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The Impact Of Soil Amendments On Brassica Carinata's Bioavailability, Transformation, And Accumulation Of Heavy Metals

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Abstract
The purpose of this study is to determine the impact of farm yard manure (FYM), recommended doze of fertilizer (RDF), and Trichoderma viride additions on heavy metal-contaminated soil. In this study, amendments using FYM, FYM + RDF, and FYM + Trichoderma viride were applied to the heavy metal-contaminated soil in four application rates (0, 1, 2,3,4 and 5ppm), with the goal of considerably decreasing the bioavailability of heavy metals for Brassica carinata from irrigation soils. The use of various amendment ratios can enhance soil pH by 0.11-0.30 units while simultaneously increasing organic matter content by 3.1-35.1%. All of the adjustments successfully reduced the concentration of accessible chromium (Cr), cadmium (Cd), and zinc (Zn) in the CaCl2 extract.After adding varied ratios of amendments to the soil, the CaCl2 extractable Cd dropped by 33-48% compared to the control group. Furthermore, increasing the quantity of compost and farmyard manure-bioagent combinations reduced the readily exchangeable fractions of Cr, Cd, and Zn while increasing the oxidation and residual fractions.
When soil amendments were provided, fresh root and shoot weight rose by 29-63% and 39-85%, respectively. After applying varied amendment ratios, Cd concentrations in Brassica carinata roots and shoots reduced by 21-44% and 26-53%, respectively. All of the amendments were efficient in lowering Cd, Zn, and Cu uptake by Brassica carinata roots and shoots while concurrently reducing Cr absorption in the roots. Fertilizer applications, as soil amendments, can dramatically lower heavy metal levels in Brassica carinata. While increasing biomass output, a greater application rate is more efficient than a lower application rate.
Keywords: *Brassica carinata, Bioavailability, Heaymetals, Bioagent.*

INTRODUCTION
Mining, fertilizer, and sewage irrigation cause heavy metal accumulation in agricultural soil, making China one of the world's most heavily polluted countries (Kumar Pandey et al., 2022). More than 36 million hectares of farmland in China are contaminated by a variety of heavy metals, one of which is cadmium (Cd). Over the last few decades, sewage irrigation has deposited more than 100 tons of Cd into the soil, resulting in severe Cd contamination in China (Maurya et al., 2023). Chromium (Cr), copper (Cu), and zinc (Zn) are also found in the soil, but in smaller levels and in less contaminated places than Cd. Excessive heavy metal exposure can harm human health, with Cd and Cr being the most common and representative elements, causing a wide range of negative impacts, including both non-carcinogenic and carcinogenic dangers (Kamran et al., 2020). *Brassica carinata* are among the most significant dietary components consumed across the world. *Brassica carinata* accumulates heavy metals more than other food crops, and eating polluted leafy vegetables is a primary source of human exposure.

Overall, leafy vegetables account for 70% of total Cd accumulation in humans. As a result, reducing excessive hazardous heavy metals in plants, particularly *Brassica carinata*, is an extremely vital endeavor (Rather et al., 2022). Organic additions are increasingly being used globally to reduce heavy metal mobility and bioavailability in polluted soils. Farmyard manure, bioagent, and RDF offer distinct benefits over other soil remediation agents. Bioagent can survive in the soil for hundreds, if not thousands, of years (Nepal et al., 2024). It has a highly porous structure, alkali and cation exchange capability, and a significant number of carboxyl and hydroxyl groups, all of which can minimize heavy metal bioavailability, lowering plant absorption and food chain transfer.

However, bioagents can not only immobilize heavy metals but also immobilize important nutrients for plants, resulting in a deficit of Ca, P, and N in plants, harming plant development (Houssou et al., 2022).

FYM is a cost-effective strategy considering the cheap price of residues and by-products that may be utilized as soil additions.The rotation of organic carbon in the farmyard manure FYM can be paired with heavy metals in a farmyard manure-treated soil to stabilize heavy metals (Rani et al., 2023).

In recent years, farm yard manure (FYM) has been employed as organic mulch and plant growth medium due to its low metal concentration and plenty of organic matter. *Trichorderma Viride* revealed great microbiological stability in the tested polluted soils, with over 95% of organic carbon resistant to degradation (Dhaliwal et al., 2020). *Trichorderma Viride* is the principal constituent of organic matter, which can increase mineral nutrition absorption and plant development.In heavy metal-contaminated soil, it was discovered that *Trichorderma Viride* may immobilize Zn (increased proportion of the residual fraction), hence lowering heavy metal extractable fractions (Dhaliwal et al., 2022). In recent years, FYM, RDF, and *Trichorderma Viride* have been extensively explored for soil restoration purposes. Mixing FYM, RDF, and *Trichorderma Viride* can enhance the effectiveness of soil restoration agents (Pandey et al., 2014).

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2.0 Materials and methods

2.1 Experimented materials

The soil source for this study is Sharda University Knowledge Park III, India.The location is in the Indian city of Greater Noida. First, the surface litter was removed, and soil ranging from 0 to 20 cm was collected.After 4 weeks of room-drying at 25°C, the soil was sieved to less than 2 mm and plant debris was removed. The obtained soil was a tidal soil with a total Cd content of 4.19 mg kg—1 (Table 1). This study used three soil amendments: farmyard manure, *Trichoderma viride*, and RDF.The experiment that is used farmyard waste from Sharda University. Willow, weed, and other plant pruning remnants or litter served as the primary raw materials.Under aerobic circumstances, they are totally decomposed after crushing, adding microbial agents, and performing primary and secondary fermentation. *Trichorderma Viride* was utilized as the experiment's bioagent. The heavy metal concentrations applied to the plant and soil are 10ppm, 20ppm, 30ppm, 40ppm, and 50ppm respectively.To study the impact of Farmyard manure, RDF, and *Trichorderma Viride* on heavy metal mobility and availability in soil, various amendment ratios were completely mixed with contaminated soil (Table 2). *Brassica carinata* seedlings IARI (International Agricultural Institute India) were planted from November 3, 2022 until June 20, 2023, after two weeks of soil balancing. *Brassica carinata* seed was sown in the contaminated soil.

Table 1: Physical and chemical qualities of raw materials utilized in the pot experiment.

Properties	units	soil		FYM		RDF		Trichoderma v.	
pH	-	7.92	0.02	8.38	0.03	8.13	0.02	5.68	0.03
EC	MS cm^{-1}	332	12.5	920	12	225	10	342	9
Cd	Mg kg^{-1}	4.19	0.05	ND	ND	ND	ND	ND	ND
Cr	Mg kg^{-1}	41.7	0.32	16.60	0.81	7.25	0.56	26.88	0.52
Zn	Mg kg^{-1}	243	5.23	37.07	30	932	19	2779	42

2.2 Soil sampling and analysis

Following the harvest of *Brassica carinata*, the soil from each pot was removed and its physical-chemical parameters were assessed.An automated pH meter was used to measure the soil's pH in a 1:5 (w/v, soil/water) soil water suspension. Hydrothermal methods were used to determine the organic matter concentration. The total heavy metal content of the soil samples was determined using the HF-HClO4-HNO3 technique. CaCl2 extraction was used to assess the availability of heavy metals in all soil treatments. The mobilities of Cr, Cd, and Zn in soil samples were assessed using a four-step sequential extraction procedure. Four metal fractions were determined: the exchangeable fraction (acid soluble/exchangeable, 0.11 M HOAc), the reduction fraction (Fe and Mn bound oxides and hydroxides, 0.5 M NH2OH), the oxidation fraction (organic matter-bound, NH4OAc), and the residual fraction (Ibrahim et al., 2022).

2.3 Plant sampling and analysis

The *Brassica carinata* was harvested 40 days later. To remove heavy metals from the root surface, it was first cleaned with distilled water before immersing in 20 mm Na2 EDTA for 15-20 minutes. It was finally washed with distilled water, and the surface moisture was removed and weighed. Microwave digestion was used to prepare samples for heavy metal content determination in roots and shoots, which was then determined using inductively coupled plasma mass spectrometry (ICP-MS) (Wang et al., 2020).

Table 2: Treatment of Experiment

Treatments	Description of treatments	Heavy metal concentration
T1	Absolute control	Control
T2	RDF	10PPM
T3	RDF +FYM	20PPM
T4	RDF +gypsum	30PPM
T5	RDF +FYM +gypsum	40PPM
T6	RDF +FYM +gypsum +bioagent (Trichoderma viride)	50PPM

2.4 Statistical analysis

The SPSS (version 22.0) software was used to conduct one-way ANOVA with the LSD test at a significant threshold of CD < 0.05.A two-way analysis of variance was used to investigate the effects of soil amendment type and pace on root and shoot heavy metals, as well as heavy metal availability in the soil (Kim et al., 2022). Pearson's correlation coefficients were used in SPSS (version 22.0) to determine correlations between various factors.

3. RESULTS

3.1 Soil properties with and without treatments

After applying different proportions of FYM-*Trichoderma Viride* and FYM-RDF, the pH, EC, and organic matter content of the polluted soil varied significantly (Fig. 2).

Because the quantity of compost exceeds that of *Trichoderma Viride* and RDF, the pH of all treated soils rises. FYM, FYM + RDF, and FYM + *Trichoderma Viride* enhanced soil pH by 0.13-0.26, 0.16-0.30, and 0.11-0.25, respectively. Simultaneously, increasing the amount of soil amendment enhanced the soil's electrical conductivity. The inclusion of different remediation materials resulted in a considerable increase in organic matter compared to the unamended soil.

FYM, FYM + RDF, and FYM + *Trichoderma Viride* all enhanced soil organic matter by 3.1-16.5%, 5.7-21.1%, and 8.8-35.1 percent, respectively. The combination of FYM and *Trichoderma Viride* is the most beneficial to raising the organic matter content since humic acid is the major component of organic matter.

3.2 Changes in accessible Cd, Zn, and Cr in soil following the Brassica carinata harvest

CaCl2 extraction was used to determine the influence of FYM, FYM + RDF, and FYM + *Trichoderma Viride* on the availability of Cd, Zn, and Cr in contaminated soil (Fig. 2).

Each heavy metal's accessible concentration is far lower than its overall concentration. All modifiers successfully reduced the amount of accessible Cd, Cr, and Zn in the soil when compared to untreated soil. When 1% and 2% of FYM-*Trichoderma Viride* acid were applied, CaCl2 extractable Cd and Zn in the soil reduced by 33-48%, 36-48%, 35-42%, and 38-39%, respectively, compared to the control. For all modifications, the effective state of Cr has a lower decrease rate than Cd and Zn. Compost and FYM-*Trichoderma Viride* can lower Cr levels in soil, however FYM-*Trichoderma Viride* (T6) increases Cr availability. A two-way ANOVA (Table 6) test revealed that the amount of organic amendments had a significant influence on heavy metal concentration ($P < 0.01$), whereas the kinds of organic amendments only had significant effects on accessible Zn and As ($P < 0.01$).

Organic amendment types and rates had a significant impact on soil Zn concentration ($P < 0.05$), but not on Cd, Cr, or Zn levels.

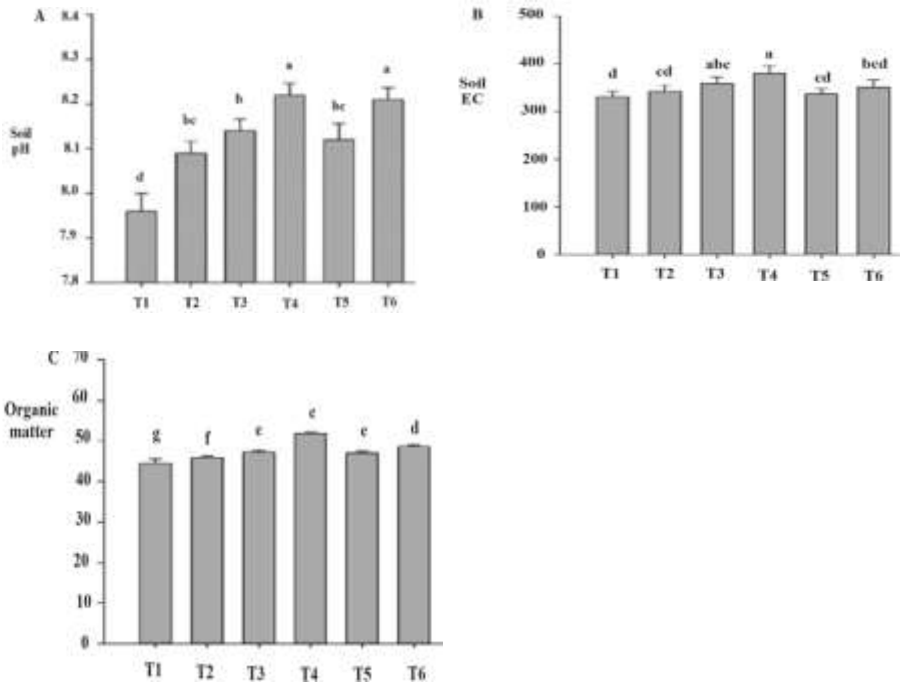

Figure 1: pH, EC and organic matter changes after treatment with various amendments.

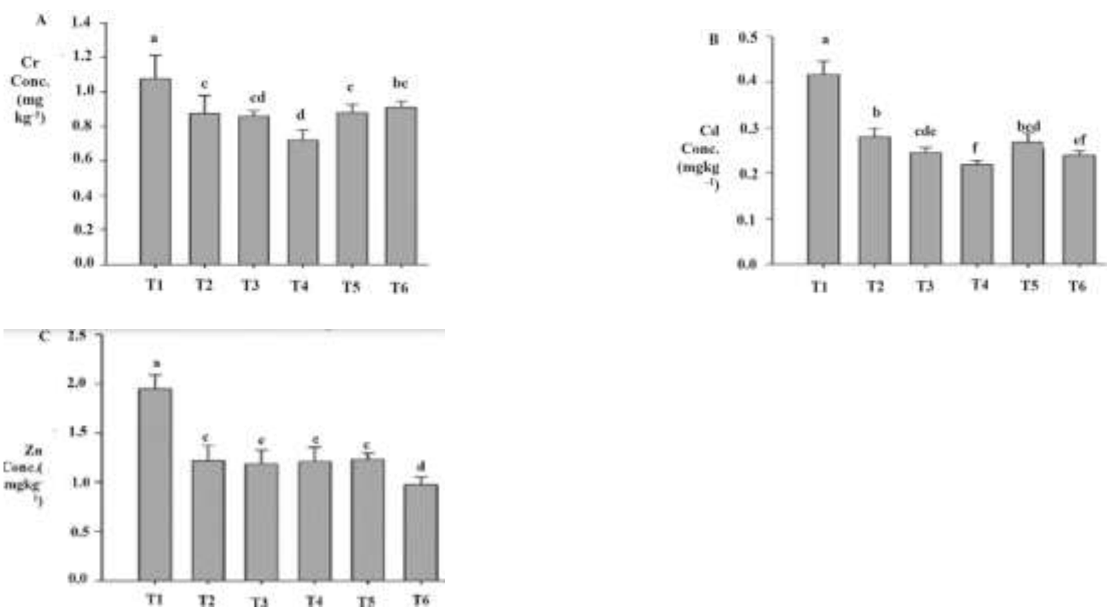

Figure 2: Concentration of accessible heavy metals in soil with various proportional amendments

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3.3 Extracting Cd, Zn, and Cr sequentially

Figure 4 summarizes the effects of consecutive extraction on Cd, Zn, and Cu levels in contaminated soil with varying ratios of amendments. According to the results of sequential extraction for Cd, after the incorporation of amendments, the easily exchangeable fraction was significantly reduced while the reduction fraction increased significantly, with the easily exchangeable fraction gradually decreasing and the reduction fraction gradually increasing with the addition of the amendments. With the addition of amendments, the oxidation and residual fractions increased marginally. The T3 therapy reduced the readily exchangeable proportion from 29.4% to 20.9%, while the T6 treatment reduced it from 29.4% to 18.7%. FYM and FYM+RDF combo are more effective than FYM + *Trichorderma Viride*, with more amendments resulting in a more noticeable impact. When amendments were added to Zn, the readily exchangeable percentage and reduction fraction dropped, but the oxidation fraction and residual fraction rose. Compared to the control, when the quantity of amendments rose, the readily exchangeable fraction declined somewhat, the reduction fraction decreased dramatically, and the oxidation and residual fractions both increased significantly. For Cd, the FYM and FYM combination lowered the readily exchangeable fraction and reduction fraction, raised the residual fraction, and the tendency became more noticeable as the extra quantity of the amendments rose. The FYM + *Trichorderma Viride* combination initially raised and later decreased the readily exchangeable percentage, while increasing the oxidation fraction and decreasing the reduction and residual fractions.

3.4 The growth and heavy metal buildup of *Brassica carinata*

Brassica carinata output rose by 30-65% (Table 3). In comparison to the control, the fresh weight of the root grew by 29-63% and that of the shoot increased by 39-85%. Table 4 shows that all amendments were efficient in lowering Cd absorption by *Brassica carinata*. The more amendments added, the more visible the effects were (Table 3). Cd concentrations in *Brassica carinata* roots were decreased by 31-44%, 24-38%, and 21-33% with FYM, FYM + RDF, and RDF + gypsum, respectively. The Cd content in *Brassica carinata* shoots was lowered by 27-51%, 31-48%, and 26-53%, respectively, using RDF +FYM +gypsum and RDF +gypsum.

The use of amendments also resulted in lower Zn and Cd contents in *Brassica carinata* than the control. Under all treatments, the Zn and Cd contents in *Brassica carinata* were within the acceptable limits. Farmyard manure was shown to be the most effective in lowering Zn intake by roots (34-36%), whereas RDF + FYM + gypsum was most effective in reducing Zn uptake by shoots (14-30%). The mean concentration of Cd in the roots and shoots reduced by 36-60% and 42-67%, respectively, when the changes were implemented. Despite the fact that all treatments reduced Cr absorption by roots, the content of Cr in the roots of *Brassica carinata* remained above permitted limits. All of the amendments had no significant influence on the Cr concentration in *Brassica carinata* shoots, which was much lower than 0.5 mg kg. The two-way ANOVA (Table 6) test revealed significant ($P < 0.01$) impacts of organic amendment types and rates on heavy metal levels in *Brassica carinata* roots. Organic amendment rates had a substantial influence on heavy metals in *Brassica carinata* shoots. However, the types of organic amendments only had a significant effect on the concentrations of Cd and Cr, with no significant effect on Cd and Zn.The types and rates of organic amendments had no significant effect on the Cd concentration of *Brassica carinata* roots and shoots, but they did on Zn, Cd, and Cr levels.

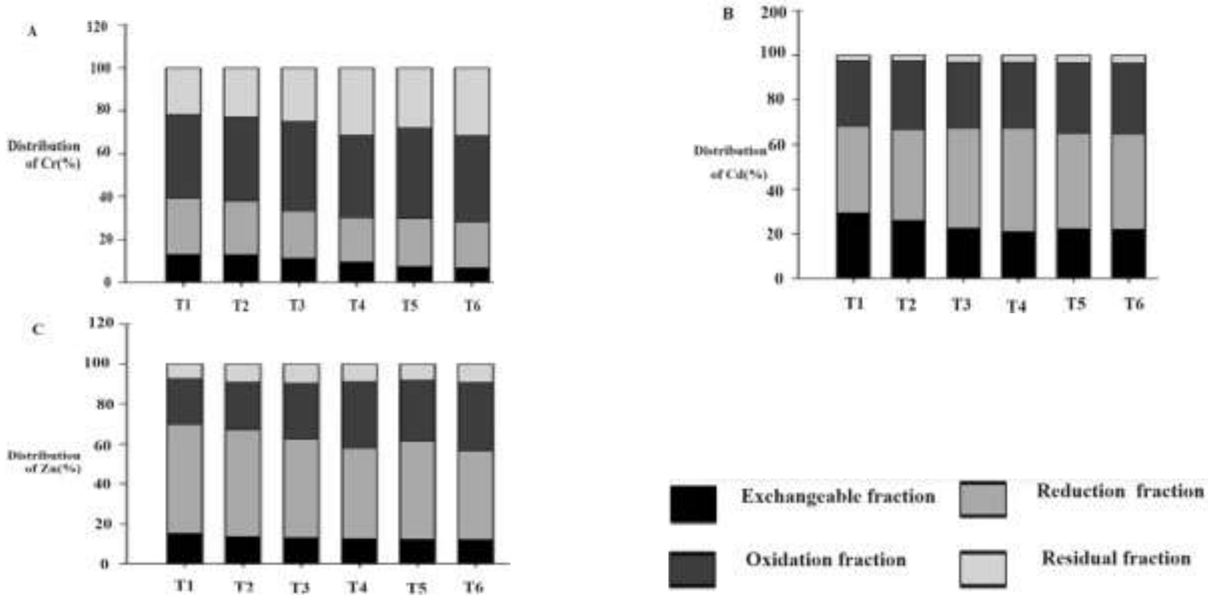

Figure 3: Speciation of heavy metal in soils amended with different proportion amendments.

		Root heavy metal (mgkg^{-1}FW)				Shoot heavy metal (mg kg^{-1} FW)		
Treatment	Root fresh weight (g)	Cd	Zn	Cr	Shoot fresh weight (g)	Cd	Zn	Cr
T1	2.25 0.14d	0.51 0.03a	14.43 0.13a	1.91 0.09a	35 3e	0.71 0.06a	11.26 0.23a	0.08 0.007d
T2	3.15 0.11c	0.35 0.01d	9.55 0.04e	1.05 0.04c	46 2d	0.51 0.04b	0.96 0.27b	0.06 0.002f
T3	3.29 0.14bc	0.34 0.01d	9.58 0.44e	0.96 0.04cd	52 3c	0.41 0.04de	8.56 0.01f	0.07 0.004e
T4	4.12 0.09a	0.28 0.01f	9.27 0.03e	0.60 0.05g	56 4ab	0.35 0.03f	7.89 0.20h	0.09 0.002cd
T5	3.25 0.13bc	0.38 0.02bc	12.00 0.01bc	1.57 0.04b	52 2c	0.49 0.03bc	9.67 0.05c	0.07 0.002ef
T6	3.42 0.14b	0.35 0.01d	11.83 0.01c	0.87 0.10de	56 2ab	0.42 0.02de	8.31 0.17g	0.09 0.011c

DISCUSSION

4.1 The effects of amendments on soil chemical properties

The results of this investigation showed that the application of amendments clearly improved soil parameters, including increases in pH, EC, and organic matter content, and that the larger the application volume, the more visible the impact (Fig. 1). FYM, FYM + RDF, and RDF +gypsum considerably enhanced the EC value; nonetheless, the EC cannot induce salty conditions.Increasing soil pH and organic matter, which is useful for heavy metal retention.As soil pH rises, accessible heavy metals are converted into hydroxide precipitation, which mixes with carbonate.

Table 4: comparison correlation coefficients between the parameters

	pH	Organic matter	Available Cr	Available Cd	Available Zn	Shoot Cr	Shoot Cd	Shoot Zn
pH	1.00							
Organic matter	0.71*	1.00						
Available Cr	-0.50	0.004	0.100					
Available Cd	-0.91**	-0.55	0.62	1.00				
Available Zn	-0.86*	-0.32	0.51	0.84**	1.00			
Shoot Cr	0.45	0.78**	0.30	-0.27	-0.06	1.00		
Shoot Cd	-0.95**	-0.68**	0.50	0.96**	0.83 **	0.96**	1.00	
Shoot Zn	-0.94**	-0.71*	0.49	0.93**	0.74	0.93*	0.86**	1.00

Significance between the parameter are indicated by *$p < 0.05$, **$p < 0.01$ level.

This reduces the mobility and biological toxicity of heavy metals in soil.The most major element impacting Cr mobility in the soil is the increase in soil pH value generated by the bioagent. In general, soil with a greater organic matter content can reduce Cd, Cr, and Zn concentrations in plants more than soil with a lower organic matter level.Average variations in Cd and Zn contents in *Brassica carinata* shoots exhibited a substantial negative correlation with soil organic matter content (Table 4).

4.2 Effects of amendments on the availability of Cd, Zn, and Cr

Adsorption of Cr (complexation and electrostatic interactions) and Cd (complexation, cation exchange, and precipitation) occurs through many methods. Cr and Cd adsorption on HA involves considerable electrostatic interaction. In this investigation, all of the amendments considerably reduced the concentration of available Cd and Zn in the contaminated soil, with FYM and RDF + FYM + gypsum being more effective in reducing metal mobility (particularly for Cd and Zn) (Fig. 2). Cd and Zn solubility and mobility were strongly inversely linked to soil pH (Table 4).The combination between bioagent with RDF raised soil pH, lowering the concentration of extractable metals containing $CaCl_2$. The addition of compost made from maize straw, sewage sludge, and bioagent to the soil considerably lowered the concentrations of mobile Cu and Cd. The content of $CaCl_2$ extractable Cd in the soil fell by 57.9% and 63.8% over the first year.

Cd and Zn levels had increased by 53.6% and 66.8%, respectively.FYM and RDF +FYM +gypsum can effectively lower the available concentration of Cr in the soil, whereas RDF +gypsum can enhance Cr availability. It was discovered that the presence of humic acid encouraged the development of a humic acid iron water complex and hindered the production of iron hydroxide, thereby boosting Cr availability and mobility in the tailings.

4.3 Effects of amendments on the speciation distribution of Cd, Zn, and Cr

Heavy metal inactivation is typically assessed using two methods: morphological analysis and heavy metal absorption during plant development.The current state of heavy metals in soil is an essential predictor of their movement, alteration, and bioavailability. Heavy metals' internal qualities, soil physical and chemical features (pH, organic matter, etc.), and environmental conditions (moisture, imported heavy metals, etc.) all have an impact on heavy metal distribution in the soil. Various amounts of all amendments can decrease the exchangeable percentage of Cd and Zn while increasing the oxidation and residual fractions (Fig. 4). The rise in pH will aid in the immobilization of Cd and Zn. The addition of amendments increases soil pH, which reduces the exchangeable percentage and promotes the immobilization of Cd and Zn.The pH of the soil rises after applying bioagent. The calcium carbonate and oxides on the surface of rice husk-derived bioagent tend to generate $CdCO_3$ and Cd-oxide compounds, which induce the adsorption and precipitation of $CdCO_3$ and limit the exchangeability of Cd in the contaminated soil. Bioagents and FYM boost soil organic matter content while also improving heavy metal and organic pollutant absorption. It is stated that the low quantity of soil organic matter and the weak binding capacity of soil Cd may contribute to the decrease, or perhaps disappearance, of the Cd residual fraction in the soil. FYM and bioagent (especially 3% bioagent) decreased water-soluble and exchangeable heavy metal components while increasing the treated soil's residual proportion. In the treated soil, the residual levels of Cr rose by 48, 56, 66, and 68%, respectively, compared to the untreated control. Furthermore, Ca, Mg, and other soil cations interchange with heavy metals, increasing the concentrations of the heavy metals' reduction, oxidation, and residual fractions while decreasing the easily exchangeable fraction. Furthermore, by lowering transportable and exchangeable heavy metals while boosting soluble nutrients, green waste FYM-bioagent is more efficient in reducing soil toxicity. Compared to the control, various quantities of FYM and RDF + FYM + gypsum considerably improved Cr, Cd, and Zn from the effective fraction to the ineffective fraction (Fig. 4).

4.4 Effects of amendments on the *Brassica carinata* growth and heavy metal accumulation

The addition of FYM, RDF + FYM + gypsum, and RDF + gypsum considerably boosted the biomass of *Brassica carinata*. The EDS patterns (Fig. 1) showed that several nutritional elements, such as K, Ca, Mg, S, and Fe, were present in FYM, encouraging *Brassica carinata* development.

One of the primary goals of adding manure to the soil is to boost plant nutrition in low-fertility soils.Numerous hydroxyl, carboxyl, and aromatic groups are present in bioagent, which raises the ion exchange point and may influence plant nutrient uptake.

As a result, adding FYM to the soil can increase yield greatly, however adding bioagent would not. Humic acid contains a lot of organic matter and improves the ability of nitrogen fixation, phosphorus decomposition (the transformation of soil organic phosphorus to available phosphorus) and potassium fixation in the soil, so humic acid promotes plant absorption of nitrogen, phosphorus, and potassium and is conducive to plant growth.

RDF +FYM +gypsum and RDF +gypsum both had a somewhat better effect on *Brassica carinata* biomass than FYM.

However, whereas FYM, RDF +FYM +gypsum, and RDF +gypsum may greatly increase *Brassica carinata* yields, the amendments only slightly lowered harvestable amounts of heavy metals, bringing the shoot heavy metal levels to their peak. Heavy metal deposition in plants varies depending on soil conditions, amendment kinds, plant species, and heavy metal contaminants.Heavy metal concentrations in plants were shown to be positively linked with metal bioavailability, which was assessed using a variety of extraction techniques and soil extractants. Cd, Zn, and Cr bioavailability in soil was shown to be strongly positively linked with heavy metal level in Brassica carinata shoots (Table 5). The results revealed that the addition of FYM, RDF +FYM +gypsum, and RDF +gypsum lowered the bioavailability of heavy metals in the soil, as well as the concentration of heavy metals in the plants' shoots and roots (Table 3).

The plant's heavy metal absorption decreased when soil alkalinity and organic matter content increased. FYM, RDF +FYM +gypsum, and RDF +gypsum significantly enhanced soil pH and organic matter content, leading in lower Cd, Zn, and Cr concentrations in the *Brassica carinata* root and shoot, respectively. The bioagent has a high pH and enhances soil organic matter content, resulting in a 38%, 39%, 25%, and 17% reduction in average Cd,Cr, and Zn concentrations in plant tissues. The use of a bioagent derived from waste products dramatically lowered Cd contents in *Brassica carinata* shoots from 34% to 80%.

All of the amendments were successful in lowering Cd absorption by *Brassica carinata*; nevertheless, Cd concentrations in the shoot of *Brassica carinata* remained above the allowed limits (0.2 mg kg-1). When compared to the control, the treatment of the bioagent lowered the amounts of Zn and Cr. All of the modifications reduced the contents of Zn and Cr in *Brassica carinata* to levels below the permitted limits (20 mg kg-1 and 10 mg kg-1, respectively).
The use of a low-dose bioagent in combination with fertilizer lowered the Cr level in grain (brown rice) by 14-16%, but not in rice straw or root. Although all treatments had no significant effect on Cr concentration in *Brassica carinata* shoots, this was owing to minor variations in Cr mobility/phytoavailability in the amended soil. The use of amendments considerably reduced Brassica carinata's absorption of heavy metals, which might be another explanation for increased biomass output when compared to control. Leaf has a high heavy metal transfer rate, and FYM, RDF +FYM +gypsum, and RDF +gypsum effectively prevent heavy metal absorption, lowering daily intake and consequently health hazards.In our investigation, the kinds and rates of organic amendments had a substantial impact on the amount of accessible heavy metals in the soil and heavy metal accumulation in the plants. Bioagent manufacture costs more than the FYM. This immediately impacts cleanup and cost control.To get economic and effective results, it's vital to alter the types and rates of organic amendments.

CONCLUSIONS

This study presents an efficient and affordable FYM for amending multimetal polluted agricultural soils.The inclusion of varied amendment ratios has the ability to lower Cd, Zn, and Cr buildup in *Brassica carinata* while increasing Brassica carinata production by 30-65%, making it a viable choice for the safe cultivation of heavy metal-contaminated soil.
Applying FYM alone or in combination with RDF +FYM +gypsum or RDF +gypsum to polluted soil might raise soil pH and organic matter content, reducing heavy metal mobility and available concentrations. All changes improved Cd, Zn, and Cr stability from effective to ineffective fractions, compared to the control group.
However, in order to balance the link between the remediation impact and cost management, it is still important to further tune the additive ratio between FYM, RDF, and Gypsum, so as to limit the buildup of heavy metals in *Brassica carinata* and cut costs as much as feasible.

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