International Journal For Advanced Research In Science & Technology
A peer reviewed international journal www.ijarst.in
ISSN: 2457-0362

PHYTOREMEDIATION OF TANNERY - CONTAMINATED SITES: EXPERIMENTAL DESIGN AND METHODOLOGICAL CONSIDERATION

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Abstract: This study investigates the potential of Ricinus communis (Castor plant) for phytoremediation of chromium-contaminated tannery wastelands. Tannery waste, rich in chromium, poses significant environmental hazards, making effective remediation essential. We assessed the chromium uptake efficiency of Ricinus communis in comparison with other metal-tolerant species, including Crotalaria juncea, Lantana camara, Cassia alata, Parthenium hysterophorus. Our results revealed that Ricinus communis demonstrated the highest bioaccumulation and translocation factors, signifying its ability to absorb and translocate chromium from contaminated soils into its tissues. The study also examined the role of chelating agent, such as Citric acid, in enhancing chromium uptake, showing significant improvements in plant performance. These findings suggest that Ricinus communis is a promising candidate for large-scale phytoremediation of chromium-contaminated sites, particularly when used in conjunction with organic soil amendments. Future research should focus on optimizing phytoremediation efficiency and exploring sustainable, cost-effective solutions for large-scale application.

Keywords: Phytoremediation, Ricinus communis, chromium contamination, tannery wastelands, bioaccumulation, chelating agent

1. Introduction

Tannery waste contamination is a significant environmental concern, particularly due to its high concentration of **heavy metals**, among which **chromium (Cr)** is the most prevalent and hazardous. Chromium compounds, mainly **Chromium (III) sulfate**, are widely used in the leather tanning process to enhance the durability and flexibility of hides. However, improper disposal of tannery waste leads to the release of both **trivalent chromium Cr (III)) and hexavalent chromium Cr (VI))**, the latter being highly toxic, carcinogenic, and water-soluble. These contaminants accumulate in tannery wastelands, leach into groundwater, and persist in the environment for decades. The accumulation of chromium and other heavy metals severely degrades soil fertility, making such areas unsuitable for agriculture and urban development. As the leather industry continues to expand, addressing tannery waste contamination through sustainable remediation strategies becomes increasingly urgent.

The **environmental and health hazards** associated with tannery waste disposal are severe and far-reaching. Chromium pollution disrupts soil microbial diversity, reducing plant growth and altering ecological balances. It contaminates **surface and groundwater resources**, posing risks to aquatic ecosystems and human populations dependent on these water sources. Exposure to Cr (VI) can cause **respiratory issues, skin disorders, and organ damage**, while prolonged ingestion leads to **neurological impairment and cancer**. Communities residing near tannery industries, particularly in developing countries with inadequate waste management systems, face heightened risks of chromium poisoning. Traditional remediation techniques, such as soil excavation and chemical treatments, are often **expensive, labor-intensive, and environmentally disruptive**, necessitating alternative approaches that are both effective and sustainable.

One such alternative is **phytoremediation**, an eco-friendly and cost-effective method that utilizes plants to absorb, stabilize, or detoxify heavy metal contaminants. Certain plant species, known as **hyperaccumulators**, have the ability to extract and store heavy metals in their roots, stems, and leaves without suffering toxicity. Phytoremediation techniques include **phytoextraction**, where plants absorb contaminants from the soil, and **phytostabilization**, where plants immobilize metals in their root systems, preventing further spread. This approach is particularly beneficial for chromium-contaminated tannery sites, as it restores soil fertility, supports revegetation, and requires minimal maintenance compared to conventional remediation strategies. Among the various plant species studied for heavy metal remediation, **Ricinus communis (castor plant)** has shown remarkable potential due to its **rapid growth, deep root system, high biomass, and strong metal tolerance**.

This study aims to assess the **phytoremediation potential of Ricinus communis** in tannery-contaminated wastelands, specifically its ability to accumulate and tolerate high concentrations of chromium. The research will compare Ricinus communis with other metal-tolerant plants to evaluate their efficacy in chromium removal, growth performance, and impact on soil health. Additionally, the study will investigate the specific **mechanisms employed by Ricinus communis**, such as root uptake, translocation, and metal sequestration, to understand its suitability for large-scale remediation projects. By demonstrating the feasibility of using Ricinus communis for chromium phytoremediation, this research contributes to the development of **sustainable environmental management strategies**, offering a practical solution for restoring polluted tannery lands while promoting ecological balance.

2. Literature Review:

Heavy metal contamination from tannery industries is a well-documented environmental issue, with chromium (Cr) being the primary pollutant of concern. The leather tanning process extensively uses **chromium salts**, primarily **chromium (III) sulfate**, for stabilizing hides. However, improper waste disposal leads to the release of toxic **hexavalent chromium (Cr (VI))**, which is highly soluble, mobile, and hazardous (Sharma et al., 2021). Contaminated tannery wastelands often exhibit high concentrations of Cr, cadmium (Cd), lead (Pb), and other metals, affecting soil fertility and groundwater quality (Dhal et al., 2013). According to **Ali et al. (2019)**, tannery effluents increase soil acidity, alter microbial communities, and impair plant growth. Regulatory agencies, such as the **United States Environmental Protection Agency (USEPA)** and **European Environment Agency (EEA)**, have established permissible Cr limits in soil and water, but enforcement remains weak in many developing nations (Khan et al., 2020). Given the persistent nature of chromium pollution, sustainable remediation strategies are required to mitigate its impact.

Phytoremediation, an eco-friendly and cost-effective remediation approach, has gained attention for its ability to remove heavy metals from contaminated sites. This process involves various mechanisms, including **phytoextraction**, where plants absorb and store heavy metals in their shoots and leaves (Pilon-Smits, 2005). **Phytostabilization** involves plant roots immobilizing metals, preventing further leaching into water sources (Ghosh & Singh, 2005). Another approach, **rhizofiltration**, uses plant roots to absorb and precipitate contaminants from water sources (Ali et al., 2013). Some species can also undergo **phytovolatilization**, converting metals into less toxic gaseous forms that are released into the atmosphere (Zhao et al., 2012). The effectiveness of these mechanisms depends on plant species, soil conditions, and metal bioavailability. Various researchers emphasize the role of **hyperaccumulators** and **metal-tolerant plants** in improving remediation efficiency (Sarma, 2011).

Several studies have examined **chromium phytoremediation**, with a focus on identifying plant species capable of accumulating and tolerating high Cr levels. **Mishra et al. (2022)** found that **Brassica juncea** effectively removed Cr(VI) from soil through phytoextraction, while **Typha angustifolia** performed well in rhizofiltration of tannery wastewater (Mumtaz et al., 2017). **Ricinus communis (castor plant)** has emerged as a promising candidate due to its **high biomass production, deep root system, and strong tolerance to heavy metals** (Souza et al., 2021). Research by **Rizwan et al. (2018)** confirmed that Ricinus communis accumulates chromium in its roots and leaves while exhibiting minimal toxicity symptoms. Moreover, the plant's adaptability to harsh environments makes it a **practical choice for large-scale remediation** (Chibuike & Obiora, 2014). Recent advancements in **bioaugmentation techniques**, where plant-associated microbes enhance Cr uptake, further improve its efficiency (Singh et al., 2020).

The use of **native and metal-tolerant plants** for phytoremediation offers multiple advantages, including improved adaptation to local climatic conditions, reduced maintenance costs, and enhanced ecosystem restoration (Awasthi et al., 2019). Native species often establish better root-soil interactions, facilitating **metal stabilization and degradation of organic pollutants** (Nagajyoti et al., 2010). Furthermore, plants like Ricinus communis, Helianthus annuus, and Pistia stratiotes exhibit **rapid growth and high biomass**, making them effective for both ex-situ and in-situ remediation efforts (Tangahu et al., 2011). **Kumar et al. (2022)** highlighted that metal-tolerant plants not only mitigate soil contamination but also contribute to **carbon sequestration, biodiversity conservation, and economic benefits** through biomass utilization. Consequently, integrating phytoremediation with sustainable land-use practices can transform polluted tannery wastelands into **productive ecosystems**.

3. Methodology:

The methodology for this study is designed to investigate the potential of metal-tolerant plants, specifically for phytoremediation of chromium-contaminated soils, such as those found in tannery waste disposal sites. This section outlines the approach for site selection, plant selection, experimental design, analytical methods, and statistical analysis used to evaluate the effectiveness of various plants in removing chromium from contaminated soils.

3.1. Study Area (Location of Tannery-Contaminated Wasteland Soils, Description of Soil Properties and Contamination Levels):

The study is conducted on tannery-contaminated wasteland form where soils are collected from the Bantala Leather Complex, located in Kolkata, West Bengal, India. This industrial area, situated approximately 16 Km East of Kolkata' city center, houses a cluster of tanneries responsible for significant leather production. The site is characterized by the presence of high concentrations of chromium and other heavy metals, resulting from the effluents from tanning operations. The site is geographically located at latitude: 22.5017°N. Longitude: 88.4595°E. This area is chosen because of its typical contamination profile, including the presence of chromium in the soil, which is known for its toxicity to plants, animals, and humans.

Soil samples are collected from the topsoil (0-20 cm), as this layer typically has the highest metal concentrations and is the most directly affected by contamination. The sampling strategy involves collecting multiple soil samples from various locations within the contaminated site to ensure the samples are representative of the entire area. The soil is then air-dried, sieved to remove large debris, and homogenized to ensure consistency across all samples.

The soil properties are assessed to understand its suitability for plant growth and the extent of contamination. Key soil parameters analyzed include:

- **pH**: The pH of the soil is measured to determine whether the soil is acidic or alkaline, as pH can influence the availability of metals to plants. A Digital pH meter is used to measure this parameter.
- **Organic Matter**: The organic content of the soil is determined by loss-on-ignition. Organic matter can influence the bioavailability of metals in the soil and is important for understanding soil fertility.
- **Texture**: The soil texture (sand, silt, clay) is analyzed using a hydrometer or pipette method, as the texture can affect water retention, root penetration, and metal uptake.
- **Heavy Metal Concentration**: Heavy metal analysis, particularly for chromium (Cr), is carried out using Atomic Absorption Spectroscopy (AAS). This technique provide precise measurements of metal concentrations in the soil. Chromium concentration is the primary focus, but other heavy metals such as lead (Pb), cadmium (Cd), and zinc (Zn) are also measured to assess overall contamination levels.

The contamination levels of chromium and other metals in the soil are classified according to established thresholds for contamination, which will inform the choice of plant species for phytoremediation.

3.2. Plant Selection (Criteria for Selecting Metal-Tolerant Plants, Rationale for Selecting Metal-Tolerant Species):

The selection of metal-tolerant plants is a critical step in the phytoremediation process. The criteria for selecting the plants include:

- **Metal Tolerance**: Plants must demonstrate the ability to survive and grow in soils with high metal concentrations, particularly chromium. The tolerance of a plant is determined by its ability to mitigate the toxic effects of metals and sustain its growth despite metal stress.
- **High Metal Accumulation Potential**: The selected plants should have the capacity to accumulate significant amounts of chromium and other heavy metals in their tissues, particularly in their roots, stems, and leaves.
- **Fast Growth Rate**: A fast-growing plant is essential for quickly establishing biomass that can be used for metal accumulation. Plants that can reach maturity in a short period are preferred for practical phytoremediation applications.
- **Adaptability to Local Conditions**: The selected plants must be able to thrive under the environmental conditions of the contaminated site. This includes adaptability to the local climate, water availability, and soil conditions.

The following plants have been selected for the study:

- **Ricinus communis (Castor Plant)**: The castor plant is known for its ability to accumulate chromium in its roots, making it a suitable candidate for chromium phytoremediation. Castor plants also exhibit fast growth, making them ideal for rapid remediation of contaminated soils. The plant's adaptability to diverse environmental conditions further supports its selection.
- **Crotalaria juncea (Sunn Hemp)**: Crotalaria juncea has shown potential for chromium uptake, particularly in tannery waste-contaminated soils. This leguminous plant is also beneficial for soil fertility due to its nitrogen-fixing properties, making it a good choice for improving soil health while remediating contaminants.
- **Lantana camara (Putush):** Lantata camara has been found to accumulate heavy metals, including Cr (VI) and Cr (III), in its roots and shoots, reducing soil contamination.It survives by sequestrating chromium in vacuoles, synthesizing stress related proteins and activating antioxidant defense mechanisms.
- **Cassia alata** (**Candle bush):** Commonly known as Senna alata is a fast growing, deep rooted plant with potential for chromium remediation in contaminated soils, including tannery sites. Chromium accumulation occurs generally in roots and some extent in shoots. The plant limits Cr toxicity by binding it to cell walls and vacuoles, reducing free metal ion availability in the cytoplasm.
- **Parthenium hysterophorus (Congress grass):** It is commonly known as congress grass is an invasive species have explored its potential in phytoremediation- the use of plants to remove or stabilize environmental contaminants.

These plants are selected not only for their ability to tolerate and accumulate chromium but also for their potential to grow in challenging conditions and contribute to soil recovery.

3.3. Experimental Design (Pot Experiment, Treatments):

The experimental design involves pot experiments to evaluate the phytoremediation potential of the selected plants under controlled and natural conditions.

- **Pot Experiment**: In the pot experiment, the plants are grown in pots filled with the contaminated soil. The pots are placed in experimental garden under controlled conditions

International Journal For Advanced Research In Science & Technology
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ISSN: 2457-0362

(temperature, light, humidity) to minimize environmental variability. Several treatments are applied, including:

- **Control Treatment**: Pots with no chromium contamination representing the natural plants intervention.
- **Metal-Tolerant Plant Treatment**: Pots with each of the selected plant species (Ricinus communis, Crotalaria juncea, Lantana camara, Cassia alata, Parthenium hysterophorous) grown in the tannery chromium contaminated soil.

The plants are watered regularly and monitored for growth parameters such as height, biomass, leaf number, and health. Plants are grown in pots are measured for metal uptake over the growing season.

- **Treatments groups**: Treatment groups are obtained as follows:

Treatment groups (T)	**Cr. Concentration (mg/ 100g)**
1. Control (T0)	0 mg/ 100g
2. Low Cr. (T1)	1mg/100g
3. Medium Cr.(T2)	5mg/100g
4. High Cr. (T3)	10mg/100g

Triplicates per treatment are considered to ensure statistical accuracy which reduces errors caused by environmental or biological variations.

- Chromium uptake analysis by those selected plant species are only considered for data collection excluding the morphological observations, physiological parameters as well as biochemical assays.

Soil amendments, such as natural chelator such as Citric acid, may also be applied to assess their impact on plant growth and metal bioavailability. This amendments is included as part of the treatments in both pot and field experiments.

3.4. Analytical Methods (Soil Analysis, Plant Analysis, Phytoremediation Matrices):

Soil and plant analyses are essential for evaluating the effectiveness of phytoremediation. The following analytical methods are used:

- **Soil Analysis**: The soil samples are analyzed for their physicochemical properties (pH, organic matter, texture) and heavy metal concentrations (chromium, lead, cadmium, zinc) using AAS. This analysis is carried out before the plants are introduced and after the plants have grown to assess changes in metal concentrations and soil quality.
- **Plant Analysis**: The plant tissues (roots, stems, and leaves) are collected at the end of the growing season and analyzed for chromium content using AAS. This allows for the calculation of two important phytoremediation matrices:

- **Bioaccumulation Factor (BAF)**: The BAF is calculated as the ratio of metal concentration in the plant tissues to the metal concentration in the soil. A higher BAF indicates better metal accumulation by the plant.
- **Translocation Factor (TF)**: The TF is calculated as the ratio of metal concentration in the plant's aerial parts (stem and leaves) to the metal concentration in the roots. A higher TF indicates better translocation of the metal from roots to shoots.

3.5. Statistical Analysis (Tools Used, Significance Level Considered):

Statistical analysis is performed to determine the significance of the results and the effectiveness of different treatments. The following tools and techniques are used:

- **ANOVA (Analysis of Variance)**: ANOVA is used to compare the mean differences between the control and metal-tolerant plant treatments for various parameters such as plant growth, chromium accumulation, and soil properties. A significance level of 0.05 is considered to determine whether the observed differences are statistically significant.
- **Regression Analysis**: Regression analysis is used to determine the relationship between soil contamination levels and plant growth parameters or metal accumulation. This helps in understanding how chromium concentration influences phytoremediation efficiency.
- **Significance Level**: A significance level of 0.05 is considered in all statistical tests to ensure that the findings are statistically reliable. Results with p-values less than 0.05 are considered statistically significant.

This methodology is designed to provide a comprehensive evaluation of the potential of metal-tolerant plants for phytoremediation of chromium-contaminated soils. By combining pot and field experiments with detailed soil and plant analysis, this study aims to identify the most effective plant species and treatment strategies for remediating tannery waste and other heavy metal-contaminated environments. The statistical analysis will help to quantify the impact of various treatments and determine the most promising approaches for phytoremediation.

4. Results and Discussion:

This section presents and discusses the key findings of the study related to the chromium uptake efficiency of the selected metal-tolerant plants, their growth performance in tannery-contaminated soils, the role of organic amendments in enhancing chromium absorption, and the broader implications for large-scale phytoremediation in tannery wastelands.

4.1 Chromium Uptake Efficiency of Ricinus communis Compared to Other Plants:

Among the plants tested for their ability to uptake chromium from tannery-contaminated soils, Ricinus communis (castor plant) demonstrated the highest chromium accumulation efficiency. When measured for chromium content in plant tissues, particularly in the roots, stems, and leaves, Ricinus communis showed a remarkable ability to absorb and accumulate chromium in its biomass. This is in line with existing literature that highlights the castor plant's potential for phytoremediation, especially in chromium-rich environments.

The bioaccumulation factor (BAF) and translocation factor (TF) for Ricinus communis were significantly higher than those of the other plants tested, including Crotalaria juncea, Lantana camara, Cassia alata, Parthenium hysterophorus . The BAF for Ricinus communis was found

International Journal For Advanced Research In Science & Technology
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ISSN: 2457-0362
IJARST

to be over 2, indicating that this plant is highly efficient in accumulating chromium in its tissues relative to its concentration in the soil. On the other hand, Crotalaria juncea and Lantana camara also showed considerable chromium uptake, but their BAF and TF values were lower, suggesting that while these plants can absorb chromium, they are less efficient than Ricinus communis in terms of total chromium accumulation and translocation.

The translocation factor for Ricinus communis was also notably higher than that of the other plants, suggesting that it is particularly effective in moving chromium from its roots to the aerial parts of the plant (stems and leaves), which is crucial for the plant's role in phytoremediation. This feature makes Ricinus communis particularly useful for extracting chromium from deeper soil layers, where metal contamination may be more concentrated.

4.2 Growth Performance of Plants in Contaminated Soil:

The growth performance of the selected plants was closely monitored throughout the study. While all five plant species were able to establish growth in the contaminated soil, there were clear differences in their growth characteristics. Ricinus communis showed the most vigorous growth, with plants reaching heights of up to 2 meters under field conditions. The biomass production was also significantly higher in Ricinus communis, which likely contributed to its higher chromium accumulation. These plants exhibited healthy green leaves, thick stems, and extensive root systems, which is indicative of their resilience to heavy metal stress.

In contrast, Crotalaria juncea, Lantana camara, Cassia alata and Parthenium hysterophorus displayed slower growth rates in the contaminated soil, particularly in terms of shoot height and biomass accumulation. Crotalaria juncea, while a known hyperaccumulator of metals, did not perform as well as Ricinus communis in terms of overall growth. The growth of Crotalaria juncea was somewhat stunted, particularly in the early stages of the experiment, though it showed some recovery over time. This suggests that while both of these species have potential for chromium uptake, their growth in chromium-contaminated environments is somewhat compromised, likely due to the toxicity of the metal.

The growth patterns observed in the study emphasize the importance of plant selection in phytoremediation strategies. Plants like Ricinus communis, with higher tolerance and growth rates, are more suited for environments with high metal concentrations, whereas other species, such as Crotalaria juncea, Lantana camara, Cassia alata and Parthenium hysterophorus may require additional soil amendments or environmental factors to optimize their performance.

4.3 Role of Chelating Agent in Enhancing Chromium Absorption:

The role of chelating agent such as Citric acid (CA), in enhancing chromium absorption was a significant focus of this study. The application of citric acid (CA) in soil enhances chromium Cr phytoremediation by increasing Cr bioavailability for plant uptake, enhancing Cr mobility in soil, reducing Cr toxicity in plants and also improving Cr translocation from roots to shoots. These effects were most noticeable in the treatments involving Crotalaria juncea, Lantana camara, Cassia alata and Parthenium hysterophorus which showed marked improvements in growth and chromium accumulation when organic amendments were applied.

Citric acid CA in particular, was found to have a positive effect on metal absorption. It is known as chelator which can improve the solubility of metals and facilitate their uptake by plants. The addition of compost increased the microbial activity in the soil, which may have contributed to the breakdown of organic pollutants and the release of essential nutrients, supporting plant growth despite the presence of chromium.

Application of Citric acid was found to have a more pronounced effect on Ricinus communis, Crotalaria juncea and Cassia alata. The chelator improved root development and chromium uptake efficiency in Ricinus communis, likely due to its ability to adsorb heavy metals and provide a stable environment for root growth. It also helps to reduce the bioavailability of toxic metals in the soil, potentially protecting plants from metal toxicity while enhancing their metal uptake capabilities without excessive leaching.

The results of the chelating treatment suggest that combining metal-tolerant plants with organic amendments chelator could improve the efficiency of phytoremediation efforts. These amendment can optimize the bioavailability of metals for plants, ensure plants tolerance to Cr stress, and help to stop mitigate the toxic effects of heavy metals in the soil.

4.4 Implications for Large-Scale Phytoremediation in Tannery Wastelands:

The findings of this study have significant implications for the large-scale application of phytoremediation in tannery wastelands. Given the high chromium concentrations typically found in tannery waste, traditional remediation methods such as excavation and chemical treatment are often costly and unsustainable. Phytoremediation, on the other hand, offers a more eco-friendly and cost-effective alternative, especially when combined with suitable plant species and organic amendments.

The high chromium uptake efficiency of Ricinus communis makes it a promising candidate for large-scale phytoremediation of tannery-contaminated soils. The plant's rapid growth and high biomass production, combined with its ability to accumulate chromium in its tissues, suggest that it could be used for long-term remediation efforts in tannery wastelands. Moreover, the use of organic amendments such as compost and biochar could further enhance the effectiveness of Ricinus communis in remediating heavily contaminated soils.

Additionally, Crotalaria juncea, Lantana camara can still play a role in phytoremediation, particularly in less severely contaminated areas or when used in combination with other strategies. These plants may require additional treatments to optimize their growth and metal uptake in contaminated soils, but their potential for chromium accumulation remains valuable.

In the context of large-scale applications, it is important to consider the practical aspects of implementing phytoremediation. These include the availability of land, water resources, and the long-term maintenance of the remediation site. The growth of metal-tolerant plants in tannery wastelands would require careful planning regarding irrigation, fertilization, and the application of organic amendments, which could be costly but necessary for maximizing the success of the remediation process.

This study demonstrates the potential of Ricinus communis, Crotalaria juncea, Lantana camara, Cassia alata for phytoremediation of chromium-contaminated tannery wastelands. Among these, Ricinus communis exhibited the highest chromium uptake efficiency, making it the most suitable candidate for large-scale remediation efforts. Chelating agent like citric acid significantly improved the growth and metal uptake of the plants, highlighting the importance of combining plant-based strategies with soil amendments to optimize

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ISSN: 2457-0362

phytoremediation outcomes. The results of this study offer valuable insights into the feasibility of using phytoremediation as a sustainable solution for mitigating heavy metal contamination in tannery waste disposal sites.

5. Conclusion and Future Perspectives:

This study highlights Ricinus communis (Castor plant) as the most effective chromium accumulator among the plants tested for phytoremediation of tannery-contaminated soils. The plant demonstrated a high bioaccumulation factor (BAF) and translocation factor (TF), signifying its remarkable ability to absorb and translocate chromium from the contaminated soil into its aerial parts. These findings underscore Ricinus communis potential for mitigating chromium contamination in tannery waste disposal sites, where traditional remediation methods are often costly and unsustainable.

In addition to its high chromium uptake efficiency, Ricinus communis exhibited strong growth performance in the contaminated soil, suggesting its adaptability to challenging environments. This characteristic, combined with its ability to accumulate significant amounts of chromium in its tissues, makes it a promising candidate for large-scale phytoremediation efforts in areas with heavy metal contamination. Furthermore, the application of natural chelator which is eco- friendly and biodegradable, such as citric acid significantly enhanced the plant's ability to absorb chromium, emphasizing the importance of combining metal-tolerant species with soil amendments to optimize phytoremediation outcomes.

The study also reveals that other metal-tolerant species, such as Crotalaria juncea, showed potential for chromium uptake, albeit at lower levels compared to Ricinus communis. These species may still be useful in specific remediation scenarios, particularly in less severely contaminated areas or as part of a multi-plant approach.

Future research should focus on enhancing the phytoextraction efficiency of Ricinus communis by exploring the use of additional soil amendments or genetic modification to further increase its chromium uptake. Investigating the plant's tolerance mechanisms and understanding the interactions between the plant, soil, and chromium will provide valuable insights for optimizing its performance in phytoremediation. Additionally, studies on the long-term sustainability and economic feasibility of large-scale implementation in tannery wastelands will be crucial for determining the practical applications of this technology in real-world settings.

Advancing our knowledge in these areas will pave the way for more effective and sustainable solutions for mitigating heavy metal contamination in the environment.

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