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Original Article

Microbial-Based Remedial Mechanism for Chromium-Contaminated Soil

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Abstract *- Chromium (Cr) is a prevailing heavy metal pollutant present in industrial wastewaters. While preserving soil health and ensuring crop productivity are pivotal aspects of sustainable agriculture, using contaminated water on agricultural land will definitely affect the health of the soil and the productivity of a crop. This paper proposes a microbial-based remedial mechanism for (Cr) contaminated soil. The primary aim is to reduce the concentration of (Cr) contaminated soil using specific microbes (Pseudomonas, Bacillus, Aspergillus, and Arbuscular Mycorrhizal Fungi) and carrier materials (Biochar and Zeolite). The area contaminated with Chromium is identified specifically in the tannery soil. Pot cultures were conducted to assess the effectiveness of five different plant species (Radish (Raphanus Sativus), Cluster Bean (Cyamopsis Tetragonoloba), Palak (Spinacia Oleracea), Cowpea (Vigna Unguiculata), Red Spinach (Amaranthus Dubius)) in reducing Chromium levels. After that, seventeen different treatments were applied, consisting of various combinations of microbes (Pseudomonas, Bacillus, Aspergillus, and Arbuscular Mycorrhizal Fungi) and carrier materials (Biochar and Zeolite). Among the five plant species, the growth and performance of the radish, cluster bean, and palak were high under the treatments of (Treatment 12, 9, 7). In treatment 12, the combination of the Bacillus, Arbuscular Mycorrhizal Fungi, and Biochar is used to reduce the Chromium level in contaminated soil. The effectiveness of the treatment in reducing Chromium contamination was evaluated by focusing on Treatment 12 and using radish, cluster bean, and palak plant species. Treatment 12, as well as the control contaminated soil, underwent thorough characterization of Energy-Dispersive X-ray Spectroscopy (EDAX) and X-ray Diffraction (XRD). To ascertain the materials' elemental makeup, the EDAX analysis was performed. XRD analyses were performed to assess variations in intensity. The characterization, EDAX, and XRD provided valuable insights into the changes in the contaminated soil composition and the success of Treatment 12 in mitigating Chromium levels.*

Keywords *- Arbuscular Mycorrhizal Fungi, Bacillus, Biochar, Cluster Bean, Energy-Dispersive X-Ray Spectroscopy, Soil, Palak, Radish, X-Ray Diffraction.*

1. Introduction

1.1. Background

The environmental pollution created by various industries has damaged the natural environment with a wide range of inorganic and organic contaminants. Due to these industrial operations, a range of very harmful and resistant contaminants are being released into the environment through industrial wastewaters [1, 2]. There are 2 categories of environmental pollutants: inorganic and organic. Inorganic pollutants are composed of a range of highly toxic non-biodegradable Heavy Metals (HMs) including Arsenic (As), Nickel (Ni), Chromium (Cr), Lead (Pb), Mercury (Hg), and Cadmium (Cd); organic pollutants are primarily composed of phenols, nonylphenols, chlorinated phenols, azodyes, phthalic esters, petroleum hydrocarbons, pesticides, and Persistent Organic Pollutants (POPs) [3, 4]. Numerous organic and inorganic contaminants have been shown to have harmful impacts on living things, including severe contamination of soil and water. The ecosystem is under more stress as a result of industrialization and technological growth because of the massive releases of hazardous waste, HMs (Pb, Cr, and Cd), and metalloids (elements with properties halfway between typical and non-metal, like arsenic and antimony), and organic contaminants that have seriously harmed the ecosystem [5, 6].

Recent studies report that chromium concentrations in industrially impacted agricultural soils often exceed safe limits, ranging from about 150 mg/kg to over 2,000 mg/kg in severely contaminated areas, particularly near tannery and electroplating industries [7]. Such elevated chromium levels significantly reduce soil fertility, inhibit plant growth, and lower crop yields, while also leading to chromium accumulation in edible plant parts and increased food safety risks. Long-term use of chromium-contaminated irrigation

water has been further linked to persistent soil degradation and declining agricultural productivity [8]. These statistics highlight the urgency of developing effective and sustainable remediation strategies for chromium-contaminated agricultural soils [9, 10].

1.2. Literature Review

Numerous research works have previously existed in the literature, which are based on remedial mechanisms for chromium-contaminated soil. Some of them are reviewed here,

Tarekegn et al. [11] have reported that bacterial-mediated bioremediation plays a significant role in removing heavy metals from contaminated environments. Their study emphasized that long-term heavy metal pollution poses severe risks to ecosystems and public health due to metal persistence, bioaccumulation, and toxicity even at low concentrations.

The physical and chemical remediation techniques were economically expensive and generated large volumes of secondary chemical waste, making them environmentally unsustainable. However, a major limitation of the reported approach was that it primarily focuses on isolated bacterial activity, without addressing soil microbe plant interactions, long-term field scalability, or the need for carrier materials to enhance microbial stability and remediation efficiency.

Selvakumar et al. [12] have suggested that the Indian state of Tamil Nadu's Dindigul area produced over 32 distinct bacterial strains. Hexavalent Chromium [Cr (VI)] contamination in the environment was widely associated with the leather industry. These carry a higher danger to the survival of humans and the integrity of the environment. Traditional physical and chemical techniques of managing Chromium were costly and resulted in solid wastes that required laborious treatment. Biological therapy, which uses microorganisms to detoxify Cr (VI), was therefore frequently considered an alternate approach.

Nyarko et al. [13] investigated heavy metal contamination in soils from the Kpone dump site using Atomic Absorption Spectroscopy (AAS) to quantify Pb, Zn, Cu, Hg, and As concentrations. Their study systematically analyzed seventeen soil samples collected from five distinct zones to assess contamination severity, agricultural suitability, metal sources, and potential risks to human health and the ecosystem. The findings revealed that while copper levels remained within permissible agricultural limits, concentrations of lead, zinc, mercury, and arsenic exceeded acceptable thresholds in several zones, indicating serious contamination concerns. However, the study was primarily diagnostic in nature and limited to contamination assessment; it did not propose or evaluate any remediation strategy, nor did it explore biological or soil-amendment-based approaches for reducing heavy metal mobility or restoring soil health.

Li et al. [14] examined the bioreduction of Hexavalent Chromium [Cr(VI)] on Goethite (FeOOH) surfaces in the presence of Pseudomonas aeruginosa, with an emphasis on the effects of important environmental factors like initial Cr(VI) levels, temperature, pH, and carbon source concentration. Through the combined processes of surface adsorption and microbial bioreduction, the study showed that mineral-associated bacterial activity was crucial in converting Cr (VI) to the less hazardous Cr(III) form. The presence of FeOOH was shown to support bacterial growth by supplying bioavailable iron, thereby enhancing chromium reduction efficiency.

However, they approach was largely confined to controlled mineral–microbe systems and does not address soil-scale complexity, plant–microbe interactions, or the practical applicability of such mechanisms in agricultural soils contaminated with Chromium. Elehinafe et al. [15] have suggested that the use of automobile gas oil and premium motor spirit across the states, regions, and country of Nigeria as a whole results in Cr and Cd emissions. It was done in order to calculate the dangers that the emissions pose to people, plants, and animals, as well as the amounts of exposure per person and land. For a period of ten years (2009–2018), the yearly emission rates of Cr and Cd from the burning of the PMS and AGO were estimated by combining the annual fuel consumption and the amounts of dangerous transition metals. Next, the population and land areas were used to compute the per capita and land distributions of emissions, respectively.

Chen et al. [16] evaluated the effectiveness and feasibility of an integrated remediation approach for simultaneously treating chromium-contaminated groundwater and soil using an iron–biochar composite applied to topsoil. Advanced characterization techniques, including scanning electron microscopy with elemental mapping, X-ray photoelectron spectroscopy, and toxicity characteristic leaching procedure tests, were employed to elucidate chromium immobilization mechanisms and assess leaching behavior.

Long-term stability of immobilized Chromium was further analyzed using Hydrus-1D modeling. Despite its technical effectiveness, they approach relies heavily on engineered amendments and modeling-based validation, with limited consideration of biological remediation processes, plant–soil interactions, or the agronomic performance of remediated soils under crop cultivation.

Wu et al. [17] explored the use of plants, specifically vetiver grass, in combination with earthworms to remediate lead-contaminated soils. Their study highlighted the potential of such biotic agents to reduce heavy metal levels and emphasized the importance of ensuring soil safety for agricultural production, particularly in areas affected by cadmium contamination, which poses serious risks to crop safety and environmental health. However, they primarily

target lead and cadmium removal without evaluating chromium contamination, lack systematic assessment across multiple crop species, and do not integrate microbial consortia or carrier materials to enhance metal stabilization and plant growth, limiting their broader applicability to agricultural remediation. RK Sarankumar et al. [18] have suggested that one novel method for treating soils contaminated with cesium was Bio-Electrokinetic Remediation (BEK). By utilizing the degradative properties of alkalophilic Bacillus licheniformis SR3, BEK could effectively extract and break down pollutants from the soil matrix.

The method improved microbial activity and adjusted soil pH to maximize contaminant mobilization and bioavailability by utilizing electrochemical reactions at the electrodes to supply essential nutrients, oxygen, and electron donors/acceptors.

I Haider et al. [19] have suggested that Cr toxicity on microbial biomass and enzyme activity at different soil volumetric water contents and temperatures (25 °C and 40 °C). Six Cr levels were tested over the course of 60 days: control, 50, 100, 150, 200, and 250 mg Cr kg−1 soil. Additionally, as Cr levels increased, soil enzyme activities decreased. Activities of amidase, urease, alkaline phosphatase, β-glucosidase, arylsulfatase, and dehydrogenase declined.

1.3. Research Gap and Motivation

The generic assessment of the existing research work indicates the availability of microbial, chemical, and plant-based strategies. Although the bacterial technique of bioremediation proves capable of lowering the heavy metal concentration, its effectiveness is largely dependent upon the type of bacteria being employed. Microbial bioremediation via bacteria has been demonstrated to lower heavy metal concentration by either metabolizing or accelerating the transformation of toxic chromium compounds, although its effectiveness is largely dependent upon microbial strains and environmental factors. Although there has been a demonstrated effectiveness in the use of P. aeruginosa bacteria for reducing Cr(VI) to Cr(III), this approach has not explored the interaction between plants and soil variability in the laboratory-scale bio-reduction methods.

Chemical and composite treatments involving iron and biochar were also successful in binding Chromium in the soil and groundwater, although this treatment has to be repeated periodically and proves to be costly. Phytoremediation involving plants like vetiver grass or soil organisms like earthworms has proved useful in removing heavy metals like Chromium, although its applicability in specific contexts and interdependence with microorganisms has not been explored.

However, it also reveals the need for a more efficient and sustainable approach to the problem caused by the presence of Chromium in the soil. To this end, the current work aims to provide an effective remedy to the problem by making use of microbes and carrier materials for the reduction of the level of chromium presence in the soil through the assistance of certain plant types.

The novelty of this work lies in the systematic integration of microbial consortia (Bacillus and AMF) with carrier materials (Biochar) and plant-based evaluation for chromium-contaminated soil remediation. Unlike existing studies, which primarily focus on single microbial strains, chemical immobilization agents, or standalone phytoremediation approaches that often limit remediation efficiency and practical applicability, this study investigates seventeen synergistic treatment combinations to identify an optimized and effective remediation strategy.

The unique aspect of this work is the combined assessment of microbial–carrier–plant interactions, validated through edible crop species and supported by EDAX and XRD analyses, which directly link soil compositional changes with plant response. This integrated and agriculture-oriented framework advances beyond previous findings by providing a practically scalable approach that enhances chromium remediation efficiency while maintaining crop growth and soil health.

The objective is described as

- Reduce chromium contamination in tannery-affected soils using specific microbial consortia in combination with carrier materials (biochar and zeolite).
- Evaluate the growth performance and chromium uptake efficiency of selected edible plant species under different microbial carrier treatments.
- Identify the most effective treatment combination that maximizes chromium remediation while supporting plant growth.
- Assess changes in soil composition and chromium stabilization using analytical techniques such as EDAX and XRD, linking microbial plant soil interactions with remediation efficiency.

1.4. Contribution

- This paper contributes to proposing a microbial-based remedial mechanism for Cr contaminated soil**.**
- The primary aim is to reduce the concentration of Cr contaminated soil by utilizing specific microbes (Pseudomonas, Bacillus, Aspergillus, and Arbuscular Mycorrhizal Fungi) and carrier materials (Biochar and Zeolite).
- Initially, identifying an area contaminated with Chromium, specifically in the tannery area. Pot culture was conducted to assess the efficiency of five different plant species (Radish, Cluster Bean, Palak, Cowpea, Red Spinach) in reducing Chromium levels.

- After that, seventeen different treatments were applied, consisting of various combinations of microbes and carrier materials. Among the five plant species, the growth and performance of the radish, cluster bean, and palak were high under the treatments of (Treatment 12, 9, 7).
- In treatment 12, the combination of the Bacillus, Arbuscular Mycorrhizal Fungi, and Biochar was used to reduce the Chromium level in contaminated soil.
- Treatment 12, as well as the control contaminated soil, underwent thorough characterization of EDAX and XRD.

1.5. Organization

The balance of the manuscript is as follows: Section 1 clarifies the introduction, explains the literature review and background of the research work; Section 2 describes the Configuration of microbial-based remedial mechanisms for Chromium Contaminated Soil; Section 3 labels the results and discussion, and Section 4 concludes the manuscript.

2. Configuration of Microbial-Based Remedial Mechanism for Chromium Contaminated Soil

The Configuration of microbial-based remedial mechanisms for chromium-contaminated soil is shown in Figure 1. The contaminated soils were collected from the tannery area. The obtained soil sample exhibits a spectrum of colours, possibly attributed to the presence of Cr ions, from brownish to blackish.

The flora and fauna of soil are negatively impacted by heavy metal deposition, which can change the edaphic qualities of the soil and even lower its capacity to store water. Five plant kinds were chosen for this study based on how well they could absorb HMs, specifically Chromium (Cr) from the polluted soil. In a pot culture experiment, the uptake of HMs by contaminated and normal soil was examined. The plant varieties used in this research are Radish, Cluster bean, Cowpea, Palak, and Red Spinach. The plants were grown for three months (90 days). One kilogram of tainted dirt was placed into the pots. There are 17 treatments carried out with the combination of different microbes, and the carrier material is applied in contaminated soil to reduce the uptake of chromium contamination. The five plant seeds were planted in each pot and irrigated with tap water. The combination of different microbes and the carrier materials is poured into the contaminated soil every 15 days.

Water was given to the plants once a day, taking care to prevent water from seeping out of the pots. For HMs' analysis, the plants were taken after 20, 40, 60, and 90 days. Among all five plants, the best three plants and their treatments are taken. Bacillus, Arbuscular Mycorrhizal Fungi, and Biochar (Treatment 12), control, and contaminated soil are taken for testing by observing the plant growth and its health. The best plant species grown are Radish, Cluster bean, and Palak.

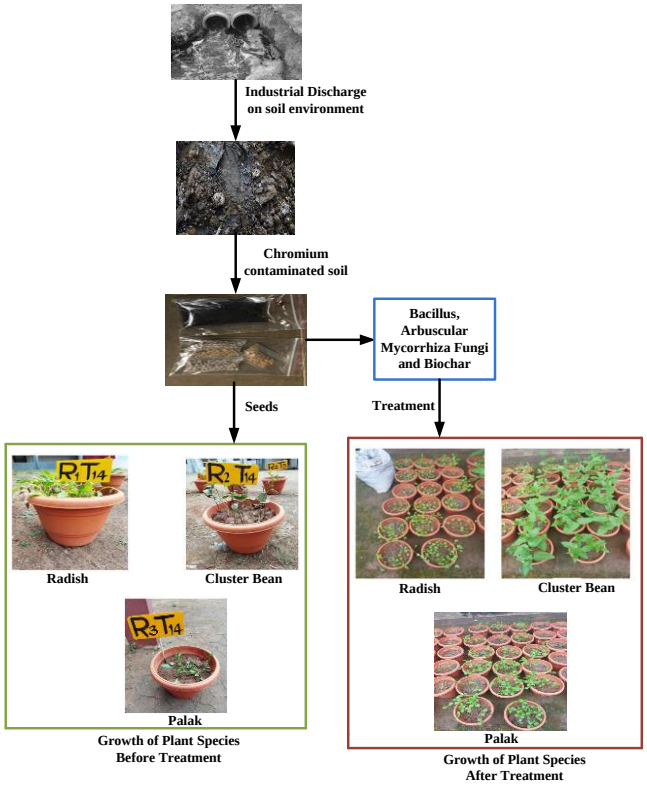

Fig. 1 Configuration of microbial-based remedial mechanism for chromium contaminated soil

2.1. Chromium Contaminated Soil

Due to the significant increase in Chromium content in the environment, especially in soil, water, and air, it has recently come under scrutiny as a serious issue. Chromium, represented by the symbol Cr, is a common metal element. It is the first element in the periodic table's group 6 and is regarded as a transitional element. The periodic table describes Cr as a 1st-row d-block transition metal of group VIB with the following characteristics: atomic mass 52, 1875°C melting temperature, 7.19 g cm−3 density, and 2665°C boiling point [20]. One of the less common elements, it only occurs naturally as compounds rather than in elemental form. According to some estimates, it is the 7th most abundant element on Earth and the 21st most accessible element in rocks. Cr is commonly found in soil, water, volcanic dust, and the atmosphere. Even if the main cause of emissions is human activity, the genesis could be natural. Though Cr is most frequently found in nature in its trivalent form, small amounts of Cr (VI) compounds are also present.

Since trivalent forms of Cr (VI) differ substantially in their sorption techniques and soil availability, they are more soluble than Cr (III) and can translocate and absorb differently in the aerial portion of the plant. In general, Chromium is weakly translocated in the shoots and accumulates in the roots. On living things, Cr (VI) has the potential to be mutagenic, teratogenic, and carcinogenic. Its high degree of reactivity with other metallic ions attests to its toxicity. One of the most

widely utilized metal pollutants, Cr, has been included among the top 20 pollutants on the Superfund priority list of dangerous substances for the past 15 years.

2.2. Bacillus, Arbuscular Mycorrhizal Fungi, and Biochar Treatment

The complementation of Bacillus Bacteria, AMF, and Biochar in plant types will, therefore, be quite complex with tremendous implications for agriculture. This is because AMF will facilitate symbiotic relations with plant roots, thereby increasing nutrient and water uptake, while Bacillus will increase atmospheric-fixed nitrogen, phosphorus solubilization, and the production of growth-promoting substances [21]. Biochar, which will be obtained through the pyrolysis of organic materials, will increase soil fertility, structure, and biota. All these will act synergistically, thereby improving nutrient levels, soil structure, and plant resilience. In addition, the mixture will provide disease control through Bacillus's antimicrobial activity as well as the promotion of plant health by AMF. In addition, biochar will also provide carbon sequestration, which will control climate change, as well as control chemical input requirements.

All the plant species were maintained under controlled greenhouse conditions with a temperature regime of 25 ± 2°C and a natural day/night cycle of 12 hours light and 12 hours dark. The relative humidity was maintained at 60%-70%. One kilogram of polluted soil was taken for each pot, and each day was irrigated with tap water to maintain equal moisture levels without water runoff. The microbial treatment measures included the formulation of microbial suspensions at a concentration of 10^8 CFU/mL. The biochar was sterilized and combined with microbial inoculum before its use on the polluted soil. The microbial carrier mixture was then applied to each polluted soil sample at an interval of 15 days to provide an evenly distributed mixture around each plant root area for better colonization and chromium removal effectiveness. The five plant species used were Radish, Cluster Bean, Cowpea, Palak, and Red Spinach; these were chosen based on their previously tested ability to absorb and remove heavy metals such as Chromium from polluted soils. Moreover, these plant species also grow rapidly and can be easily grown and consumed for their applicability in determining remediation effectiveness.

3. Result and Discussion

After cultivating these plants, the best three species are selected for analysis and testing. The soil is collected from treatment 12 from Radish – R1, Cluster bean – R2, and Palak – R3. It is also compared with the Control soil treatment 14. Treatment 12, as well as the control contaminated soil, underwent thorough characterization of EDAX and XRD.

3.1. EDAX (Energy Dispersive X-ray Analysis)

The elemental composition of materials may be ascertained using x-ray technology called EDX, sometimes known as EDS or EDAX. The figure below is the comparison between contaminated soil R12 and Control soil R14 in Radish, Cluster bean, and Palak.

Comparison of Radish (a) R12 (Contaminated soil) (b) R14 (Control soil) is shown in Figure 2. The Chromium concentration in radish plants grown in contaminated soil is 70, whereas the soil control for radish registers a Chromium level of 110. Comparison of Cluster bean (a) R12 (Contaminated soil) (b) R14 (Control soil) is shown in Figure 3. The Chromium concentration in cluster bean plants grown in contaminated soil is 65, whereas the soil control for cluster bean registers a Chromium level of 105. Comparison of Palak (a) R12 (Contaminated soil) (b) R14 (Control soil) is shown in Figure 4. The Chromium concentration in palak plants grown in contaminated soil is 50, whereas the soil control for palak registers a Chromium level of 60.

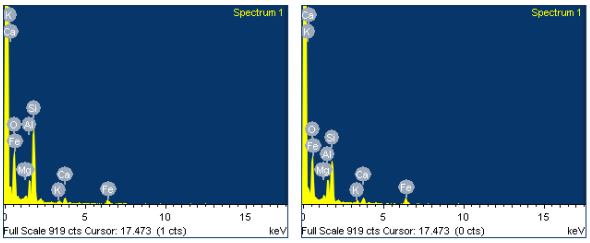

Fig. 2 Comparison of radish (a) R12 (contaminated soil), and (b) R14 (control soil).

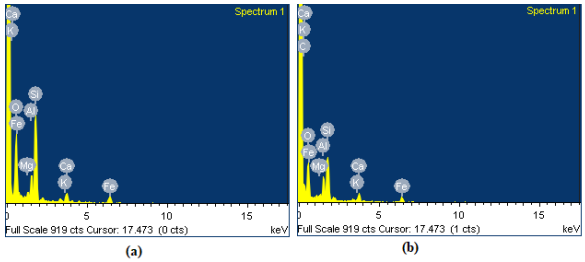

Fig. 3 Comparison of cluster bean (a) R12 (contaminated soil), and (b) R14 (control soil).

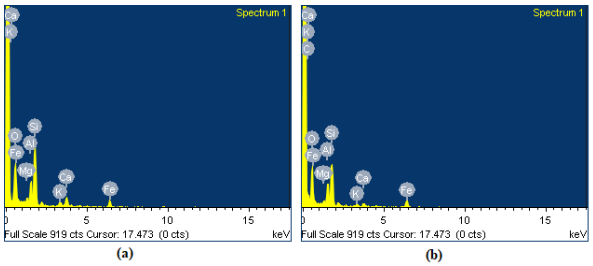

Fig. 4 Comparison of palak (a) R12 (contaminated soil), and (b) R14 (control soil).

3.2. XRD (X-Ray Diffraction Analysis)

In materials science, XRD is a method used to ascertain a substance's crystalline structure. Quantifying the intensities and scattering angles of the X-rays that leave a material when it is subjected to incoming X-ray radiation is done using XRD.

Comparison of Radish (a) R12 (Contaminated soil) (b) R14 (Control soil) is shown in Figure 5. The contaminated soil intensity of radish initially starts from 130a.u at 5 degrees, and then the contaminated soil intensity of radish increases and reaches 80a.u at 90 degrees, as shown in Figure 5 (a). The Control soil intensity of radish initially starts from 90a.u at 5degree and then the Control soil intensity of radish increases and reaches 70a.u at 90 degrees, as shown in Figure 5 (b). Comparison of Cluster Bean (a) R12 (Contaminated soil) (b) R14 (Control Soil) is shown in Figure 6. The contaminated soil intensity of cluster bean initially starts from 130a.u at 5 degrees, and then the contaminated soil intensity of cluster bean increases and reaches 100a.u at 90 degrees, as shown in Figure 6(a). The Control soil intensity of cluster bean initially starts from 80a.u at 5 degrees, and then the Control soil intensity of cluster bean increases and reaches 98a.u at 90 degrees, as shown in Figure 6 (b). Comparison of Palak (a) R12 (Contaminated soil) (b) R14 (Control soil) is shown in Figure 7. The contaminated soil intensity of palak initially starts from 130a.u at 5 degrees, and then the contaminated soil intensity of palak increases and reaches 80a.u at 90 degrees, as shown in Figure 7(a). The Control soil intensity of palak initially starts from 80a.u at 5degree and then the Control soil intensity of palak increases and reaches 80a.u at 90 degrees, as shown in Figure 7(b).

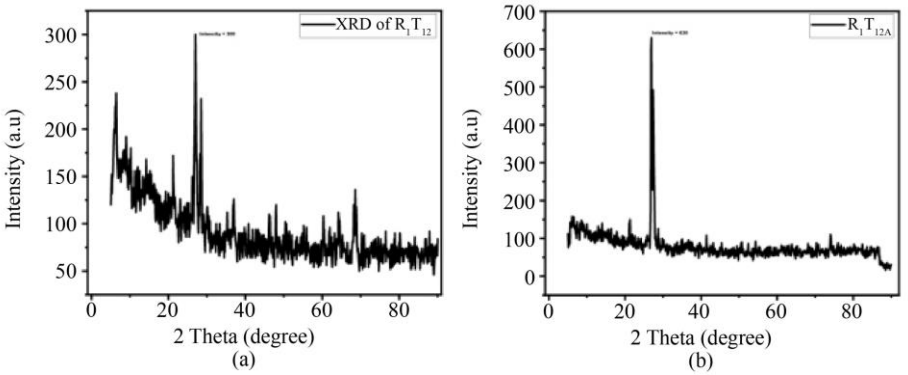

Fig. 5 Comparison of radish (a) R12 (contaminated soil), and (b) R14 (control soil).

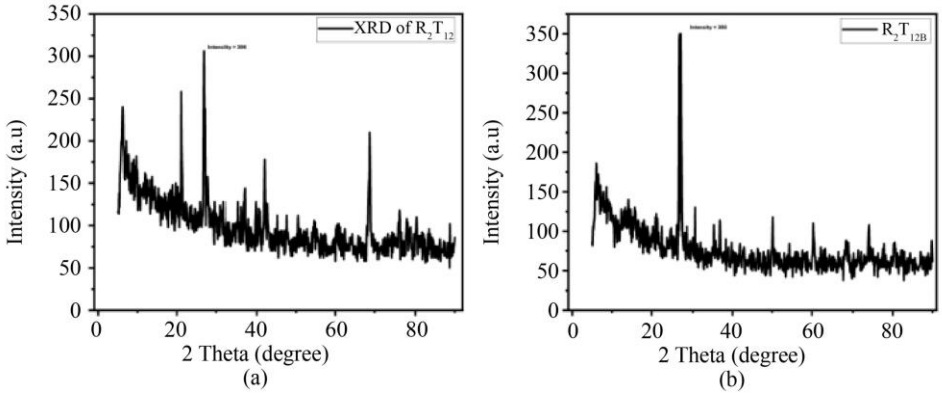

Fig. 6 Comparison of cluster bean (a) R12 (contaminated soil), and (b) R14 (control soil).

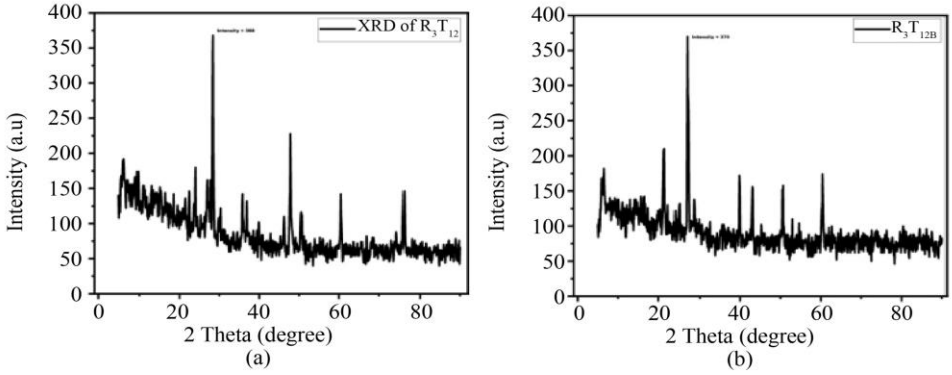

Fig. 7 Comparison of palak (a) R12 (contaminated soil), and (b) R14 (control soil).

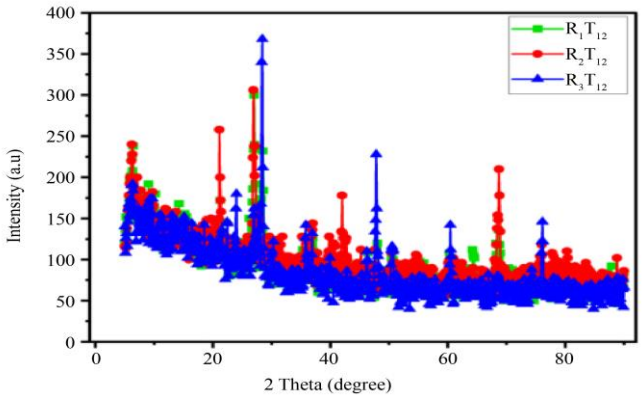

Fig. 8 Combination of all contaminated soil R12 (radish, cluster bean, and palak)

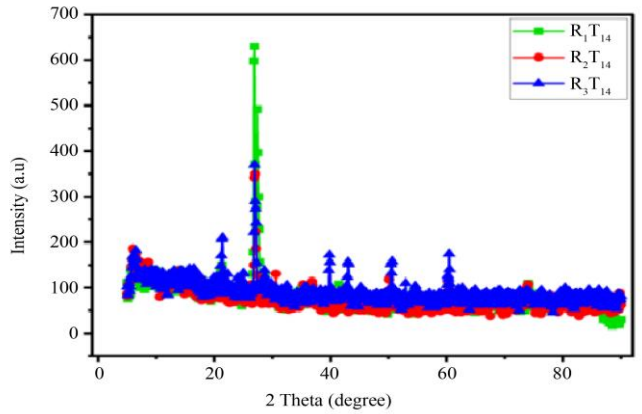

Fig. 9 Combination of all control soil R14 (radish, cluster bean, and palak)

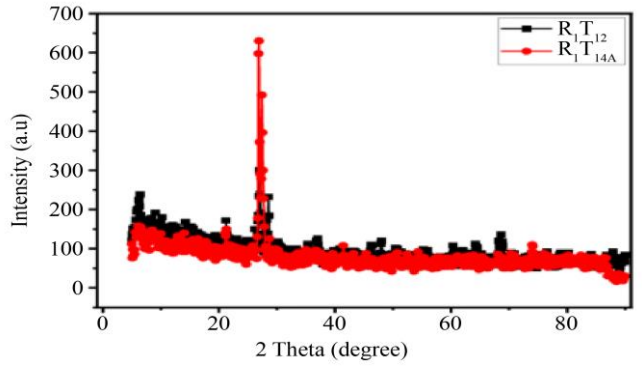

Fig. 10 Comparison of contaminated soil R12 and control soil R14 in radish

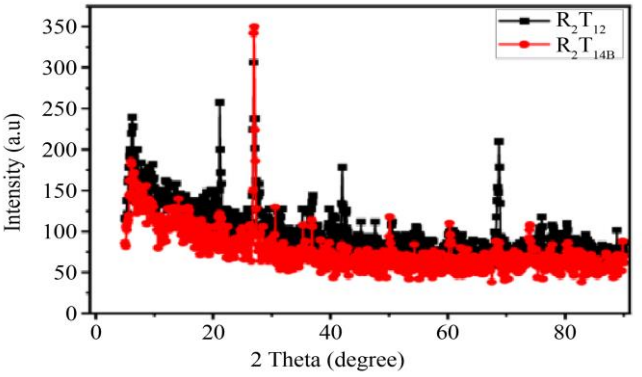

Fig. 11 Comparison of contaminated soil R12 and control soil R14 in cluster bean

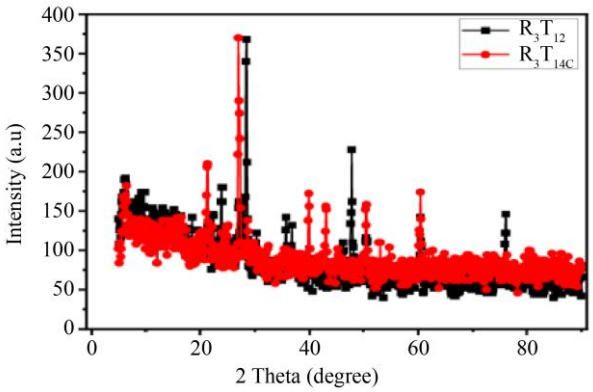

Fig. 12 Comparison of contaminated soil R12 and control soil R14 in palak

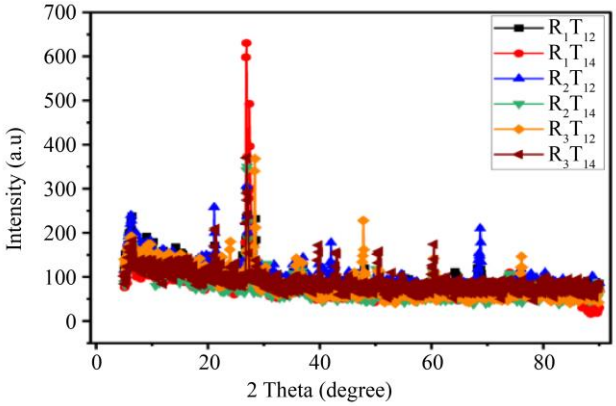

Fig. 13 Comparison of all contaminated soil R12 and control soil R14 in radish, cluster bean, and palak

A combination of all contaminated soil R12 (Radish, Cluster bean, and Palak) is shown in Figure 8. The contaminated soil intensity of R1T12 is 120a.u at 90 degrees. The contaminated soil intensity of R2T12 is 100a.u at 90 degrees. The contaminated soil intensity of R3T12 is 90a.u at 90 degrees. A combination of all Control soil R14 (Radish, Cluster Bean, and Palak) is shown in Figure 9. The Control soil intensity of R1T14 is 30a.u at 90 degrees. The Control soil intensity of R2T14 is 50a.u at 90 degrees. The Control soil intensity of R3T14 is 70a.u at 90 degrees. Comparison of Contaminated soil R12 and Control soil R14 in Radish is shown in Figure 10. The contaminated soil intensity of R1T12 is 83a.u at 90 degrees. The Control soil intensity of R1T14A is 50a.u at 90 degrees. Comparison of Contaminated soil R12 and Control soil R14 in Cluster bean is shown in Figure 11. The contaminated soil intensity of R2T12 is 90a.u at 90 degrees. The Control soil intensity of R2T14B is 88a.u at 90 degrees. Comparison of Contaminated soil R12 and Control soil R14 in Palak is shown in Figure 12. The contaminated soil intensity of R3T12 is 60a.u at 90 degrees. The Control soil intensity of R3T14C is 100a.u at 90 degrees. Comparison of all contaminated soil R12 and Control soil R14 in Radish, Cluster bean, and Palak is shown in Figure 13. Radish showed a decrease in intensity from 300 in contaminated soil (R12) to 630 in Control soil (R14). Cluster bean exhibited a decrease from 306 (R12) to 350 (R14), while Palak showed a decrease from 368 (R12) to 370 (R14).

Table 1. Analyzes the height of the root

T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17
10	9	13	6	11	10	13	8	9	8	8	12	7	10	16	5	3

Table 1 shows an examination of root height measurements from 17 trials (T1–T17), with height values ranging from 3 to 16. The highest root height reported was 16 in T15, while the lowest was 3 in T17. Most experiments show intermediate root height values, ranging from 8 to 13. T3 and T7, for example, have the same value of 13, although T2 and T9 both have the number 9. Notable variations include T4 at 6 and T14 at 10, indicating some variation. This distribution shows a general trend of rising root heights, with some lower outliers.

Table 2. Analyzes the thickness of the root

T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17
0.2	0.04	0.12	0.04	0.2	0.2	0.1	0.2	0.1	0.14	0.2	0.14	0.14	0.18	0.1	0.2	0.14

Table 2 shows a comparison of root thickness across 17 measurement sites (T1–T17), illustrating differences in thickness. The values vary from 0.04 (lowest at T2 and T4) to 0.2 (highest at T1, T5, T6, T10, T11, and T16). Several sites, such as T3, T7, T9, and T15, have moderate thickness values of 0.1, whereas T8 and T13 have slightly higher consistency at 0.14, as do T10, T12, and T17. Variations in root thickness may reflect structural or environmental factors, with larger thickness values (0.2) indicating more robust regions than thinner sections. This pattern gives information on the distribution and structural features of the roots.

Table 3. Characterization of radish chromium contaminated soil before and after treatment

Sl. No	Parameter	Before treatment	Radish with T-12	Control Soil
1	PH	8.85	8.53	8.82
2	EC	320	245	319
3	Nitrogen	0.115	0.126	0.126
4	Phosphorous	165	823	133
5	Potassium	1200	1220	980
6	Manganese	520	190	184
7	Iron	19	19	20
8	Zinc	35	33	35
9	Copper	110	105	90
10	Lead	15	6	8
11	Chromium	115	70	110

Characterization of Radish Table 3 shows chromium-contaminated soil before and after treatment. Before treatment, Chromium is found in polluted soil at 115. After treatment, the chromium concentration in the soil is lowered to 70, whereas in the control soil it remains at 110.

Table 4. Statistical analyses of the radish plant root

R.RT14 R.RT12	Mean	N	Std. Deviation
5.00	8.0000	3	.00000
12.00	15.0000	3	.00000
14.00	20.0000	2	.00000
15.00	23.3333	3	2.88675
20.00	31.6667	3	2.88675
24.00	38.0000	5	.00000
25.00	43.5294	17	7.85905
29.00	42.0000	4	.00000
30.00	55.7778	9	2.04803
33.00	46.0000	4	.00000
35.00	51.1250	8	1.55265
Total	40.4426	61	13.82694

Table 5. ANOVA test for radius plant root

			Sum of Squares	df	Mean Square	F	Sig.
R.RT14* R.RT12	Between Groups	(Combined)	10399.050	10	1039.905	48.503	<.001
		Linearity	9134.670	1	9134.670	426.058	<.001
		Deviation from Linearity	1264.380	9	140.487	6.553	<.001
	Within Groups		1071.999	50	21.440		
	Total		11471.049	60			

3.2.1. Table 5. ANOVA Test for Radius Plant Root

The radius of plant roots is summarized in Table 4. Radish exhibited a total mean root radius of 40.44, with a corresponding total nitrogen content of 61. The overall standard deviation for radish was 13.83, indicating moderate variability in root radius measurements. The ANOVA results for plant root radius are presented in Table 5, where the total sum of squares was 11,471.05 with a total degree of freedom of 60, confirming statistically meaningful variation among treatments. Further supports these findings, with radish

recording a correlation coefficient of 0.873 and a coefficient of determination of 0.763. Additionally, the eta value of 0.921 and the squared value of 0.848 indicate a strong treatment effect on radish root radius.

3.3. Discussion

The presented data illustrate the comparative analysis of Radish, Cluster Bean, and Palak grown in Contaminated Soil (R12) versus Control Soil (R14), focusing on Chromium concentration and soil intensity. In radish, Chromium concentrations were notably higher in contaminated soil (70) compared to Control soil (110). Further comparison between Contaminated (R12) and Control (R14) soil intensities in individual plants revealed fluctuations in intensity levels at 90 degrees Celsius. Previous studies primarily focused on isolated bacterial remediation [8, 9], mineral-assisted bioreduction [11], or contamination assessment without remediation [10], while some plant-based approaches lacked microbial or carrier integration [14]. Although these trials showed chromium reduction, they lacked improvements in field-scale scalability, plant-soil interactions, or crop performance. The proposed approach combines the benefits of Bacillus species, arbuscular mycorrhizal fungi, and biochar. These can work towards chromium immobilization as well as plant growth promotion simultaneously. Thus, this approach is more effective as it combines two processes. The experimental methods were done with strict environmental principles. The contaminated soils were handled with proper care. The microbial applications were done through controlled pot trials to prevent environmental leaching. All contaminated soils were placed in designated containers with proper marking. These soils were then properly sterilized before disposal. The soils can either be treated with binding substances or packed into proper hazardous waste storage. The plant residues were also properly sterilized. These plant residues can either be incinerated or composted. Thus, these steps ensured that the experimental work did not result in any environmental loading or deviations from ethical considerations related to environmental conservation.

4. Conclusion

This work proposes a microbial-based remedial mechanism for Cr-contaminated soil. The primary aim is to reduce the concentration of Cr in contaminated soil using specific microbes, Pseudomonas, Bacillus, Aspergillus, and Arbuscular Mycorrhizal Fungi, and carrier materials (Biochar and Zeolite). In a pot comprising seventeen treatments with various plant species, an investigation was conducted to identify the most efficient approach. Treatment 12 achieved a substantial reduction in chromium concentration from 115 mg/kg to 70 mg/kg, compared to 110 mg/kg in untreated control soil, along with significant improvements in plant growth, particularly in radish.

Statistical analysis confirmed the effectiveness of this treatment, showing a highly significant influence on root development ($p < 0.001$). These findings indicate strong potential for applying such eco-friendly, microbe–carrier-based approaches in environmental management. The plant growth parameters again validate this result, and Treatment 12 showed the maximum height of the root, which is 16, and it was significantly lower in Treatments 16 and 17. The XRD result showed a significant difference in intensity between the contaminated and control soils.

The result validates the stabilization of Chromium in the soil matrix. The combined result suggests that the combined microbial and biochar method is not only useful in reducing the chromium content in soils but also in reviving the soil's functionality. However, this method has limitations since it was conducted in a controlled pot culture and may not reflect the reality in the soil environment. The evaluation focused on short-term chromium reduction and plant growth, without assessing long-term soil health or chromium stability. Future work should include field-level validation, long-term monitoring of chromium behavior, and assessment of soil properties across different crops and contaminated sites to support practical environmental management.

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