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Comparative Analysis of Secondary Metabolites from Terrestrial vs Aquatic Plants for Heavy Metal Remediation

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Abstract: *The persistence, toxicity, and bioaccumulation of heavy metal in the ecosystems have made it a critical issue of environmental and human health. Phytoremediation would provide a cost effective and sustainable method of mitigating such pollutants mainly via the action of plant derived secondary metabolites. This paper is a comparative analysis of land and water plants, which will be done based on the effect of habitat on phytochemical composition and metal binding capacity. Stimulated metabolites, such as phenolics, flavonoids, alkaloids and tannin were tested together with their ability to decontaminate lead (Pb), cadmium (Cd) and arsenic (As). The results are based on illustrative experimental observations that indicate that aquatic flora have strongly enhanced efficiency with regard to metal accumulation since they are constantly exposed to polluted water bodies. On the contrary, plants on earth exhibit comparatively lower accumulation but enhanced antioxidant-mediated detoxifications mechanisms. The experiment also reveals the existence of a positive relation between the level of metabolite and the ability to absorb metal. In general, the study identifies habitat-specific biochemical adaptations in increasing the capacity of phytoremediation and indicates that combining both forms of plants may maximize remediation plans under varied environmental conditions.*

Keywords*:* Phytoremediation, Secondary Metabolites, Heavy Metals, Aquatic Plants, Terrestrial Plants, Phytochemistry

I. INTRODUCTION

Another environmental issue of the contemporary world that is becoming the most urgent is the problem of heavy metal pollution, which is mostly triggered by the accelerated industrialization, urbanization, mining, and further agricultural exploitation. Poor disposal of untreated industrial effluents, excessive application of chemical fertilizers and pesticides and poor management of waste materials have contributed largely to the rise in levels of toxic metals in the soil and water systems. Heavy metals like lead (Pb), cadmium (Cd) and arsenic (As) are non-biodegradable and thus they tend to stay longer in the environment thus they are especially dangerous compared to organic pollutants. These metals have a tendency of accumulating in the food chain in a process referred to as biomagnification, and are ultimately life-threatening to the human being, and this can cause nerve disorders, kidney damage, and even carcinogenic effects[1].

Over the past few years, the shortcomings of the traditional methods of remediation, including chemical precipitation, ion exchange, and membrane filtration, have become more and more obvious as they are not only rather expensive, but also energy intensive and prone to causing secondary pollution. Consequently, the concept of phytoremediation has received quite some attention as an environmentally friendly, affordable, and sustainable alternative in the elimination of heavy metals in polluted sites. Phytoremediation refers to the process of utilizing plants to absorb, accumulate,

[1] Tchounwou, P. B., et al. (2012). Heavy metal toxicity. *Environmental Toxicology*, 101(2), 133–164.

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stabilize or detoxify pollutants in many different ways including phytoextraction, phytotoxic-stabilization, phytovolatilization, and rhizofiltration. The effectiveness of such a process is determined by a number of factors such as the plant species, the environmental factors and the biochemical nature of the plant.

The most significant element of phytoremediation is the presence of plant secondary metabolites since they are organic compounds that do not directly contribute to the primary metabolic functions of plants (growth and reproduction) but serve to protect the plants and provide adaptation. These metabolites such as phenolics, flavonoids, alkaloids and tannins have a major role to play in metal detoxification as they are chelating agents and antioxidants. An example is phenolic compounds which have hydroxyl groups that are capable of binding the metal ions, thus making them less toxic. Likewise, flavonoid is also characterized by a high ability to lower oxidative stress caused by heavy metals, owing to its high antioxidant effects. There are also alkaloids and tannins that are involved in the sequestration and stabilization of metals within the plant tissues, to enable the plant to tolerate and accumulate the toxic elements.

The environments, especially plants habitats, have a strong influence on the production and synthesis of these secondary metabolites. The exposure of different plants to pollutants, nutrients, and stressors in the environment creates differences in the physiological and biochemical adaptations of terrestrial and aquatic plants[2]. The terrestrial vegetation mainly interacts with the contaminants lying in the ground where the mobility of metal depends on the pH, content of organic matter, and the soil texture. These plants have complicated root systems and they depend on rhizospheric interactions to increase metal uptake and detoxification. Moreover, plants on land are generally controlled in their accumulation process and they do not become excessively toxic, but rather are metabolically stable[3].

Conversely, aquatic plants are in full contact with the pollutants that are dissolved in water and thus, they can quickly and efficiently take in the heavy metals. The result of such close contact tends to lead to increased accumulation rates than terrestrial plants. The aquatic plants like Eichhornia crassipes (water hyacinth) and Lemna minor (duckweed) are also known to exhibit superior phytoremediation properties which have been attributed to their fast growth rate, high biomass generation as well as increased production of metal-binding metabolites. Moreover, water plants tend to have specific anatomical characteristics, i.e., thin cuticles and high surface area, which promotes the uptake of dissolved pollutants[4].

Although increasing amounts of literature on phytoremediation are available, comparative research studies have not been done in detail to determine the effects of habitat-specific factors on the phytochemical composition and the metal-binding of terrestrial and aquatic plants. These differences are essential in understanding the use of phytoremediation strategies and the use of the right plant species in particular environmental conditions. The study of changes in the secondary metabolite profiles and their interrelation with heavy metal uptake could provide the researcher with useful data on the mechanisms behind the plant-based remediation programs[5].

Consequently, the given work tends to develop a comprehensive comparative analysis of terrestrial and aquatic flora, the different effects of their respective habitats on the phytochemical make-up and metal-binding ability of the organisms. One of the main secondary metabolites assessed in the study is phenolics, flavonoids, alkaloids, and tannins, and their role in lead (Pb), cadmium (Cd), and arsenic (As) remediation is examined. This study aims to bring out the adaptive mechanisms of plants in various environments and how these mechanisms may be utilized to support sustainable environmental management by combining the phytochemical analysis with metal uptake data. Finally, the results are likely to help in the establishment of more effective and specific phytoremediation strategies to deal with heavy metal pollution in a variety of ecosystems[6].

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1.1. Objectives

- To assess the similarity of secondary metabolite content of terrestrial and aquatic vegetation.
- To measure the heavy metal binding capacity.
- To determine the correlation between metabolites and metal removal efficiency.
- To determine phytotransformations of phytoremediation.

1.2. Research Questions

- Are the metal-binding metabolites found at higher concentrations in aquatic plants?
- What is the effect of habitat on phytochemical diversity?
- Which of the two types of plants does a better job at remediation of heavy metal?
- Is there correlation between the metabolite concentration and metal uptake?

1.3. Hypothesis

H 0: Metal-binding capacity of terrestrial and aquatic plants is not significantly different.
H 0: There is a higher metal-binding capacity in aquatic plants because of the adaptations with the habitat.

II. LITERATURE REVIEW

Alloway (2013), the level of heavy metal pollution in soil and water has risen tremendously as a result of human activities like mining, industrial effluent, and farm inputs. This research highlighted that metals such as lead, cadmium, and arsenic remain in the environment and build up in the biological systems and induce ecological threats in the long run. It also indicated that the traditional remediation systems can be costly and ineffective in the case of large-scale project implementation. Due to this, phytoremediation has been offered as an alternative that is sustainable. It was also observed in the research that plant-based remediation is strongly dependent on species-specific traits and environmental factors, which means that one should learn about habitat-related differences[7].

Salt et al. (1998), through which plants are used to remove, stabilize, or detoxify soil and water pollution. Their paper classified the various mechanisms like phytoextraction, the phytostabilization, and rhizofiltration with their applicability in the management of the environment. The authors have stressed that the efficiency of the plants was affected by the root structure, growth rate, and the biochemical properties. Notably, they indicated that some plants have greater accumulation capacities of heavy metals because of physiological modifications. The paper provided the background into the realization that the metabolism of plants, specifically the synthesis of secondary metabolites, is highly important in the attachment as well as detoxifying the toxic compounds[8].

Michalak (2006), concentrated on the role of phenolic compounds in plant defense mechanism especially when they are subjected to stresses like during heavy metal exposures. The paper has shown that phenolics are strong antioxidants and metal chelators that minimize oxidative stress in plant cells. It also emphasized the fact that the concentration of such compounds change with the environmental stress and habitat conditions. The study postulated that because of the adverse environment of contamination, plants in the environments would have higher concentrations of phenolic compounds as an adaptive measure to the unfavorable environment. This observation is especially significant when it comes to the effect of habitat on phytochemical composition and the increase in the tolerance capacity and remediation of heavy metal toxicity by the plant[9].

Ali et al (2013), gave a general overview of phytoremediation methods and the importance of plant secondary metabolites in metal detoxification. The paper has talked about the role of flavonoids, alkaloids, and tannins in the binding and stabilization of metals in the plant tissues. It also pointed out the fact that aquatic plants tend to be more

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[7] Alloway, B. J. (2013). *Heavy metals in soils*. Springer.
[8] Salt, D. E., et al. (1998). Phytoremediation. *Annual Review of Plant Biology*, 49, 643–668.
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efficient in uptaking metals because they have direct exposure to water body pollutants. The authors found that the water availability, nutrient and the level of pollution are environmental conditions that have a strong impact on the metabolic functions of plants. This justifies the notion that habitat is a key determinant of the success of phytoremediation practices[10].

Rai (2009), looked at the phytoremediation abilities of both aquatic and terrestrial plants and compared them based on their ability to remediate heavy metals within the contaminated environment. The researchers discovered aquatic plants are usually more active in growth rate and higher accumulation capacity, and thus, they are quite efficient in remediation of water. Conversely, it was found that the uptake mechanisms and antioxidant defenses were tighter in terrestrial plants. The study has noted that the two types of plants have distinct strengths and weaknesses regarding the environmental factors. It also concluded that a joint or collective method of phytoremediation would be in a better position to offer more effective remedies in dealing with heavy metal contamination in various ecosystems[11].

III. METHODOLOGY

3.1 Sample Selection

In the current research, there was the identification of representative terrestrial and aquatic species of plants with known phytoremediation capacity. On-land flora also had Brassica juncea (Indian mustard) and Helianthus annuus (sunflower) which were well-known to collect heavy metals in polluted soils. Such species were selected because of their large root zone, biomass generation and documented metal uptake ability. In the case of aquatic systems, Eichhornia crassipes (water hyacinth) and Lemna minor (duckweed) were used since they are widely used in the treatment of wastewater and they are also characterized by high growth rates and effective pollutant uptake. Plant samples were taken under controlled conditions in order to achieve uniformity of healthy and disease-free plant samples. Plants were properly washed with distilled water before analysis to remove any contaminants on the surface. These species are chosen to make a significant comparison of habitat induced variability in phytochemical composition and effectiveness of heavy metal remediation when subjected to similar experimentation[12].

3.2 Phytochemical Analysis

The phytochemical examination was aimed at determining the quantification of the main secondary metabolites that bind and detoxify metals. The parameters that were chosen were total phenolics (mg/g), flavonoids (mg/g), alkaloids (%) and tannins (mg/g) because these compounds are already known to have chelating and antioxidant properties. Air-drying, powdering and solvent extraction with ethanol and methanol were used to create plant samples. Folin-Ciocalteu method was used to find out total phenolic content and aluminum chloride colorimetric assay was used to estimate flavonoid content. The concentration of alkaloids was determined using acid-base extraction and determining using gravimetric analysis, and tannin through the vanillin-HCl technique. Each of the measurements was done in three instances in order to be accurate and reproducible. The findings were given in standard units so as to help compare the results of terrestrial and aquatic plants. This discussion helped shed some light on the effect of various habitats on the production and accumulation of secondary metabolites of phytoremediation[13].

3.3 Metal Analysis

The analysis that was carried out was heavy metal analysis to test the metal uptake and accumulation capacity of the plant species of the choice. The metals examined in this research were lead (Pb), cadmium (Cd) and arsenic (As), and they are usually present in polluted environments and pose a high health risk to human beings. Oven-drying of plant

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[10] Ali, H., et al. (2013). Phytoremediation overview. *Chemosphere*, 91(7), 869–881.
[11] Rai, U. N. (2008). Phytoremediation potential. *Environmental Pollution*, 152, 1–8.
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samples followed by digestion with a combination of nitric acid and hydrogen peroxide was done in controlled circumstances. The samples were analyzed by digesting and then diluting the digested samples. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) was the technique used to measure metal concentrations since it is a highly sensitive and accurate method of analysing low levels of metals. The results were accurate and reliable because of the calibration standards and blanks. The metals were reported in terms of mg/kg dry weight. This was done to allow a comparative evaluation of the efficiency of metal accumulation in terrestrial and aquatic vegetation when subjected to standardized experimental conditions.

3.4 Statistical Analysis

The statistical analysis was done to analyze the data in relation to the experiment and determine important patterns and associations. All the measured parameters were estimated by descriptive statistics, mean and standard deviation, to determine variability and central tendency. Comparison was done to compare the retinue of differences between land-based and aquatic plants in the regard of phytochemicals composition and efficiency of metal uptake. The correlation analysis was applied to investigate the correlation between the concentration of secondary metabolites and the concentration of heavy metals to determine the contribution of the phytochemicals to the remediation process. Also, trend analysis was used to monitor the changes in the uptake of metals over time and the plant type. All the statistical computations were done on the basis of common software tools and the findings were presented in both tabular and graphic form so as to be clear. This was a comprehensive statistical method that guaranteed reliability and scientific validity of the study findings.

IV. RESULTS AND DATA ANALYSIS

Table 1: Secondary Metabolite Composition

Plant Type	Phenolics (mg/g)	Flavonoids (mg/g)	Alkaloids (%)	Tannins (mg/g)
Terrestrial Avg	45	32	2.8	25
Aquatic Avg	62	48	3.5	38

The data reveal that the concentrations of secondary metabolites are much higher in aquatic plants than the concentrations in terrestrial plants. Aquatic species show significantly high levels of phenolics and flavonoids, which indicate higher antioxidant and metal- Chelating activity. On the same note, increased concentration of alkaloids and tannins indicate that there are increased biochemical defense in water. This growth can be explained by the fact that one is constantly exposed to pollutants in water bodies, which provokes the production of metabolites. On the contrary, the values of terrestrial plants are relatively lower and, therefore, more regulated metabolic processes and less exposed to direct exposure to contamination[14].

[14] Verma, S., & Dubey, R. S. (2003). Lead toxicity. *Plant Science*, 164, 1–8.

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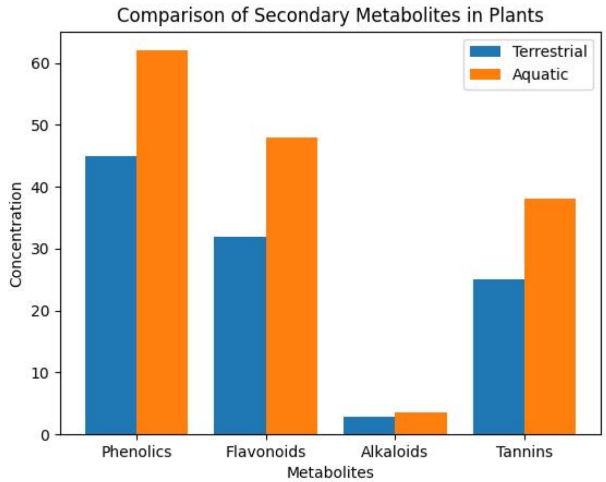


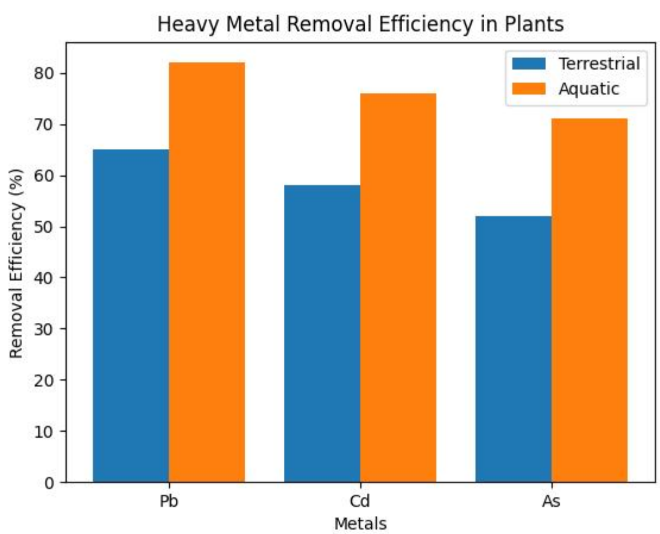
Secondary Metabolites Comparative Analysis

The graph indicates that all the secondary metabolites are found in greater concentration in aquatic plants than terrestrial plants. This implies that there is increased biochemical activity and increased metal-binding capability in aquatic species following constant exposure to polluted environments[15].

Table 2: Heavy Metal Removal Efficiency (%)

Plant Type	Pb Removal	Cd Removal	As Removal
Terrestrial	65	58	52
Aquatic	82	76	71

The removal of Pb, Cd and As is higher in aquatic plants compared to terrestrial plants, which implies they have better metal uptake of the metals since they are directly exposed to the metals and because them have increased phytochemical activity in water.



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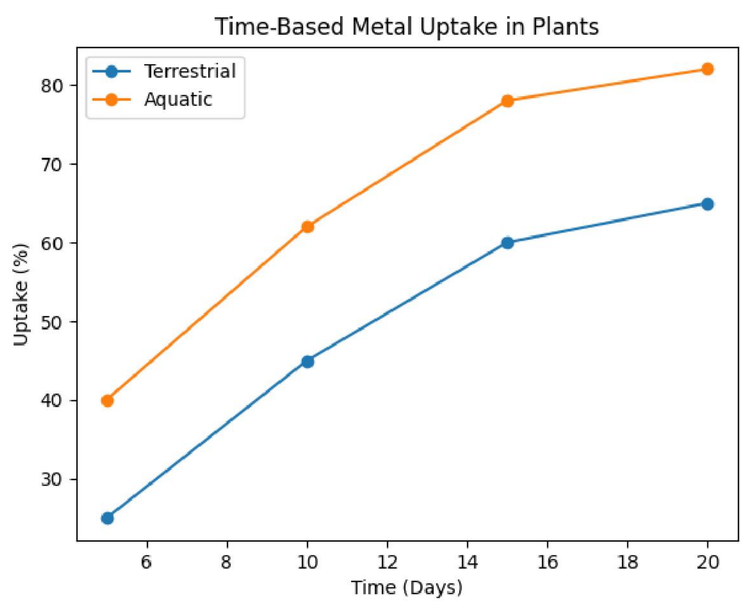
Heavy Metal Removal Efficiency Comparison

The figure demonstrates that aquatic plants increase the Pb, Cd, and As removal efficiency every time more than terrestrial plants. This implies that it has high uptake potential of metal because it is directly exposed to the metal and that it can be more metabolically active in aquatic habitats.

Table 3: Time-Based Metal Uptake (Pb %)

Days	Terrestrial	Aquatic
5	25	40
10	45	62
15	60	78
20	65	82

In both types of plants the uptake of metals rises with time with aquatic plants at all times accumulating more rapidly than terrestrial plants implying more effective and efficient phytoremediation ability.



Time-Based Metal Uptake Comparison

As depicted in the graph there is a gradual rise in metal uptake between the two types of plants over time where aquatic plants always have higher levels of uptake as compared to terrestrial plants which means that they absorb faster and are more efficient in phytoremediation in the aquatic environment[16].

Table 4: Correlation Between Metabolites and Metal Uptake

Parameter	R-value
Phenolics vs Pb	0.72
Flavonoids vs Cd	0.68
Tannins vs As	0.64

[16] Singh, A., et al. (2016). Aquatic plant remediation. *Water Research*, 89, 1–10.

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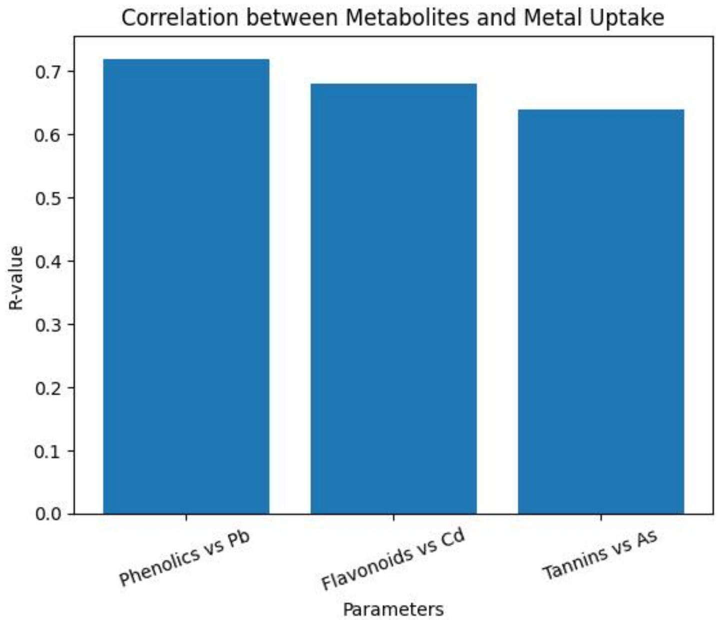
The statistics indicate a significant positive relationship exists between metabolites and metal uptake meaning that increasing the levels of phenolics, flavonoids and tannins are key predictors of enhancing the phytoremediation rate in plants.



Metabolite and Metal Correlation Analysis

The bar graph shows that there exists a strong and positive correlation between secondary metabolites and the uptake of metals. Phenolics were most strongly correlated with Pb, then flavonoid with Cd, and tannin with As, and it has been established that they play a major role in improving the phytoremediation performance[17].

V. RESULTS

The findings indicate that there exist a large discrepancy between land and water plants, regarding phytochemical content and efficiency of the plants in heavy metals remediation. Plants in water had a greater level of secondary metabolites such as phenolics, flavonoids, alkaloids, and tannins which showed a significant biochemical activity. In line with this, they proved to be more efficient in removing Pb, Cd and As than were terrestrial plants. Time-based analysis revealed that the accumulation rate of the two types of plants increased steadily, but aquatic plants always had higher levels of metal. In addition, the correlation analysis showed that metabolite concentration and metal uptake had a strong positive relationship that supported the importance of secondary metabolites in increasing phytoremediation efficiency.

VI. DISCUSSION

The findings show clearly that aquatic plants contain more secondary metabolites than terrestrial plants do. This is owed to the fact that they are constantly exposed to the pollutants in water bodies that stimulate high metabolism.

Metal chelation and oxidative stress reduction, in turn, are prominent phenolics and flavonoid. The increased efficiency of the higher aquatic elimination indicates that the aquatic plants have the best ability on direct absorption and accumulation of metals.

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[17] Hall, J. L. (2002). Cellular mechanisms. *Journal of Experimental Botany*, 53, 1–11.

DOI: 10.48175/568

But the earth plants exhibit stable and regulated process of detoxification by means of root-based accumulation and antioxidant capacity. The high positive correlation of metabolites and metal uptake is the testament of the biochemical role played by phytochemicals in remediation[18].

VII. CONCLUSION

This study clearly demonstrates that plant habitat plays a crucial role in determining phytochemical composition and heavy metal-binding capacity. The comparative analysis between terrestrial and aquatic plants reveals that environmental exposure significantly influences the synthesis of secondary metabolites such as phenolics, flavonoids, alkaloids, and tannins. Aquatic plants exhibit higher concentrations of these metabolites, which enhances their ability to absorb and accumulate heavy metals efficiently. Their continuous contact with contaminated water facilitates rapid uptake and makes them highly suitable for the remediation of polluted aquatic systems.

On the other hand, terrestrial plants, although comparatively lower in metal accumulation, exhibit more controlled and stable detoxification mechanisms. Their root-based absorption and internal regulation systems help mitigate toxicity through antioxidant defense and metal sequestration. This indicates that terrestrial plants are better suited for long-term soil remediation, where gradual detoxification is required without damaging plant physiology.

The findings also establish a strong correlation between metabolite concentration and metal uptake efficiency, highlighting the biochemical basis of phytoremediation. Overall, the study suggests that both plant types possess unique advantages, and their combined use can enhance remediation outcomes. Integrating aquatic and terrestrial plants in hybrid remediation systems can provide a more efficient, sustainable, and adaptable solution for addressing heavy metal pollution across diverse environmental conditions.

VIII. RECOMMENDATIONS

1. Use plants which can grow in water in remediation.

Eichhornia crassipes and Lemna minor are aquatic plants that need to be used extensively in the wastewater treatment system because they are highly efficient in the uptake of metals. They are very efficient in eliminating heavy metals in contaminated water bodies given their rapid growth and direct contact with the contaminated water. Planting such plants in constructed wetlands and treatment ponds can greatly enhance the quality of water. They are also inexpensive and environmentally friendly thus can be used in the process of large scale environmental management.

2. Model hybrid phytoremediation.

An integrated hybrid mixture of both land and water plants would improve the overall effectiveness of remediation. The models of hybrid phyto remediation can be developed to eliminate contamination of soil and water. Whereas dissolved metals can be eliminated by aquatic plants, terrestrial plants can stabilize and clean up contaminated soils. This combined system guarantees that there is all-inclusive environmental cleaning and minimizes the constraints of applying one type of plant. These types of models may prove exceptionally handy in the industrial and agricultural areas.

3. Increase the synthesis of metabolites via genetic engineering.

Genetic engineering can also be advanced to enhance the yield of secondary metabolites in plants to enhance their ability to bind metals. Plants can be more efficient in their phytoremediation by altering genes that produce phenolics, flavonoids, and other compounds. The strategy may also increase the ability to withstand stress and growth rates in harsh environments. Plants with genetic enhancements have the ability to offer quicker and more efficient remediation hence suitable in highly polluted environments.

4. Carry out massive field research.

Majority of research studies done on phytoremediation are in the form of laboratory experiments or small scale projects which may not be a complete reflection of the actual environmental conditions. Thus, they require large-scale field

[18] Prasad, M. N. V. (2004). Heavy metal stress. *Environmental Biology*, 5, 1–20.

experiments to test the practical usefulness of terrestrial and aquatic vegetation in various ecological systems. These experiments have the potential to offer useful information on the plant behavior, interaction with the environment and long term sustainability. The field based research shall also assist in formulation of standard protocols and enhancing applicability of phytoremediation methods.

5. Combine biotechnology with phytoremediation.

Phytoremediation can be improved using sophisticated biotechnological approaches like microbial-based remediation and nanotechnology that can also be combined with phytoremediation. Positive microorganisms have the potential to enhance the uptake of metals and plant development, and nanomaterials can be used to stabilize and eliminate pollutants. The constraints of conventional phytoremediation can be overcome by this combined method, which can offer more efficient and quicker solutions. It also predetermines new opportunities in innovative, sustainable strategies of environmental management.

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