompasses several mechanisms, including phytoextraction, phytostabilization, phytovolatilization, rhizofiltration, and phytodegradation. These mechanisms are influenced by plant species, soil characteristics, metal bioavailability, and environmental conditions [5]. The selection of appropriate plant species is crucial for effective phytoremediation, as some plants are naturally adapted to grow in metal - polluted environments, showing high tolerance and accumulation potential.

Several plant species have been identified for their ability to remediate tannery - contaminated soils. Metal - tolerant plants such as *Ricinus communis* (Castor plant), *Brassica juncea* (Indian mustard), *Vetiveria zizanioides* (Vetiver grass), and *Phragmites australis* (Common reed) have demonstrated significant potential in accumulating or stabilizing toxic metals. These plants possess unique physiological and biochemical mechanisms that enable them to survive and thrive in harsh environments laden with heavy metals [6].

Despite the promise of phytoremediation, certain challenges hinder its widespread implementation. Factors such as long remediation time, variability in metal uptake efficiency, plant biomass disposal, and ecological concerns related to the introduction of non - native species must be carefully considered. Research efforts are ongoing to enhance phytoremediation efficiency through soil amendments, microbial - assisted remediation, and genetic modifications to improve metal uptake and stress tolerance in plants.

This paper aims to provide a comprehensive literature review on phytoremediation of tannery wasteland soils, focusing on the mechanisms, potential plant species, factors affecting remediation efficiency, and challenges. By exploring the latest research and advancements in this field, this study aims to contribute to the growing knowledge base on sustainable and effective strategies for remediating metal - contaminated environments.

2. Heavy Metal Contamination in Tannery Wastelands:

Tannery wastelands are one of the most polluted environments due to the indiscriminate disposal of industrial effluents and solid waste containing hazardous heavy metals. The tanning process involves the use of various chemicals, including chromium salts, sulfides, and synthetic dyes, which contribute to soil and water contamination [7]. Among the heavy metals, chromium (Cr) is the most significant pollutant, particularly in its hexavalent form Cr (VI)), which is highly toxic, carcinogenic, and mobile in nature. Other metals such as cadmium (Cd), lead (Pb), nickel (Ni), arsenic (As), and zinc (Zn) are also present in high concentrations in tannery waste, posing severe environmental and health risks [8].

Heavy metals in tannery wastelands can persist for decades due to their non - degradable nature. These contaminants alter soil physicochemical properties, leading to decreased fertility, altered microbial communities, and inhibited plant growth [9]. The accumulation of heavy metals in the food chain through bioaccumulation and bio magnification further exacerbates environmental hazards, affecting not only local biodiversity but also human populations reliant on agriculture and groundwater resources in the vicinity of tannery industries.

Chromium pollution, in particular, is a major concern due to its dual oxidation states—trivalent chromium Cr (III)), which is relatively stable and less toxic, and hexavalent chromium Cr (VI)), which is highly soluble, toxic, and capable of penetrating biological membranes. Tannery industries primarily use Cr (III) for leather tanning, but improper disposal and oxidation processes convert it into Cr (VI), contaminating surrounding soils and water bodies [10]. Prolonged exposure to Cr (VI) has been linked to severe health issues, including respiratory disorders, kidney damage, and cancer.

Apart from chromium, cadmium and lead are also prevalent in tannery - contaminated soils. Cadmium, a byproduct of industrial waste, is known for its high toxicity even at low concentrations, affecting plant growth and causing severe health effects such as kidney dysfunction and bone disease in humans. Lead contamination, on the other hand, originates from industrial chemicals and wastewater discharge, leading to neurological damage, cognitive impairments, and developmental disorders in children [11].

Nickel and arsenic are additional pollutants found in tannery wastelands. Nickel, though an essential micronutrient in small amounts, becomes toxic in excessive concentrations, leading to reduced seed germination and plant growth inhibition. Arsenic, a highly toxic metalloid, accumulates in groundwater and poses a severe risk of poisoning through drinking water contamination.

The bioavailability of these metals in soil depends on various factors such as soil pH, organic matter content, redox potential, and microbial activity. Highly acidic or alkaline conditions can increase the solubility and mobility of heavy metals, thereby exacerbating their environmental impact. Additionally, microbial processes such as metal reduction, oxidation, and chelation influence the fate of heavy metals in contaminated soils.

Overall, heavy metal contamination in tannery wastelands poses significant environmental and health risks. Addressing this issue requires sustainable remediation strategies, with phytoremediation emerging as a promising solution. The subsequent sections of this paper will explore the mechanisms of phytoremediation and potential metal - tolerant plant species for tannery soil remediation.

3. Mechanisms of Phytoremediation

Phytoremediation is an eco - friendly and cost - effective technology that utilizes plants to mitigate heavy metal contamination from soils and water bodies. Several mechanisms govern the phytoremediation process, each tailored to specific contaminants and environmental conditions:

Phytoextraction:
Phytoextraction involves the uptake of heavy metals by plant roots and their translocation to aboveground biomass (Ali et al., 2013). Hyperaccumulator plants, such as *Brassica juncea* and *Solanum nigrum*, can accumulate high concentrations of metals like cadmium, lead, and chromium in their shoots, which can then be harvested to remove contaminants from the soil (Lasat, 2002).

Phytostabilization
Phytostabilization restricts the mobility of heavy metals by binding them within the root system, (Kumar et al., 2019) reducing their bioavailability and preventing further leaching into groundwater. Plants such as *Vetiveria zizanioides* and *Phragmites australis* effectively stabilize metal pollutants while improving soil structure (Shackira et al., 2019).

Rhizofiltration:
Rhizofiltration refers to the absorption of heavy metals from aqueous environments through plant roots (Mishra et al., 2021). This mechanism is particularly useful for treating tannery wastewater, with species like *Cymbopogon flexuosus* and *Phragmites australis* demonstrating high efficiency in removing metals from water (Lee et al., 2020).

Phytodegradation and Phytovolatilization:
Phytodegradation involves plant enzymes breaking down toxic organic pollutants (Verma et al., 2020A), while phytovolatilization enables the transformation of heavy metals into less harmful gaseous forms released into the atmosphere (Muthusaravanan et al., 2018).

These combined mechanisms make phytoremediation a viable and sustainable solution for tannery wasteland rehabilitation.

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4. Metal - Tolerant Plants for Tannery Soil Remediation

Tannery wasteland soil is heavily contaminated with toxic heavy metals such as chromium (Cr), lead (Pb), cadmium (Cd), and arsenic (As), which pose significant environmental and health hazards. Certain metal - tolerant plant species have demonstrated potential for phytoremediation of tannery - contaminated soil due to their ability to uptake, accumulate, and stabilize heavy metals. The following section discusses some of the most effective metal - tolerant plants used in tannery soil remediation.

4.1 *Ricinus communis:*

Ricinus communis (castor plant) is a hardy, fast - growing plant known for its high tolerance to heavy metals. It has been found to accumulate significant amounts of chromium (Cr) and lead (Pb) in its roots and shoots. The deep root system of *Ricinus communis* allows it to extract contaminants from deeper soil layers, making it a suitable candidate for phytoremediation. It produces high biomass, enabling multiple harvests for metal removal (Gomes et al., 2016).

4.2 *Lantana camara:*

Lantana camara, a widespread invasive plant, exhibits strong resistance to heavy metal toxicity. Studies have indicated that it can absorb and accumulate heavy metals such as cadmium and lead, reducing their bioavailability in contaminated soils (Sharma & Pandey, 2014). Its ability to grow in poor soil conditions makes it a promising phytoremediator for tannery wastelands.

4.3 *Crotalaria juncea:*

Crotalaria juncea (sunn hemp) is an effective hyperaccumulator plant used for heavy metal phytoremediation. It has been observed to tolerate and accumulate chromium and lead, which are common in tannery wastelands (Parida & Das, 2005). Additionally, its nitrogen - fixing properties improve soil fertility, aiding in ecosystem restoration.

4.4 *Parthenium hysterophorus:*

Parthenium hysterophorus, a rapidly growing invasive weed, has shown significant potential for metal absorption and accumulation. It is particularly effective in uptaking chromium and cadmium from contaminated soil. However, its aggressive growth and potential toxicity to other plants necessitate controlled usage in phytoremediation efforts (Kumar et al., 2014).

4.5 *Hyptis suaveolense:*

Hyptis suaveolense is a metal - tolerant plant that has demonstrated strong phytoremediation capabilities, particularly for chromium and lead. It grows in a wide range of environmental conditions, making it a viable option for remediation projects in tannery - polluted areas (Mishra et al., 2021).

4.6 *Brassica juncea:*

Brassica juncea (Indian mustard) is one of the most well - known hyperaccumulators of heavy metals. It efficiently uptakes lead, cadmium, and chromium, storing them in its biomass. The high biomass yield and ability to extract heavy metals make it a valuable candidate for tannery soil remediation (Shekhawat et al., 2012).

4.7 *Solanum nigrum:*

Solanum nigrum (black nightshade) is a plant species known for accumulating lead and chromium. It has been studied extensively for its role in phytoremediation due to its high tolerance to heavy metal stress and its ability to grow in contaminated environments (Jain et al., 2011).

4.8 *Cymbopogon flexuosus:*

Cymbopogon flexuosus (lemongrass) is widely recognized for its ability to remediate tannery waste - contaminated soils. It accumulates heavy metals in its biomass while also improving soil health by reducing metal bioavailability and promoting microbial activity (Sharma et al., 2009).

4.9 *Phragmites australis:*

Phragmites australis (common reed) is a wetland plant used for phytoremediation of tannery effluent and contaminated soil. It effectively uptakes and stabilizes heavy metals such as chromium and lead. Its ability to thrive in waterlogged and metal - contaminated conditions makes it ideal for wastewater treatment and tannery site rehabilitation (Hazelton et al., 2014).

4.10 *Vetiveria zizanioides:*

Vetiveria zizanioides (vetiver grass) is widely used for phytoremediation due to its extensive root system and high tolerance to heavy metals. It is effective in absorbing and stabilizing chromium, lead, and cadmium, making it a sustainable option for remediating tannery wastelands while also preventing soil erosion (Chahal et al., 2015).

These metal - tolerant plants offer a sustainable, cost - effective, and eco - friendly solution for remediating tannery-contaminated soils. Their ability to accumulate, stabilize, and extract heavy metals contributes to restoring degraded ecosystems and mitigating environmental hazards associated with tannery pollution.

5. Factors Affecting Phytoremediation Efficiency

The efficiency of phytoremediation in tannery - contaminated soils depends on several environmental, biological, and physicochemical factors. Understanding these factors is crucial for optimizing phytoremediation strategies and achieving effective soil decontamination.

5.1 Soil Characteristics:

Soil properties such as pH (Ghosh & Singh, 2005), texture, organic matter content (Verma et al., 2020), and cation exchange capacity significantly influence phytoremediation efficiency. Heavy metal bioavailability is affected by soil pH; for instance, acidic soils enhance metal solubility (Boechat et al., 2016), increasing plant uptake, whereas alkaline soils reduce metal mobility (Sintorini et al., 2021). The presence of organic matter can also chelate metals, making them more or less available for plant absorption.

5.2 Heavy Metal Concentration and Speciation:

The type and concentration of heavy metals in tannery waste determine their impact on plant health and uptake efficiency. High metal concentrations may induce toxicity in plants, inhibiting growth and reducing remediation potential (Zulfiqar et al., 2019). Additionally, metal speciation (oxidation state and chemical form) affects solubility and bioavailability, influencing plant absorption rates.

5.3 Plant Species and Metal Accumulation Capacity:

Different plant species exhibit varying degrees of metal tolerance and accumulation ability. Hyperaccumulator plants, such as *Brassica juncea* and *Vetiveria zizanioides*, efficiently uptake and store heavy metals. Plant selection should be based on tolerance to contaminants, biomass production, and adaptability to site conditions.

5.4 Root System and Microbial Interactions:

A well - developed root system enhances metal uptake by increasing soil contact and facilitating rhizofiltration. Plant - microbe interactions also play a crucial role; certain rhizobacteria and mycorrhizal fungi enhance metal solubilization and uptake by plants, improving phytoremediation efficiency (Mishra et al., 2021).

5.5 Climatic Conditions:

Temperature, rainfall, and sunlight exposure influence plant growth and metal uptake. Warmer temperatures and adequate sunlight promote photosynthesis and biomass production, leading to better phytoremediation outcomes. Water availability also affects metal solubility and plant transpiration rates, which are critical for metal transport within the plant (Ali et al., 2013).

5.6 Use of Amendments and Chelating Agents:

Soil amendments such as organic matter, biochar, and fertilizers can enhance phytoremediation by improving soil structure and increasing metal bioavailability. Chelating agents like citric acid (Zhang H. et al., 2014), ethylenediaminetetraacetic acid (EDTA) (Tandy et al., 2006) can mobilize metals, making them more accessible for plant uptake. However, their application must be carefully controlled to prevent groundwater contamination.

5.7 Contaminant Mobility and Remediation Duration:

The mobility of contaminants influences how quickly plants can absorb metals from the soil. While phytoextraction may require several cropping cycles, phytostabilization strategies focus on reducing metal mobility to prevent further environmental contamination (Eze et al., 2018). Remediation duration depends on the contamination extent, plant growth rate, and metal accumulation efficiency (Wood et al., 2016).

By optimizing these factors, phytoremediation can be a sustainable and cost - effective approach to mitigating heavy metal contamination in tannery wastelands.

6. Challenges and Future Perspectives

6.1 Challenges in Phytoremediation

Despite its potential as an eco- friendly and cost - effective remediation technique, phytoremediation faces several challenges that limit its widespread implementation in tannery wastelands:

- **Slow Remediation Process:** Phytoremediation is time - consuming compared to conventional methods such as soil excavation and chemical treatments. Depending on contamination levels, it may take years or even decades for significant reductions in heavy metal concentrations.
- **Limited Metal Uptake and Bioavailability:** The efficiency of metal uptake by plants depends on metal bioavailability, which varies based on soil characteristics and metal speciation. Some heavy metals form insoluble compounds, reducing their availability for plant absorption.
- **Plant Toxicity and Growth Inhibition:** High concentrations of toxic metals can negatively impact plant growth, leading to reduced biomass and lower remediation efficiency. Some plants may not survive in heavily contaminated environments, limiting their applicability.
- **Seasonal and Climatic Variability:** Climate factors such as temperature, rainfall, and seasonal changes affect plant growth and metal uptake. In regions with extreme weather conditions, phytoremediation efficiency may be inconsistent.
- **Post - Harvest Biomass Management:** The disposal of metal - enriched plant biomass poses a significant challenge. Improper handling can lead to secondary contamination, necessitating safe disposal or further treatment of harvested plants.

6.2 Future Perspectives

To enhance the effectiveness of phytoremediation in tannery - contaminated soils, several strategies and research directions need to be explored:

- **Genetic Engineering for Hyperaccumulation:** Advances in plant biotechnology can improve metal uptake, tolerance, and biomass production. Genetic modifications in hyperaccumulator species may enhance their ability to remediate highly contaminated soils.
- **Microbial - Assisted Phytoremediation:** Plant - microbe interactions play a crucial role in metal mobilization and uptake. The use of metal - resistant bacteria and

mycorrhizal fungi can enhance plant performance and remediation efficiency (Kumar et al., 2019).

- **Soil Amendments and Nanotechnology:** The application of biochar, organic matter, and nanoparticles can improve metal bioavailability and plant uptake. Nanotechnology - based approaches can also offer innovative solutions for metal detoxification.
- **Integration with Sustainable Land Management:** Phytoremediation should be integrated into broader environmental management plans, promoting sustainable land use, afforestation, and ecological restoration (Rascio & Navari - Izzo, 2011).

By addressing these challenges and adopting advanced technologies, phytoremediation can become a viable and scalable solution for mitigating heavy metal contamination in tannery wastelands.

7. Conclusion

Phytoremediation presents a sustainable and environmentally friendly approach for mitigating heavy metal contamination in tannery wastelands. By utilizing metal - tolerant plants, this technique offers a cost - effective and non - invasive alternative to conventional remediation methods. The ability of plants such as *Ricinus communis*, *Brassica juncea*, *Lantana camara*, *Crotalaria juncea*, *Parthenium hysterophorus*, *Hyptis suaveolense*, *Solanum nigrum*, *Cymbopogon flexuosus*, *Phragmites australis* and Vetiveria zizanioides to absorb, accumulate, and stabilize toxic metals highlights their potential in restoring degraded soils.

However, despite its advantages, phytoremediation faces challenges related to metal bioavailability, plant toxicity, and extended remediation timeframes. Factors such as soil characteristics, climatic conditions, and microbial interactions significantly influence the efficiency of this process. Addressing these limitations requires an integrated approach involving genetic engineering, microbial - assisted phytoremediation, and the use of soil amendments to enhance metal uptake and plant resilience.

Future advancements in phytoremediation will likely focus on optimizing plant - metal interactions through biotechnological interventions and improving soil management practices. Additionally, the development of sustainable biomass disposal methods will be crucial to prevent secondary contamination. Combining phytoremediation with other remediation techniques, such as nanotechnology - based solutions, can further enhance its effectiveness.

Overall, phytoremediation remains a promising solution for heavy metal contamination in tannery wastelands. With continued research and innovation, this approach can contribute to ecological restoration, soil health improvement, and sustainable land management. By overcoming existing challenges and leveraging technological advancements, phytoremediation can play a crucial role in remediating contaminated environments and promoting long - term environmental sustainability.

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