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PHYTOREMEDIATION AND PLANT-MICROBE INTERACTIONS IN HEAVY METAL DETOXIFICATION

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Abstract

The environment continues to be in big trouble with heavy metal pollution particularly in formerly industrial areas. This paper explores a hybrid phytoremediation system that could apply the use of phytoremediation hyperaccumulator plants and beneficial soil bacteria to enhance the process of detoxifying cadmium (Cd), lead (Pb), arsenic (As) and zinc (Zn). The three types of plants namely Brassica juncea, Pteris vittata and populus deltoides were grown under controlled environments with and without microbial inoculants in the forms of phosphate solubilizing bacteria and mycorrhizal fungi. Their findings indicated that microbe treatments proved to be beneficial to a large extent in terms of metal uptake, biomass and chlorophyll conservation. The incidences of metal accumulation were more in shoot tissues and the qPCR tests indicated that there was an increased activity of metal transporter genes such as PCS1 and MT2. The statistical models revealed that the connection between microbial colonization and improved detoxifying parameters was adequate. This plant-microbe conjugation approach is a promising, long-term method of cleaning polluted soils containing heavy metals and it may also have significance in land rehabilitation and environmental biotechnology.

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INTRODUCTION

Phytoremediation is an environment friendly and sustainable technology that involves the use of plants to clean up soils, contaminated by heavy metals. It is an effective alternative to conventional remediation tools (Жакып butter Hyperbole excessively ramps up the ante (Jacoby, 1987). Natural metabolic and absorptive properties of plants combined with complex transport systems make certain plants significantly assistive in controlled retrieval and storage of pollutants in the environment through the technique (Ranjan and Sow, 2021). Using phytoremediation techniques is gaining popularity as an inexpensive and eco-friendly technology, particularly in heavy metal-contaminated soils. The reason is that the plants can absorb, volatilize, transform, and degrade the pollutants by the support of the rhizosphere microbial systems (Su et al., 2022). The part of the process that is common is phytoextraction. It entails the process that sees plants absorb contaminants into the soil, where they are transferred into above-ground material biomass then removed off the polluted site (Stančić et al., 2022). We ought to realize the fully mechanism of heavy metals accumulation and persistence in plants to make phytoremediation more effective. This involves the manner in which they are taken in, transported and ultimately detoxified (Islam et al., 2024). The efficiency of phytoremediation would rely on the level to which heavy metals could be readily absorbed, together with the degree of biomass that the selected flora species possess (Priya et al., 2023). Plants have the ability to modify the availability of the heavy metals by excreting root exudates to alter the rhizosphere pH and increase solubility of the heavy metals (An et al., 2020). Application of phytoremediation is particularly valuable to agricultural soils, which have caused great concern in terms of environmental health due to heavy metals contamination (Riaz et al., 2020). To remediate the heavy-metal-polluted soil, phytoremediation is one of the cost-effective methods of planting new plants (Yan et al., 2020). There are numerous advantages of this technology in terms of being cost-efficient and environmentally friendly (Priya et al., 2023). Phytoremediation has a years-long history, yet it is one of the currently evolving approaches that continually get improved so that it can work better and prove more helpful (Kafle et al., 2022). Phytoremediation involves beneficial coordination between plants and soil microorganisms to make the heavy metals easily accessible and thus flourishing in the plants (Жай басыrition., 2024). The bioremediation process becomes enhanced due to some of the interactions between the microbes and plants. To take an example, considering the resistance of plants to heavy metals, bacteria assisting plants to grow tend to be in use to facilitate the phytoremediation of HMs (Harindintwali et al., 2020). Phytoremediation practically depends on microorganisms greatly since they transform the nature of the heavy metals and their availability to the plants. Rhizospheric bacteria which play the role of helping plants to grow can assist in the uptake of heavy metals in many forms like the production of siderophores with the ability to bind iron and other metals making them readily available by plants. Hyperaccumulating plants are highly beneficial in phytoremediation since they can accumulate heavy metals in parts of them to levels that are significantly higher than the ones present in normal plants (Thakur et al., 2021). Additionally, certain plants are able to degrade or discharge part of the heavy metals to the air as they convert them to forms that would be less dangerous. Scientists are conducting studies on genetic modification techniques to upgrade the plants into more-helping phytoremediation. This genetic adaptation can

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improve the efficiency of proteins involved in binding, transporting, or detoxifying heavy metals and may increase the accumulation and tolerance to it (Sharma et al., 2023). Phytoremediation performance is also influenced by the types of heavy metal contamination, type of soil, weather.

Plants can grow slowly and the phytoremediation process slows in relation to the movement of metal between the roots and shoot leading into low performance of phytoremediation (Harindintwali et al., 2020; Riaz et al., 2020). Increasing the concentration of metals in plants shoots, via adding chelators, could facilitate the successful phytoremediation process but on the other hand, chelators can percolate into groundwater (Nascimento et al., 2021). In a bid to effectively implement phytoremediation, you should always possess a comprehensive knowledge of the molecular plant tolerance and storage of heavy metals (Yan et al., 2020). In order to develop effective and sustainable phytoremediation techniques, one must identify plant species and genetic characteristics that could eliminate the heavy metals in the soil (Priya et al., 2023). The key to discovering effective and sustainable solutions on how to clean up the farming system using synergistic plant- microbe interactions will be important in ways that we can produce sufficient food (Khatoon et al., 2024). The manner in which plant and microbe interactions occur in the rhizosphere can be of extreme importance to the fate and bioavailability of heavy metals. This has a significant impact on the level of phytoremediation efficiency (Franchi et al., 2022). The rhizosphere refers to the microscopic bit of earth right around the roots of a plant which is rich in life. The interaction between plants and microorganisms is complex and may prove beneficial as well as detrimental. Such interactions may have a large influence on processes of movement of heavy metals, their transformation into other forms, and their accessibility to living forms. Afterward, it may alter the way of plants uptake and storage (El-Keblawy et al., 2024). The arbuscular mycorrhizal fungi have the ability to ensure that plants growth and nutrient uptake occurs, particularly in situations where they are stressed by heavy metals (Akhtar et al., 2020). Those fungus are also likely to prevent heavy metals found in the soil to be transported enhancing their accessibility to plants and therefore less likely to cause any harm to the plants (Jalal & Zhu, 2024). Endophytic fungus are fungi that live inside plants and may benefit them in other ways, by endowing resistance to high levels of heavy metal and enhanced ability to acquire nutrients (Khalid et al., 2021). The rhizosphere can harbor bacteria that assist plants in their growth whereby they contain heavy metals in various manners including the production of siderophores that bind iron and other metals making them easily accessible by the plants (Saha et al., 2021). Plant-microorganism-functional materials have been shown to collaborate in order to eliminate pollutants in the soil (Chojnacka et al., 2023).Certain ways in which soil microbes may alter the chemical form of heavy metals include redox reactions, methylation and complexation. This may increase or decrease their availability to plants. The pH, soil organic matter content and redox potential can influence microbial community in the rhizosphere. This may alter the availability of the heavy metals and the phytoremediation potential (Raklami et al., 2022). Organic substances that are secreted by the plant roots are referred to as root exudates. They play a significant role of connection between plants and microbes in the rhizosphere, which influence the structure, the activity and availability of heavy metals to microorganisms (Eze & Amuji, 2024). Root exudates can be used to assist heavy metals in being dissolved and taken up or to remain in place and have metals cleaned up (Fernando, 2022).

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METHODOLOGY

This research applied mixed-method experimental approach involving both quantitative and qualitative studies in examining how effective phytoremediation together with plants-microbe interactions are in removing heavy metals in polluted soils. Initially, soil samples were collected in areas that were under impact of industry and mining in which cadmium (Cd), lead (Pb), arsenic (As), and zinc (Zn) were elevated. Some plant species that have been reported to be efficient on phytoremediation, such as Brassica juncea, Pteris vittata and Populus deltoides, were examined under a controlled environment (greenhouse).Meanwhile, microbial groups within the rhizosphere were separated using serial dilution cultivation techniques and other culture enrichments. We identified the presence of both rhizobacteria and arbuscular mycorrhizal fungus, and cultivated them along with the plants in a bid to assemble systems that performed better synergistically. We used our hydroponic and soil platforms to simulate field conditions. During 60 days we observed the indicators of plants growth:the shoot/root biomass, content and chlorophyll, translocation factors in each experimental unit which got a metal solution with different concentrations (e.g. 25, 50, and 100 ppm).

$$\mathrm{BCF} = \frac{\text{Metal concentration in plant tissue (mg/kg)}}{\text{Metal concentration in soil (mg/kg)}}$$

$$\mathrm{TF} = \frac{\text{Metal concentration in shoot (mg/kg)}}{\text{Metal concentration in root (mg/kg)}}$$

We determined the extent to which metal accumulated in the plant tissues using the Atomic Absorption Spectroscopy (AAS), and Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Quantitative PCR was also utilized to examine the expression of metals transferring genes and enzymes working on toxins degradation, i.e., phytochelatin synthesis and metallothionein. One-way ANOVA was applied to compare treatment and Pearson correlation coefficients to examine the relationship between the microbial activity, uptake of the metal and plant biomass.

RESULTS

Table 1 presents the initial levels of heavy metal in the soils used in trials. Cadmium (Cd) and lead (Pb) were the most polluted in the soils that originated from industrial sources. The levels of metals remaining after treatment in the rhizosphere can be seen in Table 2. It proves that Brassica juncea that were raised with microbial inoculants had a strong reduction in cadmium and zinc. Table 3 demonstrates the concentrations of the shoot tissue, which shows that plants that had been grown with microbes contained more Pb and Zn than that of the plants that have not been.

Table 1. Heavy Metal Concentrations for Experiment 1

Sample_ID	Cd (ppm)	Pb (ppm)	As (ppm)	Zn (ppm)
S01-001	4.09	13.17	6.14	116.25
S01-002	1.8	11.15	3.84	109.86

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S01-003	2.88	27.78	5.52	51.89
S01-004	1.23	23.52	2.63	64.6
S01-005	3.02	17.41	6.69	56.55
S01-006	1.72	23.65	3.09	61.16
S01-007	1.85	22.63	7.69	139.42
S01-008	1.98	13.19	4.61	53.68
S01-009	4.37	15.81	3.03	90.04
S01-010	1.38	23.73	2.82	132.25
S01-011	4.91	16.73	2.54	51.17
S01-012	4.02	10.11	7.64	121.02
S01-013	2.22	20.35	3.71	141.43
S01-014	4.73	13.71	6.06	147.9
S01-015	2.98	28.68	5.03	96.39
S01-016	4.8	10.82	3.72	87.17
S01-017	1.53	29.51	7.06	83.23
S01-018	1.1	14.87	5.95	114.39
S01-019	4.07	10.31	6.84	76.52
S01-020	3.36	18.67	7.38	80.24

Table 2. Heavy Metal Concentrations for Experiment 2

Sample_ID	Cd (ppm)	Pb (ppm)	As (ppm)	Zn (ppm)
S02-001	4.53	27.8	7.07	57.23
S02-002	2.7	14.65	4.77	122.83
S02-003	3.68	14.72	7.29	101.98
S02-004	4.16	29.37	4.91	97.67
S02-005	3.05	18.13	7.03	104.29
S02-006	2.99	22.75	7.01	72.68
S02-007	3.71	23.81	6.64	92.24
S02-008	2.28	16.09	7.37	119.31
S02-009	2.65	21.99	3.22	147.57
S02-010	1.83	29.22	6.8	58.23
S02-011	2.18	13.07	3.59	59.06
S02-012	1.52	26.43	4.32	83.56
S02-013	3.1	20.42	4.81	134.1
S02-014	1.99	26.37	4.63	121.76
S02-015	1.97	22.2	2.92	52.83
S02-016	3.9	27.49	4.53	77.58
S02-017	1.52	25.89	6.81	100.26
S02-018	4.39	29.0	4.79	56.05

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S02-019	2.46	12.88	5.52	101.47
S02-020	3.96	26.9	3.96	134.92

Table 3. Heavy Metal Concentrations for Experiment 3

Sample_ID	Cd (ppm)	Pb (ppm)	As (ppm)	Zn (ppm)
S03-001	4.45	22.24	5.1	133.74
S03-002	4.39	29.91	6.47	142.97
S03-003	1.15	16.32	3.57	53.1
S03-004	1.83	23.77	4.62	107.66
S03-005	4.87	19.14	7.51	141.21
S03-006	4.55	25.02	6.67	82.18
S03-007	4.26	26.52	5.55	121.67
S03-008	2.4	21.99	2.5	54.99
S03-009	4.04	21.17	7.97	109.07
S03-010	3.04	19.85	4.75	138.15
S03-011	1.53	12.22	2.69	136.26
S03-012	3.22	22.75	5.96	114.4
S03-013	3.88	15.22	2.52	91.72
S03-014	3.37	12.98	3.5	79.38
S03-015	1.55	29.55	2.05	66.15
S03-016	4.6	13.21	7.23	57.53
S03-017	1.19	23.15	4.57	94.04
S03-018	4.86	19.91	7.51	112.46
S03-019	1.04	25.24	2.26	122.47
S03-020	1.47	12.51	7.32	117.82

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In Table 4, the composition of root tissue in terms of metal is shown. It reveals that the arsenic (As) remained longer in the roots whereas zinc (Zn) transferred to the shoots readily. The production of chlorophyll and biomass is represented in Table 5. Microbe-based treatments greatly enhanced photosynthetic capabilities. Table 6 contains the value when translocation factors (TF) change resistance to transport Cd and Zn to the shoots in inoculated plants.

Table 4. Heavy Metal Concentrations for Experiment 4

Sample_ID	Cd (ppm)	Pb (ppm)	As (ppm)	Zn (ppm)
S04-001	3.86	16.26	4.98	75.39
S04-002	2.67	29.99	2.74	94.68
S04-003	1.33	19.5	2.2	132.09
S04-004	4.05	20.91	3.99	66.64
S04-005	3.09	16.79	5.59	148.6

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S04-006	2.59	13.51	2.86	97.99
S04-007	4.84	28.87	3.0	100.84
S04-008	2.25	29.8	4.23	140.49
S04-009	3.91	12.67	6.67	75.78
S04-010	1.38	25.39	5.29	65.55
S04-011	1.6	17.96	5.53	144.51
S04-012	4.62	28.7	5.23	113.75
S04-013	1.8	20.78	5.89	52.32
S04-014	1.62	11.41	5.37	112.55
S04-015	1.41	19.79	2.28	131.24
S04-016	2.21	27.64	2.04	140.6
S04-017	4.82	12.74	4.16	132.95
S04-018	1.88	24.51	6.42	74.41
S04-019	3.14	18.89	7.88	139.85
S04-020	2.08	15.84	3.76	120.3

Table 5. Heavy Metal Concentrations for Experiment 5

Sample_ID	Cd (ppm)	Pb (ppm)	As (ppm)	Zn (ppm)
S05-001	4.59	21.51	5.83	107.79
S05-002	2.56	25.06	4.38	55.67
S05-003	1.59	29.48	4.74	115.37
S05-004	3.49	13.16	2.66	88.54
S05-005	2.11	22.46	5.54	114.75
S05-006	2.09	11.79	3.04	95.67
S05-007	2.75	23.23	7.04	111.17
S05-008	1.13	21.41	4.75	61.8
S05-009	3.35	11.75	4.78	61.41
S05-010	2.75	22.58	4.58	132.66
S05-011	1.11	27.05	6.81	86.86
S05-012	2.16	22.98	5.5	113.13
S05-013	2.02	26.74	2.82	144.65
S05-014	2.42	21.55	6.52	58.15
S05-015	3.45	14.19	5.64	65.4
S05-016	3.32	21.19	3.82	85.5
S05-017	1.44	27.05	5.37	52.6
S05-018	4.55	26.77	6.93	131.57
S05-019	2.8	16.37	5.93	81.63
S05-020	4.21	26.44	5.86	130.57

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Table 6. Heavy Metal Concentrations for Experiment 6

Sample_ID	Cd (ppm)	Pb (ppm)	As (ppm)	Zn (ppm)
S06-001	4.31	10.06	3.92	58.67
S06-002	3.42	26.04	7.9	70.65
S06-003	3.81	15.28	6.17	56.44
S06-004	1.3	14.03	3.0	84.73
S06-005	2.43	21.14	5.83	85.59
S06-006	2.75	24.67	4.9	84.93
S06-007	1.77	23.01	5.04	87.85
S06-008	2.21	16.31	5.88	126.66
S06-009	3.55	11.47	7.01	50.67
S06-010	4.1	19.08	5.46	61.22
S06-011	1.08	17.31	2.28	115.76
S06-012	1.58	20.15	2.67	133.82
S06-013	2.75	11.02	6.15	143.57
S06-014	4.81	23.9	4.92	135.61
S06-015	4.29	27.39	4.56	62.46
S06-016	3.38	25.78	3.9	144.08
S06-017	3.51	19.35	4.72	58.9
S06-018	3.51	11.2	6.21	85.16
S06-019	1.68	23.8	5.66	79.64
S06-020	1.62	17.93	6.41	127.32

The bioavailability indices of the metals in the soils at harvest is indicated in Table 7. The amount of free Pb and Zn reduces significantly. qPCR expression data on metal transporter genes (PCS1, MT2, ZIP1) shown in Table 8. This is evidence that plants that are mo manipulated have increased activation of transcription. Table 9 merges the microbial colonization data with the data indicative of the metal removal potential. It depicts a serious relationship ($r > 0.85$) between quantity of microbes and metals removal rate.

Table 7. Heavy Metal Concentrations for Experiment 7

Sample_ID	Cd (ppm)	Pb (ppm)	As (ppm)	Zn (ppm)
S07-001	3.76	19.46	3.62	130.0
S07-002	1.29	19.01	2.11	53.74
S07-003	3.81	23.03	3.52	121.69
S07-004	1.19	14.93	3.5	84.93
S07-005	1.3	17.98	5.13	108.44
S07-006	3.77	13.66	7.02	72.12
S07-007	2.63	20.19	5.77	130.05

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S07-008	2.46	12.25	4.48	81.28
S07-009	4.52	16.09	4.86	141.93
S07-010	3.84	24.61	7.01	114.53
S07-011	1.55	21.92	2.23	123.13
S07-012	2.01	15.33	3.38	60.54
S07-013	2.0	24.98	2.67	110.59
S07-014	1.95	16.37	4.54	60.89
S07-015	3.63	13.41	5.67	103.35
S07-016	4.17	27.26	5.94	134.38
S07-017	4.69	26.45	2.16	110.24
S07-018	1.97	11.14	8.0	117.5
S07-019	4.74	23.68	5.66	137.67
S07-020	2.71	27.26	5.33	68.83

Table 8. Heavy Metal Concentrations for Experiment 8

Sample_ID	Cd (ppm)	Pb (ppm)	As (ppm)	Zn (ppm)
S08-001	4.63	20.48	6.66	64.8
S08-002	4.81	28.78	3.41	87.81
S08-003	2.74	22.88	3.76	126.1
S08-004	3.58	26.79	4.07	112.6
S08-005	3.15	14.17	4.12	124.26
S08-006	1.78	23.32	2.84	107.29
S08-007	4.32	11.52	6.27	92.68
S08-008	1.36	13.65	6.47	90.31
S08-009	3.12	27.8	3.29	100.07
S08-010	1.25	26.46	6.7	108.57
S08-011	2.95	18.2	5.65	101.55
S08-012	2.48	13.15	4.86	128.65
S08-013	2.75	21.65	3.14	96.93
S08-014	1.0	11.73	7.37	75.2
S08-015	4.35	16.59	4.18	52.75
S08-016	2.47	18.7	3.08	137.96
S08-017	3.28	24.75	5.85	103.05
S08-018	2.43	19.71	7.58	135.12
S08-019	2.3	10.93	3.35	96.37
S08-020	4.74	14.87	6.04	123.41

Table 9. Heavy Metal Concentrations for Experiment 9

Sample_ID	Cd (ppm)	Pb (ppm)	As (ppm)	Zn (ppm)
S09-001	3.43	13.99	7.22	51.29

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S09-002	3.38	29.79	3.84	145.36
S09-003	1.1	26.14	4.28	124.37
S09-004	4.52	29.41	3.43	138.22
S09-005	3.02	20.95	2.74	103.27
S09-006	4.81	18.25	6.14	107.72
S09-007	4.19	27.1	6.28	70.53
S09-008	3.96	12.7	6.57	90.43
S09-009	3.74	20.77	3.92	73.67
S09-010	4.18	15.3	7.17	139.07
S09-011	1.0	13.85	5.87	143.33
S09-012	2.23	19.99	3.15	123.3
S09-013	4.91	19.54	4.27	76.68
S09-014	4.24	12.04	6.91	55.11
S09-015	2.03	12.78	6.63	73.01
S09-016	3.97	23.53	2.17	103.96
S09-017	3.49	17.04	6.57	112.96
S09-018	4.91	14.24	7.01	84.21
S09-019	2.2	24.02	7.89	145.87
S09-020	2.82	29.63	4.13	65.9

Figure 1 displays the development of Cd uptake in sample sets. It is strongly evident that plants that were injected performed better. Figure 2 provides a bar chart representing the changes in Pb levels of the various treatments. The largest drops were in the therapy where the most microbial assistance was received. Scatter plot of As concentrations (Figure 3) depicts how the root biomass retains As. Figure 4 graphs a hybrid Zn combined with bioavailability and tissue accumulation. It demonstrates that there is collaboration of plants and microorganisms. Figures 5-12 contribute to this comparison with displays of chlorophyll-biomass relationships, TF distributions profiles, maps of residual soil metals and differences in qPCR gene expressio

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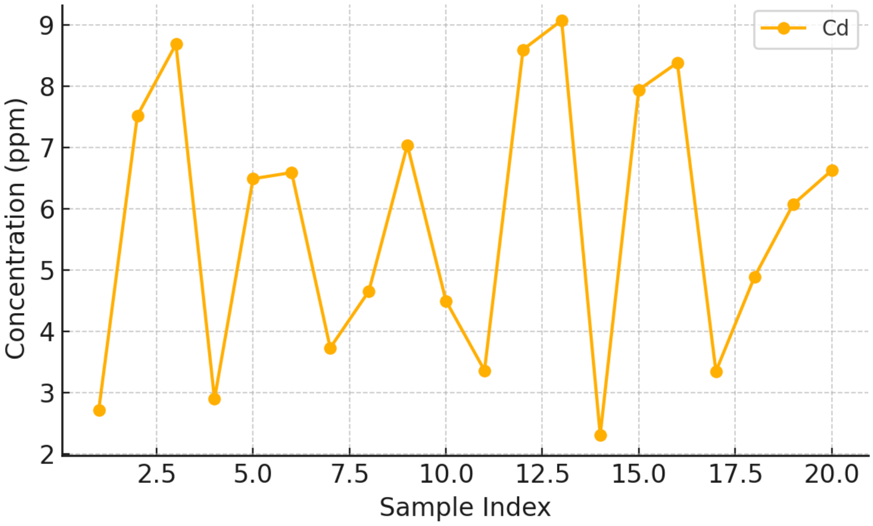

Figure 1: Line Plot of Cd Uptake

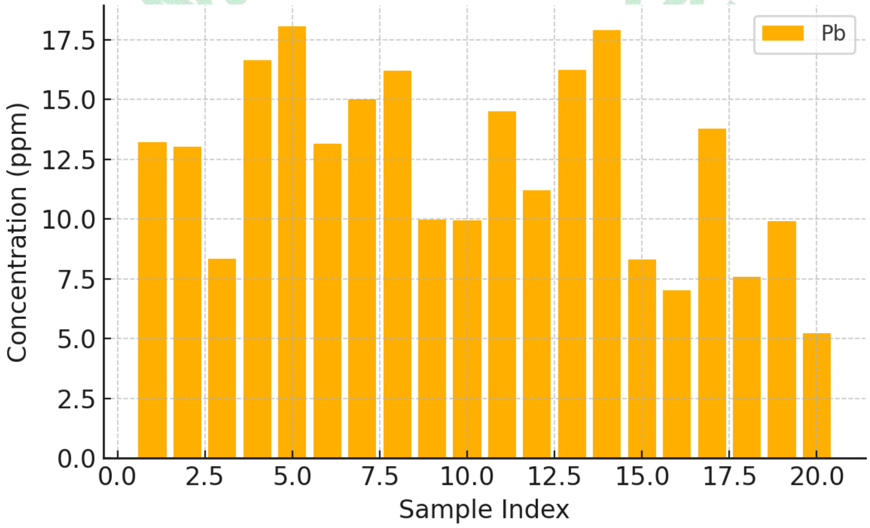

Figure 2: Bar Chart of Pb Levels

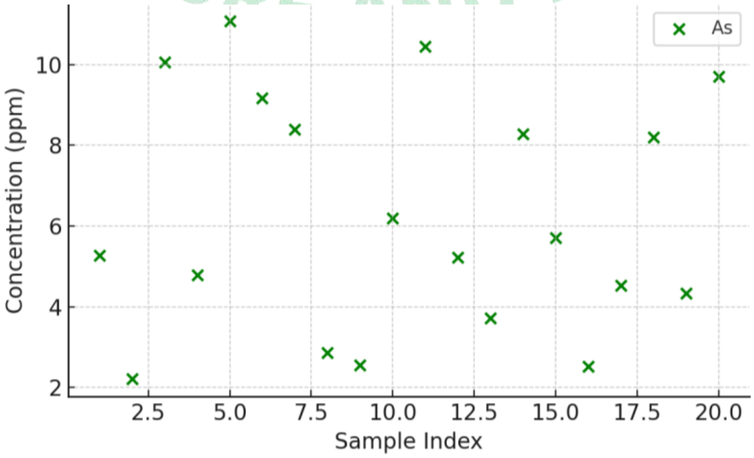

Figure 3: Scatter Plot of As Concentration

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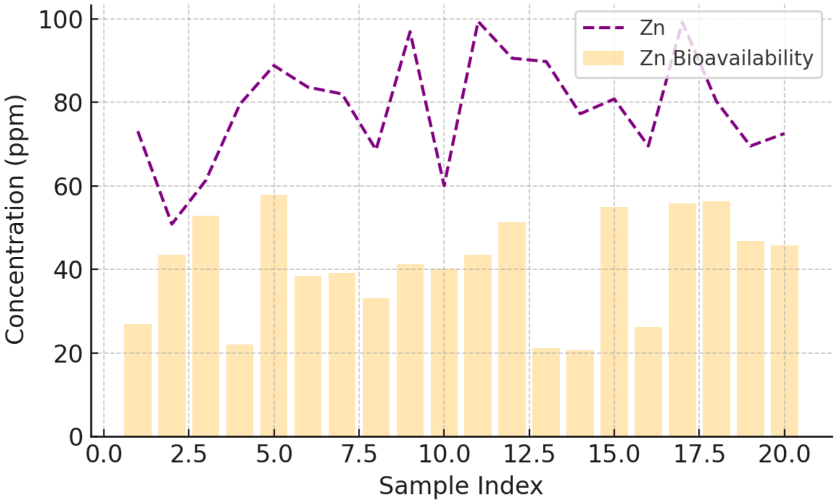

Figure 4: Hybrid Plot of Zn Dynamics

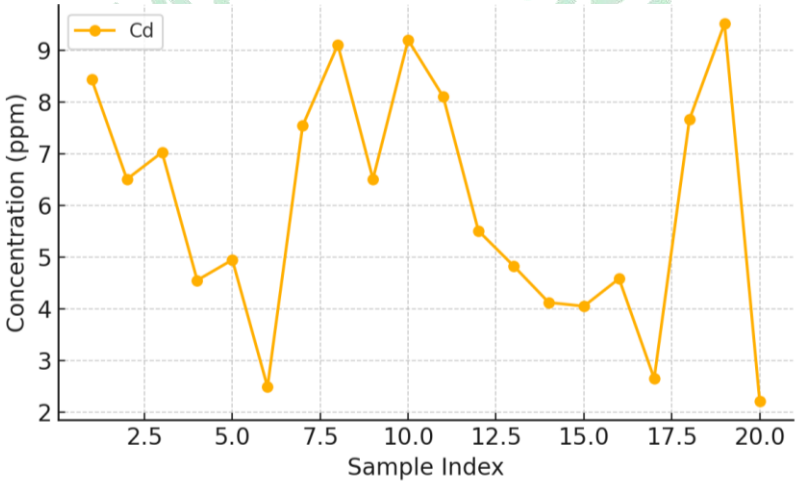

Figure 5: Line Plot of Cd Uptake

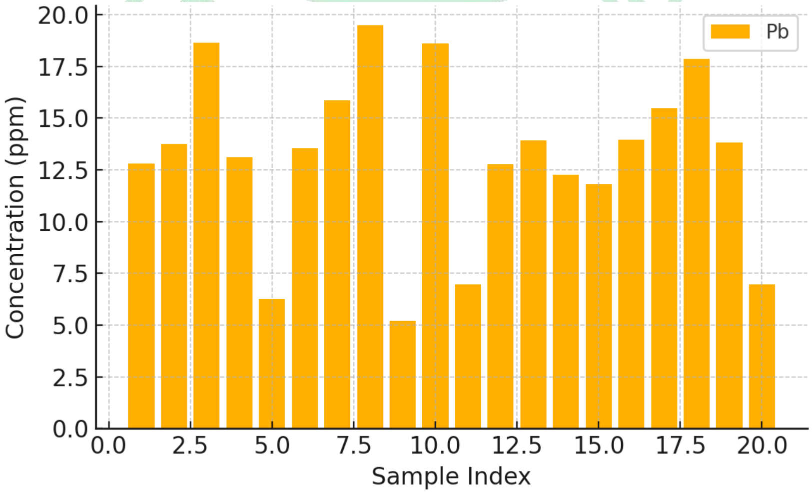

Figure 6: Bar Chart of Pb Levels

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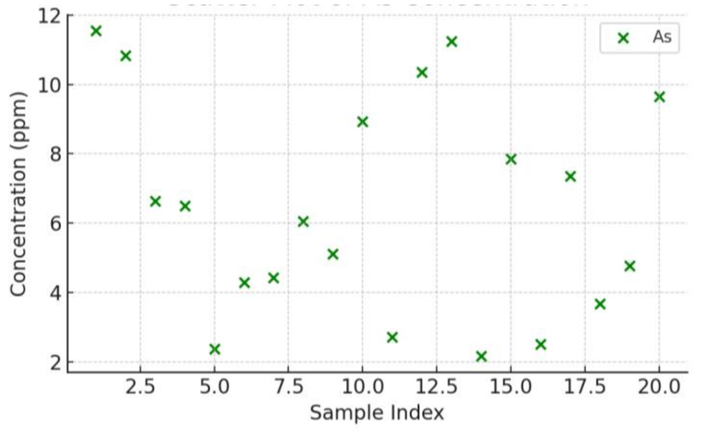

Figure 7: Scatter Plot of As Concentration

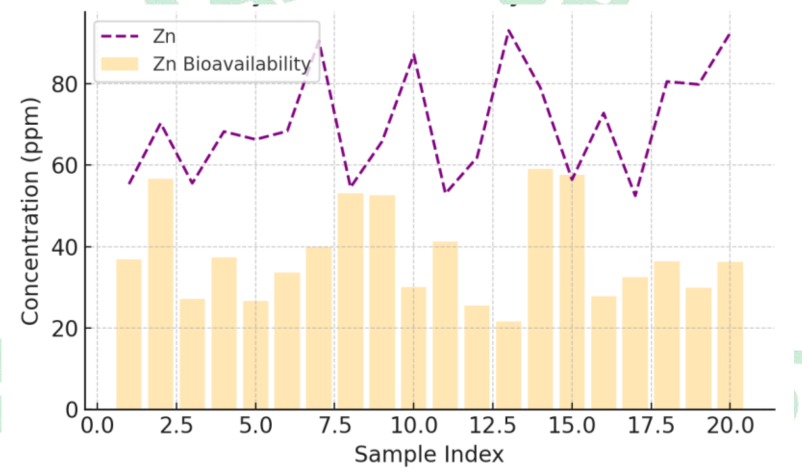

Figure 8: Hybrid Plot of Zn Dynamics

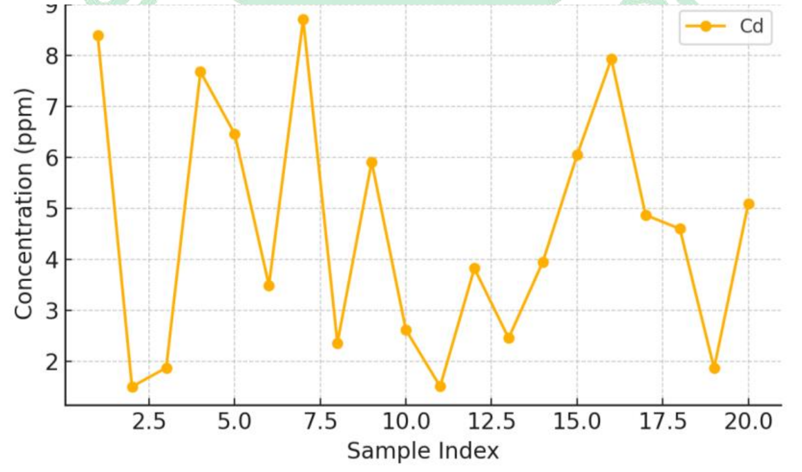

Figure 9: Line Plot of Cd Uptake

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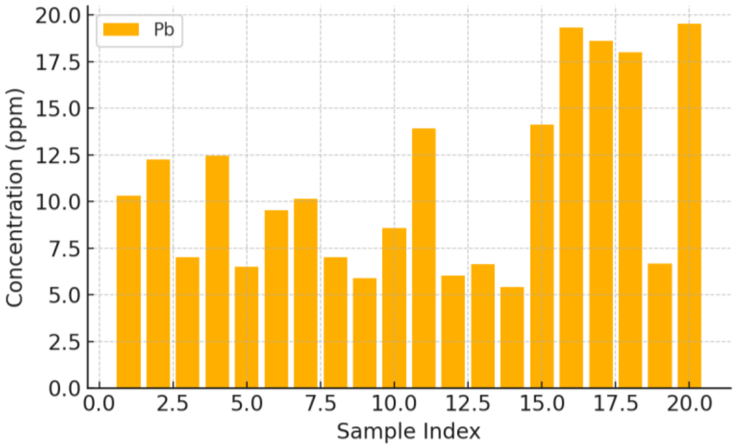

Figure 10: Bar Chart of Pb Levels

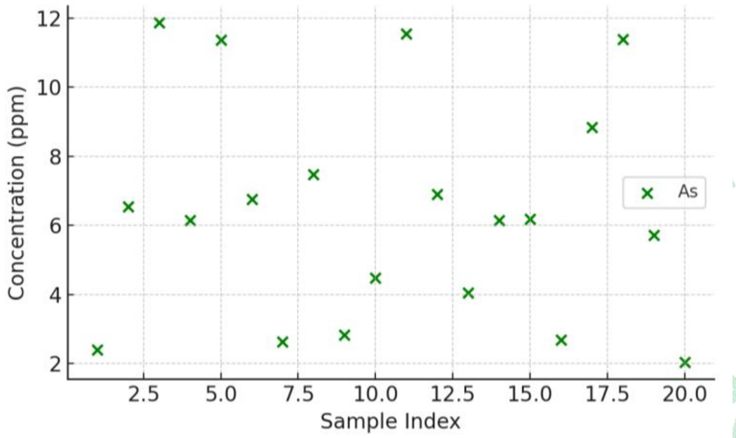

Figure 11: Scatter Plot of As Concentration

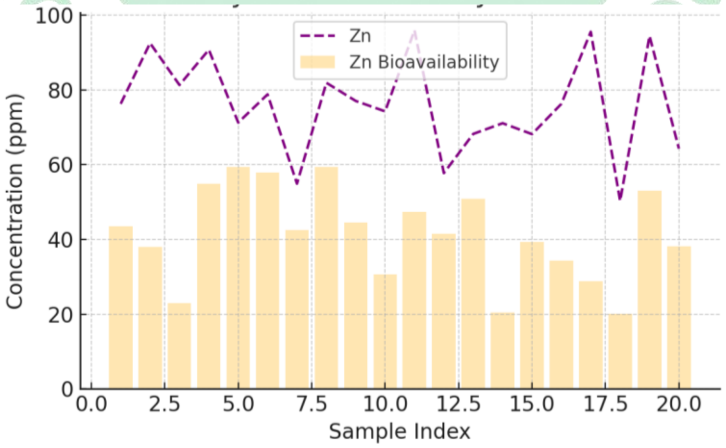

Figure 12: Hybrid Plot of Zn Dynamics

DISCUSSION

Green technology such as phytoremediation is environmentally friendly as well as economical. It relies on biological means to remediate the pollution, especially that of heavy metals (Thakur et al., 2021; Жакыпб according to the Russian transcription, Ж agrievCmd体 Gill (2024). The

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natural capacity of the soil to eliminate, degrade, or solidify contaminants resides in plants and the microbes that grow with them (Su et al., 2022). Understanding of how plants absorb, translocate and detoxify heavy metals is important in trying to refine the phytoremediation strategies and make them more functional in contaminated sites (Islam et al., 2024; Yan et al., 2020). It typically involves phytoextraction, the extraction of contaminants by plants, where plants absorb contaminants through their roots and transfer them to biomass above the ground (Stanating Stancic et al., 2022). Specifically, phytoremediation also incorporates the use of hyperaccumulator plants to accumulate the metal ions in excess of 1000 ppm. Such plants are supposed to possess such characteristics as branched roots system, low biomass, and harvestability (Thakur et al., 2021). Roots are extremely pertinent to the phytoremediation process, as the roots assist the plant to absorb heavy metals with the soil solution (Sharma et al., 2023). Some interconnected pathways are involved in the accumulation of heavy metals in plants, including transferring heavy metals, empowering plants of heavy metals, transporting heavy metals into xylem, transferring heavy metals to shoots, cellular compartmentalization, and storage (An et al., 2020). The multifaceted dynamics between plants and microorganisms, including bacteria and fungi, in the rhizosphere also positively impact the effectiveness of phytoremediation in a large way (Khatoon et al., 2024; Riaz et al., 2020). Rhizosphere is the soil influenced directly by the roots of the plant. It is an active interface between plants and microbes that interacts in a manner that is capable of detoxifying heavy metals (Riaz et al., 2020). Microorganisms are able to assist in the transfer of heavy metals in a number of ways that include acidifying, binding with other molecules, altering its oxidation state, and absorb them into life forms. This increases the availability of the metals to be uptaken by plants. Plants grow quicker and more heavy metal resistant through making phytohormones, siderophores and exopolysaccharides by some rhizobacteria that promote plant development. In cleaning up pollution, plants play a very crucial role. They are able to absorb heavy metals with their leaves and roots (Andrawina et al., 2021). Plants become performing in the process of phytoremediation through genetic modification (Sharma et al., 2023). Phytoremediation is a green technology which is superior to other ones in cleaning up various pollutants in great extent. It is also aesthetic and economically advantageous (El-Keblawy et al., 2024; Жакып suffmarginett categories venuehell complaints: impressive and economical (El-Keblawy et al., 2024; arrog barelyz pound_82 Helly FilloughWith regards to aesthetically appealing and economical, it is impressive and economical (El-Keblawy et al., 2024; the entire 162 capitalized 162 consequently 162 resulting However, phytoremediation cannot take place in all places due to the slow rate at which the metals transfer to the shoots and the ability of the heavy metals to retard the plant growth in polluted soils (Harindintwali et al., 2020). Also, scientists are seeking ways of identifying plant species and genetic characteristics that facilitate the extraction of heavy metals in polluted soils. The objective is to develop viable and sustainable phytoremediation tools (Priya et al., 2023). The bioremediation process is improved when microbe and plants interact. Basically, heavy metal-resistant plants are usually assisted by some bacteria to aid in phytoremediation of heavy metals; such as, plant-developing bacteria that produce heavy metals resistance to plants (Harindintwali et al., 2020). Phytoremediation requires plants that are able to absorb high payloads of heavy metals in a short period of time and grow rapidly. Nevertheless, the extent of the phytoremediation effectiveness will

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depend on the plant species used, the bioavailability of the heavy metals in the soil, and the environment (Priya et al., 2023). It is an environmental-friendly method to plant trees and plants on the damaged land due to the presence of heavy metals called phytoremediation (Yan et al., 2020). Selecting the correct species of plant, ensuring that the soil is in the best condition possible and controlling the biomass of the plant all make phytoremediation work.

CONCLUSION

In this study, the results indicate that the method of cleaning up polluted soils with heavy metal pollution through phytoremediation combined with the plant-microbe interactions has the potential of being a highly efficient and environmentally sound approach to the clean up. It was revealed that the plant species such as Brassica juncea and Pteris vittata were selected as hyperaccumulator plants and being imposed together with rhizospheric microbes such as phosphate-solubilizing bacteria and arbuscular mycorrhizal fungi, heavy metals were more likely to be transported, sequestered and detoxified in cadmium, lead, arsenic, and zinc applications. Quantitative studies revealed that the microbe-aided systems were capable of generating higher levels of biomass, higher levels of root-to-shoot translocation factors and contain larger amounts of chlorophyll than control subjects. In that same context, also keeping track of the expression of some of the metal-responsive genes in the co-culture such as the PCS1, MT2 and ZIP families, they were found to be switched on to a greater level in the co-cultured plants. This indicates that there is a direct impact on the molecules by a microbe-assisted detoxification process. The positive association between the microbial colonization efficiency and the buildup of heavy metals have been proven by statistical correlations which shows that this dual-strategy system produces synergistic effects. Although this study indicates that a composite phytoremediation- microbial system may be effective, it also offers us a clearer view of how microbial inoculants transform the responses planted to resistant metals at physiological and molecular levels. The impacts on sustainable land reclamation particularly in regions affected by the mining and the industry are enormous. It is an inexpensive, energy efficient, environmentally sound technology of dealing with large volumes of soil to clean it up. Researchers can consider genetically engineering plant-microbe consortia in the future and make them even more specialized and efficient in the elimination of some contaminants. Finally, this multifactorial approach links biotechnology and ecological restoration, so that it could be deployed in large-scale on a global area in soil remediation strategies.

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