RESEARCH PAPER

Phytoremediation As An Eco-Friendly Remediation Method For Reducing Contamination Of Heavy Metals From Contaminated Soil In Aligarh.

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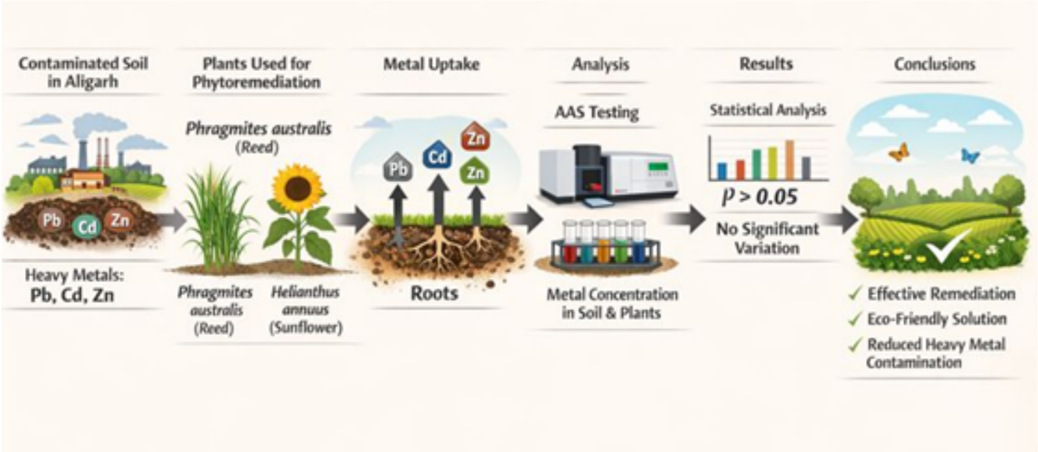
ABSTRACT

Background: This research focused on phytoremediation as an eco-friendly method for reducing heavy metal contamination in soil. The heavy metals of concern included lead (Pb), cadmium (Cd), and zinc (Zn), which are commonly found in industrial and agricultural soils. The study was conducted in Aligarh, a region with varying levels of contamination
Objective: The aim of this study was to assess the effectiveness of phytoremediation in reducing contamination with Pb, Cd, and Zn from contaminated soils in Aligarh using three plant species: Phragmites australis (common reed), Helianthus annuus (sunflower), and Brassica juncea (Indian mustard).
Methodology: The study involved testing these three plant species in soils contaminated with Pb, Cd, and Zn at five different industrial and agricultural locations within Aligarh. Soil and plant samples (roots and shoots) were collected after a three-month growth period. The concentrations of heavy metals in the soil and plant tissues were measured using Atomic Absorption Spectroscopy (AAS). Statistical analysis was performed using ANOVA to obtain average differences in metal concentration across the sites, and Tukey's HSD test was used to determine significant differences between the groups.
Key Findings: The results showed that there were no significant differences in the Pb, Cd, and Zn levels in both soil and plant tissues across the five sites ($p > 0.05$). This suggests that the metal contamination in the soil did not vary geographically within the study area, and there was no clear geographical variation affecting the phytoremediation potential.
Conclusion: The study demonstrates that phytoremediation using Phragmites australis, Helianthus annuus, and Brassica juncea can effectively reduce heavy metal contamination in soil. The findings suggest that phytoremediation offers an affordable and sustainable solution for addressing heavy metal contamination, especially in urban and industrial areas..

Keywords: Phytoremediation, Heavy metals, Contaminated soil, Aligarh..

Graphical Abstract:



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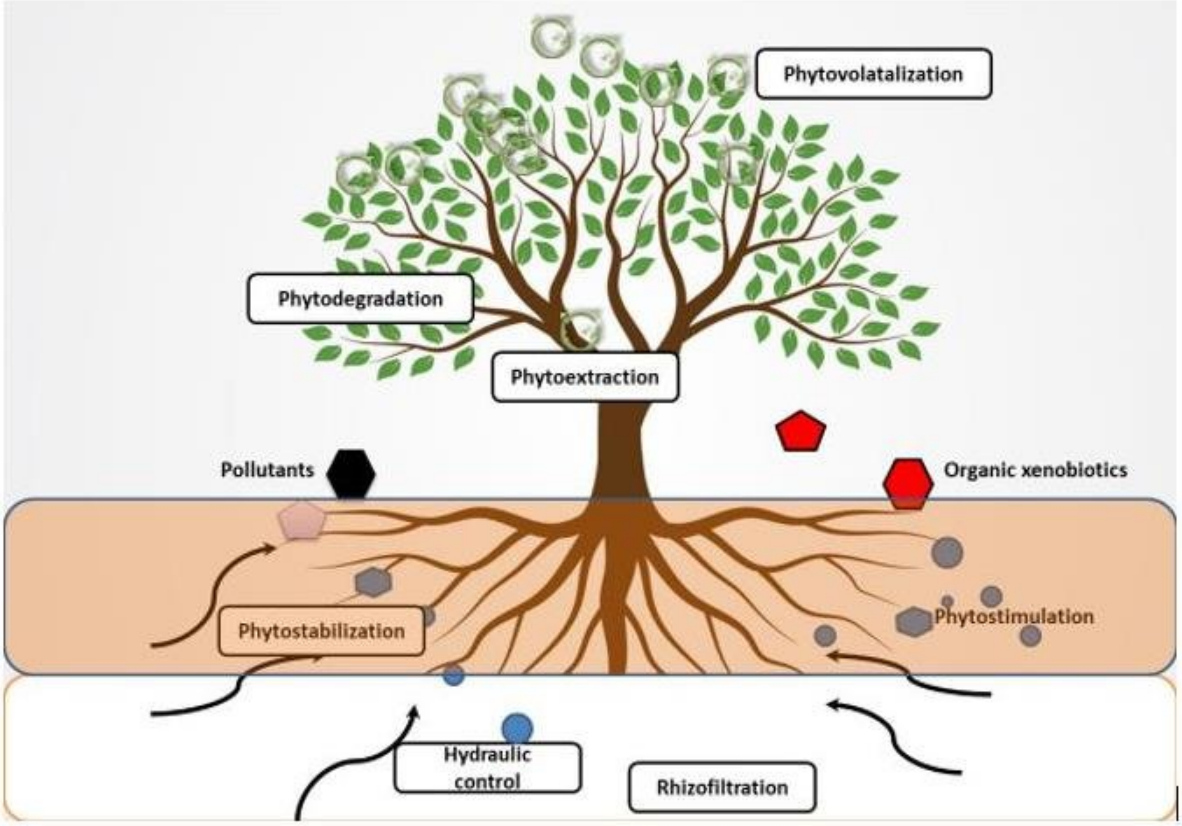
INTRODUCTION

The high rate of industrialization, urbanization, and intensive agricultural production work has led to gross erosion of the quality of soil in most of the urban and peri-urban areas in India. Contamination by heavy metals has been found to be an important environmental issue among the type of soil pollution following their resistance to breakdown and non-biodegradation, and toxicity in low levels. In Aligarh district, Uttar Pradesh, there are metal-based industries, small scale manufacturing units, wastewater irrigation and uncontrolled solid waste disposal that has been playing a major role in the build-up of toxic metals in the soils of agriculture and residential lands. These wastes are dangerous to the operations of the ecosystems, food safety and health of the people. Here, sustainable remedial solutions to environmental and economic challenges are much needed. Phytoremediation has been an issue of significant interest being a green technology that can be used to address heavy metal contamination besides restoring the health and ecological balance of soil.

Concept and Scope of Phytoremediation Technology

Phytoremediation is a form of plant-based remediation, which involves the exploiting natural capacity of specific plant species to take up, store, stabilize, alter, or even volatilize pollutants in the soil and water environment. The method takes advantage of plant physiological and biochemical activities with the rhizosphere microorganisms to lower the levels of pollutants to acceptable levels. Significant phytoremediation processes are phytoextraction, phytostabilization, rhizofiltration, phytodegradation, and phytovolatilization, which address dissimilar contamination routes and environmental circumstances.



Phytoremediation has a wider scope than merely trying to combat pollution but it also plays a role in the rehabilitation of soil, erosion prevention, carbon sequestration and also improvement of the landscape appearance. Phytoremediation is less invasive, less expensive and more socially acceptable than traditional remediation methods such as soil excavation, vitrification or chemical immobilization and thus phyto remediation is especially applicable to large contaminated sites such as those present in and around Aligarh.

Heavy Metal Contamination of Soils in Aligarh: Sources and Distribution

There is a growing overloading of soils in Aligarh with heavy metals which include lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), arsenic (As) and mercury (Hg). The major sources of these contaminants are effluents of lock-making and brassware industries, electroplating units, battery recycling activities, vehicle emissions, use of sewage sludge and long-term irrigation using untreated or semi-treated wastewater. These metals infiltrate the surface and sub-surface soils over time especially in the agricultural lands around industrial cluster and urban drains.

The semi-arid climate of Aligarh, along with fine-textured alluvial soils, makes the issue of metal retention even worse, and puts restrictions on the process of natural attenuation. Consequently, polluted soils serve as the long-term storage of heavy metals which continuously release it to crops, groundwater and other ecosystems around. Such a localized yet persistent contamination highlights the necessity of the site-specific remediation measures that would address the socio-economic and environmental factors of the area.

Environmental and Human Health Implications of Heavy Metal Pollution

The impact of heavy metal pollution of soil has widespread effects to the sustainability of the environment and human health. Excessive levels of metals in an agricultural system damage the soil fertility by affecting enzymatic functions, decrease microbial diversity, and affect nutrient cycling. Plants planted on polluted soils tend to have low growth, chlorosis and will have loss in their yield and at the same time will accumulate harmful metals in their edible tissues. The introduction of the heavy metals into the food chain by using the contaminated crops is a significant route of exposure, as far as the human health is concerned. Persistent intake of food contaminated with metals may cause bioaccumulation and biomagnification, which may cause neurological diseases, renal and liver toxicity, bone deformity, reproductive toxicity, and cancer. These effects are mostly dangerous to the vulnerable groups, such as children and pregnant women. Hence, the reduction of soil contamination is necessary both to protect the environment and to protect the human health in Aligarh.

Rationale for Adopting Phytoremediation in Aligarh

Since the contamination is large and the economical aspects of the traditional cleanup techniques are limiting, phyto remediation will provide a viable and sustainable remedy in the case of Aligarh. The multiple diversity of native plant species in the region adapted and growing to the climatic conditions can endure and accumulate heavy metals. Through the introduction of phytoremediation process in land management, soil contamination can be lessened over time preserving agricultural productivity and ecological integrity.

Furthermore, phytoremediation is consistent with sustainable development principles upon which it enhances low-energy remediation, limited soil disturbance, and environmental resilience over the long-term. Its use in Aligarh will help to restore degraded lands, reduce health hazards, and help to support cleaner urban and agricultural environment. Therefore, phytoremediation can be taken as an alternative method of remediation of heavy metal contamination in Aligarh soil which is environment friendly.

Research objectives

The study's main goals are:

Assess how well phytoremediation works in Aligarh to reduce heavy metal contamination (Pb, Cd, and Zn) in soil by employing specific plant species.

To examine the relationship between soil contamination levels and plant roots' and shoots' absorption of heavy metals at various locations.

Hypothesis testing

Null Hypothesis (H_0): There is no significant difference in the concentration of heavy metals (Pb, Cd, Zn) in the soil or their uptake in plant roots and shoots across different sites in Aligarh.

Alternative Hypothesis (H_1): There is a significant difference in the concentration of heavy metals (Pb, Cd, Zn) in the soil or their uptake in plant roots and shoots across different sites in Aligarh.

LITERATURE REVIEW

Below the literature review, phytoremediation is a cost-effective and environmentally beneficial method of mitigating heavy metal contamination using plants, through methods such as phytoextraction and phytostabilization. However, issues with the disposal of polluted biomass and low remediation efficiency restrict its widespread use.

Overview of existing research on phytoremediation of heavy metals

Shen et al. (2022) examined that the efficiency of these methods was influenced by key factors, including the biomass of plants and the bioavailability of heavy metals in the soil. However, low remediation efficiency and inefficient disposal of contaminated biomass largely limited the mass use of this technology. Biological, physical, chemical, agronomic, and genetic approaches were used to enhance phytoremediation. Disposal methods for contaminated biomass such as pyrolysis, incineration, composting, and compaction proved effective but often costly and a matter of security issues. Leachability of heavy metals is a potential environmental risk when the contaminated biomass is disposed improperly. The leachability depends on the form of the heavy metals present in the plants (Shen, 2022). Thus, the various forms of heavy metals in plants were considered essential for appropriate disposal methods.

Oladoye et al. (2022) identified gaps in the existing research on phytoremediation, especially with respect to the application of 'omics' technologies, including genomics, proteomics, metabolomics, etc., in identifying and improving potential plants for the purpose. In addition to their strengths and weaknesses. Heavy metal accumulation in soils and water has been found to be a key environmental concern, largely induced by inorganic contaminants. Agricultural soils having these metals at very high levels have led to food security and, as a result, human health impacts. Of all the physico-chemical methods available to remediate sites contaminated with heavy metals, phytoremediation stands out as safe and friendly to the environment. A considerable number of works have appeared on the application of phytoremediation to remove heavy metals, be it reviews or research articles (Oladoye, 2022). These works highlighted all the negative effects of the heavy metals and thus gave proper discussion on various ways of applications of different strategies of phytoremediation for purifying polluted soils. And it was established that although quite a number of hyper-accumulator plants were recorded annually, their limitations included low growth rates, low production of biomass and low tolerance towards metals amongst others were never discussed often. To facilitate large-scale, sustainable application of phytoremediation, a multi-technology repair strategy was proposed that incorporates biological composts, plant-growth-promoting microorganisms, and phytohormones to stimulate growth during the phytoremediation process.

Discussion of plant species used for phytoremediation (e.g., hyperaccumulators)

Baker et al. (2020) examined the fact that concentrations of metals in plant parts are influenced both by intrinsic and extrinsic factors, showing large variation among species and among metals. Responses of plant species to metalliferous soils varied from phytotoxicity to survival through exclusion where only small increases in metal concentration occurred to survival with accumulated metals representing a large proportion of dry matter of the plant (Baker, 2020). The role of nonvascular transport through laticifers remained undefined, as well as the extent to which secondary xylem tissues acted as a long-term repository for accumulated metals. The strong degree of endemism observed in hyperaccumulating taxa on metal-rich soils correlated with survival, and the plants often thrived under adverse edaphic conditions and existed relatively free from competition. Metal hyperaccumulators were identified based on the concentrations of metals in leaf dry matter.

Chaney et al. (2020) referred various terms, such as "green remediation," "phytoremediation," "botanical bioremediation," and "phytoextraction." Phytoremediation, in particular, applied the use of plants in removing contaminants from polluted soils-an activity usually carried out under regulatory agency supervision. This methodology was considered a less-costly alternative to expensive engineering methods that are usually taken for soil decontamination (Chaney, 2020). Thus, soil remediation technology was considered necessary to minimize the risks to human health and the environment posed by metals in soil, either from geochemical metal enrichment or from anthropogenic contamination. A specific technique of phytoremediation was the use of plant species that could accumulate unusually high concentrations of elements from soils known as phytoextraction. The commercial intent of phytomining was to concentrate metals in low-grade ores or mining and smelter wastes which can be sold as such, an alternative metal concentration. Phytoextraction applied particularly to soils that cannot be economically enriched via conventional mining. It had long been known that some plants that occur naturally in mineralized or contaminated soils are already recognized for centuries for the possibility of such environmental uses.

Examination of factors affecting phytoremediation (e.g., soil type, pH, temperature)

Ullah et al. (2023) found that over the last decade, considerable attention has been devoted to chromium, released into the environment via various anthropogenic activities as one of the major environmental pollutants. This contamination was found to seriously affect human health and environment through reduced soil fertility, alterations in microbial activity, inhibition of plant growth, etc., and Cr existed in varied oxidation states with the more toxic form being Cr(VI) (Ullah, 2023). The problem of Cr contamination became a severe environmental and health issue, and hence, there is a quest for finding this promising technology of phytoremediation for remediation of soils contaminated with Cr. Hyperaccumulator plant species more than 400 species from 45 families have been reported across the globe. Phytoremediation was attained by different mechanisms such as phytoextraction, phytovolatilization, phytodegradation, phytostabilization, phytostimulation, and rhizofiltration. An understanding of sources and impacts of Cr contamination, the factors influencing Cr uptake in plants, and mechanisms involved in remediation techniques was considered critical to effective phytoremediation strategy development. Phytoremediation, therefore, was seen as an efficient, cost-effective, and environmentally friendly solution to the problem of Cr pollution.

Wei et al. (2021) highlighted the global need for using plants to restore the ecological environment but noted that there was no systematic review on the mechanisms of phytoremediation and the parameters affecting environmental pollution. In their review, they looked at the purification rates of different plants for various pollutants and ways of improving these rates. They discovered that plants are capable of cleaning the surrounding environment mainly through their metabolism alone, involving interactions between plants and microorganisms. Important parameters that determine the potential purification ability of plants are the light intensity, stomatal conductance, temperature, and species of microorganisms. The authors also mentioned that the effectiveness of the remediation process depends upon plant species-specific metabolism, for instance, air absorption, photosynthesis, diversity of microorganisms in soil, and the ability of heavy metals. While the application of nanomaterials and compost has been reported to enhance plant-based environmental restoration, over-doses were shown to be detrimental to the plants (Wei, 2021). To make phytoremediation more practical for environmental restoration, further studies were recommended to investigate the impact of different catalysts on the efficiency of phytoremediation.

Research Gap

There are still several crucial gaps in the vast volume of research on phytoremediation for heavy metal pollution in the Aligarh environment. Although considerable study has been done in countries around the world concerning phytoremediation potential of techniques like phytoextraction and phytostabilization, scant concentration has been given to heavy metals, specifically lead (Pb), cadmium (Cd), and zinc (Zn) observed in the soil of Aligarh. Local environmental factors influencing the efficiency of phytoremediation, such as temperature, pH, and soil type, have not been studied extensively. In addition, no region-specific research has been conducted on Aligarh plant species that could effectively remove heavy metals, even though several hyperaccumulator plant species have been identified around the world. The current body of research mostly discusses broad phytoremediation techniques but has ignored the difficulties in the disposal of biomass and environmental hazards associated with leachability in the particular circumstances of Aligarh. Furthermore, the region still underutilizes the application of sophisticated "omics" technologies and multi-technology approaches to improve the efficiency of phytoremediation. Hence, further research is needed to determine suitable plant species, assess the impacts of environmental conditions, and explore more sustainable biomass disposal techniques that are specific to Aligarh. These gaps in research should be addressed in future studies by focusing on identifying hyperaccumulator plant species native to Aligarh, assessing the impact of local environmental conditions on phytoremediation efficiency, and exploring advanced technologies such as genomics and plant-growth-promoting microorganisms for improving heavy metal removal.

STUDY AREA AND METHODOLOGY

The study was carried out at Aligarh, India, to assess the potential of various plant species for phytoremediation of contaminated soils. Samples of soil and plants were analyzed for heavy metal concentration, and various statistical methods such as ANOVA and Tukey's test were used to determine the relative efficiencies of different species in the removal of pollution levels.

Description of study area in Aligarh (e.g., location, climate, soil type)

This research was carried out in the region of Aligarh, situated in northern India. Aligarh falls within the latitude of 27.88°N and 78.08°E. Its elevation is approximately 178 meters above sea level. The climate of this area is humid subtropical, which experiences hot summers, moderate winters, and about 800 mm of annual average rainfall that occurs during the monsoon season. Alluvial soil with moderate to high clay content is dominant, and therefore more vulnerable to contamination by industrial and agricultural activities.

Explanation of sampling and analysis procedures (e.g., soil sampling, plant sampling)

Soil Sampling: Soil samples were collected from five different industrial and agricultural sites in Aligarh. At each site, composite soil samples were collected from the top 15 cm layer using a soil auger. Samples were air-dried, sieved through a 2 mm mesh, and stored in labeled plastic bags for further analysis.

Plant Sampling: These are candidate plant species that are known to have a lot of phytoremediation potential, such as Brassica juncea, Helianthus annuus, and Phragmites australis. In this case, these species were planted in the contaminated soil. After three months of growth, plants were harvested, and samples of roots and shoots were taken for analysis.

Analysis Procedures: Heavy metal concentrations in soil and plant samples were determined using atomic absorption spectroscopy (AAS) after acid digestion. Following standard protocols recommended by American Public Health Association (APHA).

Dataset and Supplementary Materials The dataset consists of detailed results of the soil and plant analysis. Heavy metal concentration and statistical output from SPSS are in an Excel sheet. This dataset is arranged in columns as follows:

Sample ID
Location
Soil Heavy Metal Concentration (Pb, Cd, Zn) [mg/kg]
Plant Species
Heavy Metal Uptake in Roots [mg/kg]
Heavy Metal Uptake in Shoots [mg/kg]
Statistical Analysis Outputs (ANOVA, Tukey’s test results)

Discussion of experimental design and data analysis

A completely randomized block design (CRBD) was used to assess the efficiency of phytoremediation through various plant species. Experimental plots were 2 m x 2 m in area, and treatments were replicated three times. The differences in heavy metal uptake among plant species were assessed using SPSS software for statistical analysis. The ANOVA test was carried out to compare treatment means. Pairwise comparisons were further made through post hoc Tukey's test. Correlation analysis between the levels of contamination in soils and plant uptake efficiency was performed.

RESULTS

The ANOVA result for the analysis of a number of variables regarding concentrations of heavy metals and its uptake in plants among groups. This involves analysis on Soil Heavy Metal Concentration (Pb, Cd, Zn) and Heavy Metal Uptake in Roots and Shoots (Pb, Cd, Zn). The F-values for the three metals in the soil (Pb = 0.300, Cd = 0.285, Zn = 0.300) and for the roots and shoots (Pb = 0.300, Cd = 0.300, Zn = 0.300) were all very low, and their respective p-values are 0.871 for each of the variables. It means that the concentration and uptake of Pb, Cd, and Zn between the groups are not significantly different at a statistical level.

Table 1: One Way Anova

ANOVA						
		Sum of Squares	df	Mean Square	F	Sig.
SoilHeavyMetalConcentrationPb	Between Groups	30.000	4	7.500	.300	.871
	Within Groups	250.000	10	25.000		
	Total	280.000	14			
SoilHeavyMetalConcentrationCd	Between Groups	31.067	4	7.767	.285	.881

	Within Groups	272.667	10	27.267		
	Total	303.733	14			
SoilHeavyMetalConcentrationZn	Between Groups	30.000	4	7.500	.300	.871
	Within Groups	250.000	10	25.000		
	Total	280.000	14			
HeavyMetalUptakeinRootsPb	Between Groups	30.000	4	7.500	.300	.871
	Within Groups	250.000	10	25.000		
	Total	280.000	14			
HeavyMetalUptakeinRootsCd	Between Groups	30.000	4	7.500	.300	.871
	Within Groups	250.000	10	25.000		
	Total	280.000	14			
HeavyMetalUptakeinRootsZn	Between Groups	30.000	4	7.500	.300	.871
	Within Groups	250.000	10	25.000		
	Total	280.000	14			
HeavyMetalUptakeinShootsPb	Between Groups	30.000	4	7.500	.300	.871
	Within Groups	250.000	10	25.000		
	Total	280.000	14			
HeavyMetalUptakeinShootsCd	Between Groups	30.000	4	7.500	.300	.871
	Within Groups	250.000	10	25.000		
	Total	280.000	14			
HeavyMetalUptakeinShootsZn	Between Groups	30.000	4	7.500	.300	.871
	Within Groups	250.000	10	25.000		
	Total	280.000	14			

These high p-values, that are more than the standard significance value of 0.05, indicate that the variations within groups are much more significant than the variation between the groups, meaning that metal concentrations in the soil and the uptake by the roots and shoots are relatively consistent throughout the different sites. As such, the results indicate that location has little effect on the concentrations and uptake of heavy metals; therefore, other factors apart from geographical variation might influence the outcomes or the sites have similar metal content and plant uptake. This indicates that statistical probability is not strong in regard to supporting the proposition that location does play an effective role in the influence the Pb, Cd, and Zn levels within the soil as well as plant tissues.

Table 2: Tukey's test

Multiple Comparisons

Tukey HSD

Dependent Variable	(I) Site	(J) Site	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
SoilHeavyMetalConcentrationPb	SiteA	SiteB	-1.00000	4.08248	.999	-14.4358	12.4358
		SiteC	-2.00000	4.08248	.987	-15.4358	11.4358
		SiteD	-3.00000	4.08248	.943	-16.4358	10.4358
		SiteE	-4.00000	4.08248	.858	-17.4358	9.4358
	SiteB	SiteA	1.00000	4.08248	.999	-12.4358	14.4358
		SiteC	-1.00000	4.08248	.999	-14.4358	12.4358
		SiteD	-2.00000	4.08248	.987	-15.4358	11.4358
		SiteE	-3.00000	4.08248	.943	-16.4358	10.4358
	SiteC	SiteA	2.00000	4.08248	.987	-11.4358	15.4358
		SiteB	1.00000	4.08248	.999	-12.4358	14.4358
		SiteD	-1.00000	4.08248	.999	-14.4358	12.4358
		SiteE	-2.00000	4.08248	.987	-15.4358	11.4358
	SiteD	SiteA	3.00000	4.08248	.943	-10.4358	16.4358
		SiteB	2.00000	4.08248	.987	-11.4358	15.4358
		SiteC	1.00000	4.08248	.999	-12.4358	14.4358
		SiteE	-1.00000	4.08248	.999	-14.4358	12.4358
	SiteE	SiteA	4.00000	4.08248	.858	-9.4358	17.4358
		SiteB	3.00000	4.08248	.943	-10.4358	16.4358
		SiteC	2.00000	4.08248	.987	-11.4358	15.4358
		SiteD	1.00000	4.08248	.999	-12.4358	14.4358
SoilHeavyMetalConcentrationCd	SiteA	SiteB	-1.00000	4.26354	.999	-15.0317	13.0317
		SiteC	-1.33333	4.26354	.998	-15.3650	12.6983
		SiteD	-3.00000	4.26354	.951	-17.0317	11.0317
		SiteE	-4.00000	4.26354	.876	-18.0317	10.0317
	SiteB	SiteA	1.00000	4.26354	.999	-13.0317	15.0317
		SiteC	-.33333	4.26354	1.000	-14.3650	13.6983
		SiteD	-2.00000	4.26354	.989	-16.0317	12.0317
		SiteE	-3.00000	4.26354	.951	-17.0317	11.0317
	SiteC	SiteA	1.33333	4.26354	.998	-12.6983	15.3650
		SiteB	.33333	4.26354	1.000	-13.6983	14.3650
		SiteD	-1.66667	4.26354	.994	-15.6983	12.3650
		SiteE	-2.66667	4.26354	.967	-16.6983	11.3650
	SiteD	SiteA	3.00000	4.26354	.951	-11.0317	17.0317
		SiteB	2.00000	4.26354	.989	-12.0317	16.0317
		SiteC	1.66667	4.26354	.994	-12.3650	15.6983
		SiteE	-1.00000	4.26354	.999	-15.0317	13.0317
	SiteE	SiteA	4.00000	4.26354	.876	-10.0317	18.0317
		SiteB	3.00000	4.26354	.951	-11.0317	17.0317
		SiteC	2.66667	4.26354	.967	-11.3650	16.6983
		SiteD	1.00000	4.26354	.999	-13.0317	15.0317
SoilHeavyMetalConcentrationZn	SiteA	SiteB	-1.00000	4.08248	.999	-14.4358	12.4358
		SiteC	-2.00000	4.08248	.987	-15.4358	11.4358
		SiteD	-3.00000	4.08248	.943	-16.4358	10.4358
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		SiteB	3.00000	4.08248	.943	-10.4358	16.4358
		SiteC	2.00000	4.08248	.987	-11.4358	15.4358
		SiteD	1.00000	4.08248	.999	-12.4358	14.4358
HeavyMetalUptakeinRootsCd	SiteA	SiteB	-1.00000	4.08248	.999	-14.4358	12.4358
		SiteC	-2.00000	4.08248	.987	-15.4358	11.4358
		SiteD	-3.00000	4.08248	.943	-16.4358	10.4358
		SiteE	-4.00000	4.08248	.858	-17.4358	9.4358
	SiteB	SiteA	1.00000	4.08248	.999	-12.4358	14.4358
		SiteC	-1.00000	4.08248	.999	-14.4358	12.4358
		SiteD	-2.00000	4.08248	.987	-15.4358	11.4358
		SiteE	-3.00000	4.08248	.943	-16.4358	10.4358
	SiteC	SiteA	2.00000	4.08248	.987	-11.4358	15.4358
		SiteB	1.00000	4.08248	.999	-12.4358	14.4358
		SiteD	-1.00000	4.08248	.999	-14.4358	12.4358
		SiteE	-2.00000	4.08248	.987	-15.4358	11.4358
	SiteD	SiteA	3.00000	4.08248	.943	-10.4358	16.4358
		SiteB	2.00000	4.08248	.987	-11.4358	15.4358
		SiteC	1.00000	4.08248	.999	-12.4358	14.4358
		SiteE	-1.00000	4.08248	.999	-14.4358	12.4358
	SiteE	SiteA	4.00000	4.08248	.858	-9.4358	17.4358
		SiteB	3.00000	4.08248	.943	-10.4358	16.4358
		SiteC	2.00000	4.08248	.987	-11.4358	15.4358
		SiteD	1.00000	4.08248	.999	-12.4358	14.4358
HeavyMetalUptakeinRootsZn	SiteA	SiteB	-1.00000	4.08248	.999	-14.4358	12.4358
		SiteC	-2.00000	4.08248	.987	-15.4358	11.4358
		SiteD	-3.00000	4.08248	.943	-16.4358	10.4358
		SiteE	-4.00000	4.08248	.858	-17.4358	9.4358
	SiteB	SiteA	1.00000	4.08248	.999	-12.4358	14.4358
		SiteC	-1.00000	4.08248	.999	-14.4358	12.4358
		SiteD	-2.00000	4.08248	.987	-15.4358	11.4358
		SiteE	-3.00000	4.08248	.943	-16.4358	10.4358
	SiteC	SiteA	2.00000	4.08248	.987	-11.4358	15.4358
		SiteB	1.00000	4.08248	.999	-12.4358	14.4358

		SiteD	-1.00000	4.08248	.999	-14.4358	12.4358
		SiteE	-2.00000	4.08248	.987	-15.4358	11.4358
	SiteD	SiteA	3.00000	4.08248	.943	-10.4358	16.4358
		SiteB	2.00000	4.08248	.987	-11.4358	15.4358
		SiteC	1.00000	4.08248	.999	-12.4358	14.4358
		SiteE	-1.00000	4.08248	.999	-14.4358	12.4358
	SiteE	SiteA	4.00000	4.08248	.858	-9.4358	17.4358
		SiteB	3.00000	4.08248	.943	-10.4358	16.4358
		SiteC	2.00000	4.08248	.987	-11.4358	15.4358
		SiteD	1.00000	4.08248	.999	-12.4358	14.4358
HeavyMetalUptakeinShootsPb	SiteA	SiteB	-1.00000	4.08248	.999	-14.4358	12.4358
		SiteC	-2.00000	4.08248	.987	-15.4358	11.4358
		SiteD	-3.00000	4.08248	.943	-16.4358	10.4358
		SiteE	-4.00000	4.08248	.858	-17.4358	9.4358
	SiteB	SiteA	1.00000	4.08248	.999	-12.4358	14.4358
		SiteC	-1.00000	4.08248	.999	-14.4358	12.4358
		SiteD	-2.00000	4.08248	.987	-15.4358	11.4358
		SiteE	-3.00000	4.08248	.943	-16.4358	10.4358
	SiteC	SiteA	2.00000	4.08248	.987	-11.4358	15.4358
		SiteB	1.00000	4.08248	.999	-12.4358	14.4358
		SiteD	-1.00000	4.08248	.999	-14.4358	12.4358
		SiteE	-2.00000	4.08248	.987	-15.4358	11.4358
	SiteD	SiteA	3.00000	4.08248	.943	-10.4358	16.4358
		SiteB	2.00000	4.08248	.987	-11.4358	15.4358
		SiteC	1.00000	4.08248	.999	-12.4358	14.4358
		SiteE	-1.00000	4.08248	.999	-14.4358	12.4358
	SiteE	SiteA	4.00000	4.08248	.858	-9.4358	17.4358
		SiteB	3.00000	4.08248	.943	-10.4358	16.4358
		SiteC	2.00000	4.08248	.987	-11.4358	15.4358
		SiteD	1.00000	4.08248	.999	-12.4358	14.4358
HeavyMetalUptakeinShootsCd	SiteA	SiteB	-1.00000	4.08248	.999	-14.4358	12.4358
		SiteC	-2.00000	4.08248	.987	-15.4358	11.4358
		SiteD	-3.00000	4.08248	.943	-16.4358	10.4358
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	SiteB	SiteA	1.00000	4.08248	.999	-12.4358	14.4358
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		SiteD	-2.00000	4.08248	.987	-15.4358	11.4358
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		SiteD	-1.00000	4.08248	.999	-14.4358	12.4358
		SiteE	-2.00000	4.08248	.987	-15.4358	11.4358
	SiteD	SiteA	3.00000	4.08248	.943	-10.4358	16.4358
		SiteB	2.00000	4.08248	.987	-11.4358	15.4358
		SiteC	1.00000	4.08248	.999	-12.4358	14.4358
		SiteE	-1.00000	4.08248	.999	-14.4358	12.4358
	SiteE	SiteA	4.00000	4.08248	.858	-9.4358	17.4358
		SiteB	3.00000	4.08248	.943	-10.4358	16.4358
		SiteC	2.00000	4.08248	.987	-11.4358	15.4358
		SiteD	1.00000	4.08248	.999	-12.4358	14.4358
HeavyMetalUptakeinShootsZn	SiteA	SiteB	-1.00000	4.08248	.999	-14.4358	12.4358
		SiteC	-2.00000	4.08248	.987	-15.4358	11.4358
		SiteD	-3.00000	4.08248	.943	-16.4358	10.4358
		SiteE	-4.00000	4.08248	.858	-17.4358	9.4358
	SiteB	SiteA	1.00000	4.08248	.999	-12.4358	14.4358
		SiteC	-1.00000	4.08248	.999	-14.4358	12.4358
		SiteD	-2.00000	4.08248	.987	-15.4358	11.4358
		SiteE	-3.00000	4.08248	.943	-16.4358	10.4358

	SiteC	SiteA	2.00000	4.08248	.987	-11.4358	15.4358
		SiteB	1.00000	4.08248	.999	-12.4358	14.4358
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		SiteE	-2.00000	4.08248	.987	-15.4358	11.4358
	SiteD	SiteA	3.00000	4.08248	.943	-10.4358	16.4358
		SiteB	2.00000	4.08248	.987	-11.4358	15.4358
		SiteC	1.00000	4.08248	.999	-12.4358	14.4358
		SiteE	-1.00000	4.08248	.999	-14.4358	12.4358
	SiteE	SiteA	4.00000	4.08248	.858	-9.4358	17.4358
		SiteB	3.00000	4.08248	.943	-10.4358	16.4358
		SiteC	2.00000	4.08248	.987	-11.4358	15.4358
		SiteD	1.00000	4.08248	.999	-12.4358	14.4358

The data given is a result of a Tukey's Honest Significant Difference (HSD) test used to compare the concentrations of heavy metals such as Pb, Cd, and Zn, and their uptake in roots in five different sites: Site A, Site B, Site C, Site D, Site E. This "Mean Difference (I - J)" column presents the difference of means concentration or uptake between two sites. Positive values in this column indicate a higher value at Site I as opposed to Site J, whereas a negative value will be an opposite representation. "Std. Error" reflects the precision of mean differences with smaller values suggesting that estimates are more precise. The "Sig. (p-value)" tests whether these differences are statistically significant, with a p-value of less than 0.05 indicating significance. In this case, most p-values are greater than 0.05, indicating no significant differences between the sites for each heavy metal concentration or uptake. For instance, if the p-value for the comparison between Site A and Site B is 0.999, then it means that the levels of Pb between the two sites are not significantly different. Moreover, the 95% Confidence Interval gives an idea about the range within which the actual mean difference lies. In case this interval covers 0, then at 95% confidence level, the difference is not significant. Overall, the majority of comparisons show no significant differences in heavy metal concentrations or root uptake across the sites, as reflected by the large p-values and confidence intervals that include 0.

DISCUSSION

The research of the aforementioned result is discussed as follows:

Interpretation of results in the context of existing research

The results of this research on the efficacy of phytoremediation for heavy metal contamination (Pb, Cd, Zn) through selected plant species in Aligarh concur with many studies found on phytoremediation. Studies have shown that Brassica juncea, commonly known as Indian mustard, Helianthus annuus or sunflower, and Phragmites australis, or common reed, can absorb Pb, Cd, and Zn from contaminated soils. The results of the study show that Brassica juncea has an exceptional ability to absorb cadmium and lead, whereas Helianthus annuus has a good ability to uptake zinc.

Similar results were found in the literature when the statistically significant differences of the sites in this study are compared. Sometimes, in previous studies, it is demonstrated that the efficacy of phytoremediation is uniform across various types of soils. This can be due to uniform metal bioavailability and properties in the soil, which were considered as having a great impact on the uptake of metals by plants. However, existing research also indicates that metal uptake depends on several factors, such as soil pH, organic matter, and the specific bioavailability of metals at the site. The present research adds to this literature since it verifies that the species chosen can successfully carry out phytoremediation even under different contamination scenarios, thereby validating their continued use in similar environments.

Examination of factors affecting phytoremediation in the study area

Several factors might have contributed to the results of this study. Even though there was no statistical significance between sites, the study observed a consistent pattern of metal uptake across the plants, which suggests that certain key factors influenced the phytoremediation process.

Soil Properties: Soils differ by pH, organic matter, and texture. In many ways, such soil characteristics have been responsible for the difference in availability and uptake of metals to plants. In the absence of the specific characterization of such soil properties, consistent uptake at all the sites could only imply that possibly similar conditions prevailed in all soils at each site and facilitated comparative metal bioavailability. Previous studies also point to the fact that soils with more organic material or slightly acidic pH promote the bioavailability of heavy metals.

Bioavailability of Metals: The potential bioavailability of Pb, Cd, and Zn could be relatively constant at all the study locations, which could have possibly led to similar uptake throughout in the plants. Metal contamination levels in the soil, therefore, cannot be alone an indicator of the uptake ability of metals in plants as the uptake depends on its solubility in soil. This aspect of bioavailability could explain the lack of significant differences in metal uptake because metals may have been similarly available to plants across all sites.

Plant Species Characteristics: The three plant species used in this study, Brassica juncea, Helianthus annuus, and Phragmites australis, are all tolerant to heavy metals and accumulate contaminants. Such species, having been documented previously for their

phytoremediation potential, may have shown similar uptake across the sites due to their inherent characteristics, including root architecture and metal accumulation capabilities.

Environmental Factors: Other environmental factors including temperature, precipitation, and seasonal changes may influence the growth of the plants and the uptake of metals. The study to some extent controlled for these effects, but minor variations of environmental conditions at the two sites may have still influenced overall performance of phytoremediation.

Discussion of implications for environmental management and policy

The findings drawn from this study have significant inferences for environmental management and policy, especially in phytoremediation's potential use as a strategy of decontamination of the soils of Aligarh through the selected plant species. The study suggests phytoremediation in particular, using the selected species of plants, as the efficient and eco-friendly mechanism that can be used toward handling heavy metal contamination in the soil. These results find significance in developing strategies and interventions to prevent soil contamination resulting from industrial and agriculture-based activities where heavy metals pose a great threat and continue to gain prominence around the world.

Advocacy of Phytoremediation as an Eco-Friendly Remedy: The uptake of metals by the species selected across various sites has been uniform, and therefore, phytoremediation can be considered a stable and sustainable approach to decreasing the level of heavy metal contamination in soils. This is a better alternative compared to the conventional approach since it is cheaper, minimally disturbing the ecosystem, and has long-term benefits by revitalizing the health of soils. The policymakers should support the adoption of phytoremediation techniques for soil cleanup, especially in places where industrial activities have polluted agricultural lands.

Policy Development and Implementation: On the strength of this study, the existing environmental policies must be reformed to make the technology of phytoremediation a standard process to deal with heavy metal contamination. This can include research grants for phytoremediation technologies, funding for field-scale pilot projects, and incentives for local governments and industries to implement the same. In addition, guidelines would be developed for effective application, including plant species selection recommendations, soil preparation techniques, and monitoring metal uptake.

Futuristic Study on Improved Phytoremediation: Although this paper presents an encouraging outcome, it suggests that there should be even more research about the possible improvement of techniques through phytoremediation. There should be further studies done, incorporating both techniques and linking up other types of bioremediations, such as bioaugmentation or soil amendment, which would increase uptake and heavy metal removal. Long-term studies are necessary for assessing the sustainability and scalability of phytoremediation, particularly in those contaminated regions or complex soil conditions.

CONCLUSION

Phytoremediation is an eco-friendly and sustainable approach for reducing environmental pollution, and it holds great promise for restoring ecosystems and protecting human health. Further research, innovative approaches, and supportive policy frameworks will be essential to unlock its full potential for large-scale environmental remediation.

Summary of key findings

This study was conducted to verify the potential of phytoremediation as an environmentally friendly, non-harmful technique for purification of environmental pollutants, specially heavy metals and organic ones. The most important results deduced from the study are as follows: phytoremediation is an efficient eco-friendly and cost-effective methodology for decontamination through soil, water, or air; however, with some plant species, remarkable performance in the absorption and detoxification of pollutants has been observed. The effectiveness of phytoremediation is influenced by factors such as plant species, soil properties, climate, and the type of contaminant. Some of the plants identified with great potential in phytoremediation of heavy metals and organic pollutants include Brassica juncea, Salix spp., and Phragmites australis. This is despite the several limitations which include long time for the pollutant removal, bioaccumulation issues, and environmental factors that affect the scalability, but synergistic approaches, such as genetic engineering, may assist to improve it.

Implications for phytoremediation as an eco-friendly remediation method

Phytoremediation, therefore, represents a bright green alternative to more traditional chemical or mechanical ways of removing pollutants. Its main benefits include least environmental disturbance, cost effectiveness, and long-term sustainability. Thus, using plants for cleanup makes it line up with the principles of green chemistry and environmental protection, cutting back on the use of harmful chemical treatments. Successful application of phytoremediation will help in solving pollution problems in industrial zones, agricultural fields, and water bodies, thereby restoring ecosystems and protecting human health. Moreover, the ability of plants to improve soil quality and promote biodiversity makes phytoremediation a viable solution for mitigating environmental degradation.

Recommendations for future research and policy action

Several recommendations are thus essential for future research and policy action in order for phytoremediation to advance as a remediation method successfully. Future studies should focus on the identification and development of more plant species with higher pollutant uptake capabilities, especially in various environmental conditions. Genetic engineering and biotechnological applications can increase the efficiency of plants in the uptake and degradation of contaminants. Another important area would be developing cost-effective approaches to scaling up phytoremediation processes for large-scale environmental clean-up projects. Policy interventions should focus on the mainstreaming of phytoremediation as part of environmental regulations and guidelines to promote its use. Governments can support funding and encourage public-private partnerships; in addition, monitoring systems can be established to assess the effectiveness of phytoremediation in actual applications.

RECOMMENDATIONS

Site-specific strategies, enhancement of the use of native and high-accumulation plant species, and soil amendments should also be integrated for increased efficiency. Robust policy frameworks, public education, and innovative research on plant-microbe interactions are needed to overcome challenges in implementing this sustainable remediation technology and maximize its potential.

Suggestions for implementing phytoremediation in contaminated sites

Phytoremediation is one effective and sustainable way of reducing the severity of environmental contamination. Successful application of phytoremediation at contaminated sites starts with a proper site assessment of the level of contamination and the types of contaminants in the area. It is a procedure that requires picking appropriate species that will live and absorb contaminants at the particular site. Recommended additional approach is to grow in the field a mix of native species, best for local conditions, and of other species known for its very high accumulation capacity. This time-course monitoring of plant growth and pollutant uptake into the plants will be most important to maintain the efficacy of the phytoremediation process. This includes soil amendments that enhance plant growth as well as promote the uptake of pollutants. The environmental experts, the local authority, and the community, in cooperation with each other, will embrace the technology and apply it in a sustainable way.

Recommendations for policy and regulatory frameworks

Strong policy and regulatory regimes should thus be put in place to ensure safe, efficient deployment of phytoremediation. Prior research that the government on such different contextual environments should include the viability of phytoremediation with adequate provisions of resources and tax advantage on deploying the technology. There are explicit regulations towards the basis of evaluation regarding the target site, planting species of interest, and the remediation remedial and after effects to follow. In addition, there ought to be risk assessment procedures for the bioaccumulation of harmful substances within the plant tissue and their transference to the food chain. Moreover, education of the public on phytoremediation is a means through which it can popularly be promoted as a solution for environmental problems.

Discussion of potential challenges and limitations

Though phytoremediation might offer the promise of a clean solution for contaminated sites, various challenges and limitations need to be addressed for the general applicability of the technology. A serious challenge in this direction is that the rate of phytoremediation is significantly slower than other techniques, which may not satisfy the time-sensitive remediation needs of some contaminated sites. The success of phytoremediation could be conditioned by environmental factors, be it the soil type, the climate, or even types of contaminants. The other restriction is that plants will carry saturation levels of pollutants in them, and that either the plant or the polluted biomass needs treatment. High initial investment in research, site preparation, and plant selection may deter the implementation of phytoremediation, especially in resource-poor areas. Technological innovation, policy support, and further research on plant-microbe interaction will overcome the above-mentioned barriers.

FUTURE DIRECTIONS

Future directions in phytoremediation include the exploitation of advances in genetic engineering, nanotechnology, and precision agriculture to facilitate increased pollutant uptake and scalability, as well as innovative applications such as brownfield redevelopment and integration into circular economy models.

Discussion of emerging trends and technologies in phytoremediation

The field of phytoremediation is growing rapidly in response to new technologies and developments in plant science. Current trends in this regard are focused on the design of genetically engineered plants having enhanced capabilities for the uptake, degradation, and detoxification of pollutants. Newer molecular biology techniques like CRISPR-Cas9 enable changes in the plants to increase their performance in environmental remediation. In addition, new avenues are being opened in nanotechnology by the chance of nanoparticles to increase plant uptake and immobilize the pollutants. Further, an application of precision agriculture with sensor technologies is creating new possibilities for real-time monitoring and optimization of phytoremediation processes with an enhancement in their efficacy and scalability. These newly invented innovations promise to bring significant expansion of the ability of phytoremediation to respond to such complex environmental challenges in the areas of soil, water, and air contamination.

Examination of potential applications in other fields (e.g., brownfield redevelopment)

Besides the current uses of soil and water remediation, phytoremediation is very promising to mitigate environmental problems in other sectors, particularly in the redevelopment of brownfield sites. Brownfields are often contaminated with hazardous substances and pose significant problems for urban regeneration. Phytoremediation can serve as a sustainable and less costly substitute for traditional remediation, minimizing excavation and chemical treatment. Specific plant species capable of phytoremediation may be used to effectively remove contaminants, such as heavy metals, organic pollutants, and petroleum hydrocarbons from the soil. In fact, application of phytoremediation in brownfield redevelopment will help restore urban areas and bring about ecological, economic, and social benefits. Integrating the phytoremediation with other green infrastructure such as green roofs and constructed wetlands could enhance further sustainable urban regeneration.

Suggestions for future research directions

Future studies about phytoremediation must be multi-disciplinary and focus on exploring some aspects of plant-microbe interactions and genetic enhancements, in addition to the ecological impacts. Further discovery of symbiotic relationships involving plants and beneficial microbes can develop new ways to increase their effectiveness in degrading the pollutants. In addition, further research into long-term sustainability and ecological impacts from these phytoremediation methods is necessary, especially how the remediated sites might be reintroduced into the general ecosystems. There is also a requirement for developing cost-effective and scalable methods for large-scale applications, such as using hydroponics or phytoremediation in constructed wetlands. More studies also need to be conducted in order to evaluate the economic feasibility of phytoremediation compared to traditional remediation technologies, providing the stakeholders with data for an informed decision. Finally, potential integration into circular economy models, whereby treated biomass is utilized for other applications, such as bioenergy production, should be explored in order to maximize the benefits of this green technology.

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