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Analysis of the Fertilizing and Bioremediation Potential of Leaf Litter Compost Amendment in Different Soils through Indexing Method

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Abstract

This research study explored the efficacy of leaf litter compost as a sustainable soil amendment with the objective of promoting soil health and mitigating the accumulation of potentially toxic elements. The investigation encompassed the impact of various organic compost amendments, including leaf compost, cow dung manure, kitchen waste compost, municipal organic waste compost, and vermicompost. The study employed Inductively Coupled Plasma Mass Spectrometry (ICP-MS) to evaluate soil nutrient levels and concentrations of Potentially Toxic Elements (PTEs) such as arsenic, chromium, cadmium, mercury, lead, nickel, and lithium. The fertilization and bioremediation potential of these compost amendments are quantified using an indexing method. Results indicated a substantial increase in overall nutrient levels (carbon, nitrogen, phosphorus, potassium, and sulfur) in soils treated with leaf compost and other organic composts. Fertility indices (FI) are notably higher in compost-amended soils (ranging from 2.667 to 3.938) compared to those amended with chemical fertilizers (ranging from 2.250 to 2.813) across all soil samples. Furthermore, the mean concentrations of PTEs were significantly lower in soils treated with leaf compost and other organic compost amendments compared to those treated with chemical fertilizers amendments. The assessment through the indexing method revealed a high clean index (CI) for leaf compost amendment (ranging from 3.407 to 3.58), whereas the chemical fertilizer amendment exhibits a relatively lower CI (ranging from 2.78 to 3.20). Consequently, leaf compost and other organic composts exhibit the potential to enhance sustainable productivity, promoting soil health and environmental safety by improving nutrient levels and remediating potentially toxic elements in the soil.

Keywords

Bio-Compost, Soil Fertility, Potentially Toxic Elements, Bioremediation

1. Introduction

Soil degradation and pollution with toxic elements have significantly challenged sustainable productivity and environmental safety worldwide. Industrial activities, excessive use of agrochemicals, and improper waste management practices have accumulated various contaminants in soil, such as heavy metals, pesticides, and organic pollutants [1]. The contamination of soil and the environment by toxic elements presents considerable risks to human health, ecosystems, and overall environmental integrity [2]. These elements, including heavy metals such as lead, mercury, cadmium, and arsenic, pose serious concerns as they enter the food chain, impacting plants, animals, and humans. Chronic exposure can result in health issues such as neurological disorders and developmental problems [3]. Moreover, elevated levels of toxic elements disrupt soil-dwelling organisms, leading to biodiversity loss and affecting ecosystem health [4]. Soil fertility could be compromised which significantly influences sustainable productivity. Contaminated soil contributes to water pollution through leaching and runoff, posing threats to aquatic ecosystems and groundwater [5]. The persistence of toxic elements in the environment leads to bioaccumulation and biomagnification, amplifying risks over time. Furthermore, the interaction of toxic elements with carbon cycling in soil may influence climate change dynamics, contributing to broader environmental challenges. Comprehensive monitoring, remediation strategies, and sustainable soil management practices are imperative to mitigate these risks and safeguard human health and ecosystems.

Remediating contaminated soils is crucial for restoring their fertility, promoting healthy plant growth, and minimizing the potential risks associated with these pollutants. Bioremediation, a cost-effective and environmentally friendly approach, utilizes the remarkable potential of microorganisms to degrade or transform contaminants into less harmful forms [6]. Bio-composts, which are rich in organic matter and beneficial organisms, have emerged as a promising bioremediation tool for contaminated soils [7]. These bio-composts can be produced by decomposing organic wastes, such as leaf litter, kitchen waste, municipal organic solid waste, and other organic wastes [8] [9]. The bio-composts such as leaf litter, kitchen waste, and vermicompost were reported to have high fertilizing potential with low potentially toxic elements (PTEs) content [10]. The resulting bio-composts could improve soil fertility and enhance microbial activity, thus facilitating the breakdown of pollutants [11].

Various studies have explored the bioremediation potential of bio-composts in different soil types and cropping systems [12] [13] [14]. They reported that bio-composts are effective in improving soil fertility and plant health. However, a comprehensive analysis of bio-composts' effectiveness in remediating soil contamination, such as potentially toxic elements under diverse conditions, is still lacking. Therefore, this research study aims to provide a comprehensive analysis of the fertilizing and bioremediation potential of leaf litter compost and other organic waste compost, viz. cow dung manure, kitchen waste compost, municipal organic waste compost, and vermicompost, focusing on their performance in different soil types, with a specific emphasis on the novel aspects of bio-remediating PTEs and mineralization of nutrients in the soils. The assessment of the fertilizing potential was achieved through indexing method reported by Mahongnao *et al.* [10]. The fertility index (FI) was calculated based on the levels of six nutrient contents viz. carbon, nitrogen, potassium, phosphorus, sulphur, and the calculated C: N ratio, in the soil amendments.

Moreover, this study also explores the influence of leaf-based composts and other organic waste compost amendments on the bio-remediation of the potentially toxic elements in different types of soils. The bioremediation efficiency of the compost amendments was also assessed through clean indexing (CI), which was calculated based on the levels of twenty-two elements in the soil samples. By examining the performance of the bio-composts amendments, this research aims to shed light on the potential interactions between the compost amendment and bioremediation of PTEs in the soil, with an innovative perspective on how these systems can be optimized for enhanced bioremediation outcomes.

The outcomes of this comprehensive analysis will contribute to our understanding of the compost's bioremediation potential and provide valuable insights for developing sustainable soil management strategies. The findings can guide us in implementing effective bioremediation practices that restore soil health and mitigate the risks associated with toxic elements contamination. Furthermore, the novel aspects of this research will offer unique perspectives on the application of bio-composts in diverse soil types, providing innovative solutions for soil fertility and bioremediation challenges.

2. Materials and Methods

2.1. Experimental Setup, Sample Collection and Preparation

Two distinct soil types were procured from disparate locations in North Delhi, India: floodplain soil obtained from the Yamuna floodplain near Usmanpur area (28˚41'48"N, 77˚12'38"E), characterized as an alluvial soil, and residential soil from the University of Delhi's North Campus (28˚41'16"N, 77˚12'19"E), classified as sandy soil (**Figure 1**). These soils were meticulously blended with various composts, including leaf-based compost, cow dung manure, kitchen waste compost, municipal organic waste compost, and vermicompost, at a predetermined ratio of 5:1 (w/w) before potting. Additionally, a control group was established employing soil and chemical fertilizers, devoid of compost amendment. Diammonium phosphate (DAP), calcium, and phosphate were combined with soil at a ratio of 4:1:1, measured in grams per kilogram of soil. Pre-plantation

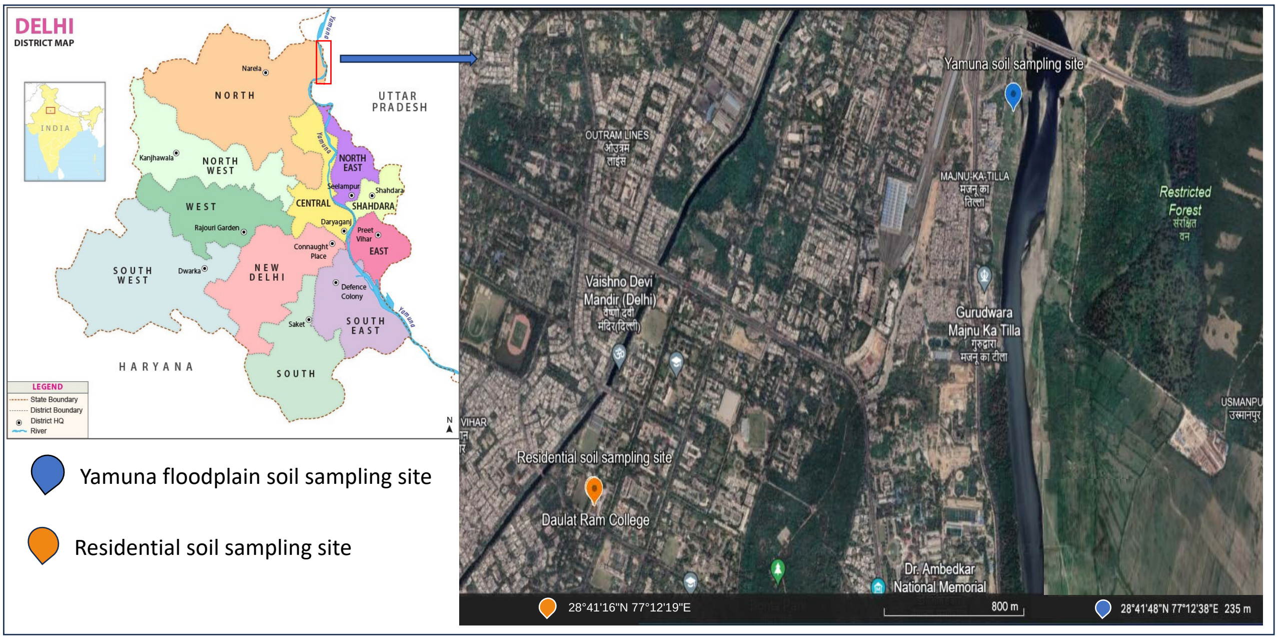


Figure 1. Mapping of the soil sampling sites. Two soil types for potting were collected from two locations, one was collected from the Yamuna floodplain soil, which is an alluvial type of soil, while the other was collected from the residential soil, which is a sandy type of soil.

soil samples weighing 250 grams each were meticulously collected in sterilized zip-lock polybags. Subsequently, red amaranth (*Amaranthus cruentus*) seedlings were potted using the aforementioned soils in different pots, with a total of six pots per soil amendment. The plantation encompassed red amaranth (*Amaranthus cruentus*), green amaranth (*Amaranthus viridis*), and spinach (*Spinacia oleracea*). The seedling and potting activities transpired in April within ambient environmental conditions, with harvest taking place in the initial week of July. Throughout the growth period, the average temperature ranged from 29˚C to 33˚C, with humidity levels between 29% and 46%. Post-harvest soil samples, amounting to 250 grams per pot, were meticulously collected at a soil depth of approximately 8 to 12 centimetres, utilizing a sterilized spatula and stored in zip-lock polybags for further analysis. The air-dried soils were grounded and sieved through a 2.00 to 4.00 mm sieve. All the samples were analysed in triplicates for each parameter and the mean values were reported.

2.2. The pH and Electrical Conductivity (EC)

The pH and EC of the soils were measured using a pH and EC meter following the standard method. For the analysis, the 12 gm of soil samples were dissolved in 24 ml of distilled water, stir it well and let stand for 2 minutes. After that, measurements were carried out using pH and EC meters [15] [16].

2.3. The Total Carbon, Nitrogen and Sulphur (CNS)

The levels of carbon (C), nitrogen (N), and sulphur (S) in the soil samples were measured using a CHNS analyser (varioEL cube, Ser.no: 19171021). About 6 to

10 mg of the soil samples were measured and put in the sample holder of the instrument. The instrument was run with the combustion temperature set at 1150˚C and the reduction temperature at 850˚C. Also, the helium pressure was set at 1200 milli-bar [17].

2.4. Micronutrients and Potentially Toxic Elements (PTEs)

The soil samples were heat-digested using tri acids (hydrofluoric acid (HF), nitric acid (HNO_3), and perchloric acid ($HClO_4$) on a hot plate following a standard method [18]. Each sample was digested in triplicates. For this process, 0.5 g of soil sample was heated on the heating plate at 90˚C for 4 hours in a Teflon crucible with tri-acids of 10 ml of concentrated HF (48%), 5 ml of HNO_3 (69% - 72%), and 2 ml of $HClO_4$ (70%). After 4 hours, the cover of the Teflon crucible was opened and continued heating till dryness. A mixture of the tri-acids, 5 ml of concentrated HF, 10 ml of concentrated HNO_3, and 2 ml of $HClO_4$ were added and continued heating with the till dryness. 10 ml of concentrated HNO_3 was added again, and heating continued at 90˚C till complete dryness. Then, 20 ml of 1 N HCl was added to bring the samples into the solution. The digested soil solution was diluted to 100 ml by adding MilliQ water. Then, the filtration was done using Whatman filter paper no. 2 and subjected to another filtration using 0.45-micron filter paper under vacuum pressure. The elemental analysis of the tri-acids-digested soil samples was done by inductively coupled plasma-mass spectrometry (ICP-MS) following standard protocol [10]. The micronutrients analysed include boron, cobalt, copper, molybdenum, manganese, and zinc. The potentially toxic elements included in this study were arsenic, cadmium, chromium, lithium, nickel, mercury, and lead. The certified reference material (CRM), SQC001 Metal in soil, Sigma, was used as the standard reference for obtaining the calibration curve. Also, the ^{129}Xe present in argon gas was measured as an internal standard, with a recovery rate between 80% - 120%. The measurements were done using an iCAP-Q ICP-MS from Thermo-Scientific in KED (kinetic energy discrimination) mode. All the elements analysed had the detected value of correlation coefficient (R^2) less than 99.0%, and the average percentage offset was less than 10 per cent. For the data validation, a fixed concentration of CRM-SQC001 was run after every ten samples as an unknown sample. The data generated were analysed using QTEGRA ISDS software. All the values reported in this study are the means of three independent runs.

Different parameters were given the score values from 1 to 5 based on the analytical values. Each parameter was also given a weightage factor based on their biological importance.

2.5. Fertility Index (FI) and Clean Index Calculation

The methodology for calculating the Fertility Index (FI) and Clean Index (CI) is derived from the modified model proposed by Mahongnao *et al.* [10]. The Fertility Index is determined based on six parameters of nutrient levels, each assigned a score value (“Si”) and a corresponding weightage factor (“Wi”) as outlined in Table 1. The FI is computed using the following formula:

$$\text{Fertiling Index} = \sum SiWi \Big/ \sum Wi \tag{1}$$

Where “Si” represents the score value of the “i^{th}” fertility parameter, and “Wi” is the weightage factor associated with the same parameter.

Similarly, the Clean Index is computed based on the score values (“Sj”) and weightage factors (“Wj”) of twenty-two metals found in the soil amendments, as detailed in Table 2. The CI is determined using the following formula:

$$\text{Clean Index} = \sum SjWj / Wj \tag{2}$$

In this equation, “Sj” signifies the score value of the “j^{th}” element, and “Wj” represents the weightage factor associated with that particular element.

Different elements were given the score values from 1 to 5 based on its concentration levels. Higher concentration range was given a lower score value. Each parameter was also given a weightage factor based on their biological importance and its toxicity levels. More toxic elements were given higher weightage.

2.6. Statistical Analysis

The parameters analysed were subjected to the ANOVA analysis using GraphPad Prism 10.0 software to identify the statistically significant variation of the analytical data among the samples. Two-way ANOVA was performed on all the analytical parameters keeping the organic compost amendment and plantation as two influencing factors. A post-hoc analysis through Dunnett’s test ($p < 0.05$) was also performed keeping the fertilizer amendment and the referencing sample.

Table 1. The score value and weightage factor of the parameters for calculating the fertility index (FI).

Parameters	**Score Value (Si)**					**Weightage Factor (*Wi*)**
	5	**4**	**3**	**2**	**1**	
Total Carbon (TC)	>9.0	6.0 - 9.0	3.0 - 6.0	01.0 - 3.0	<1	5
Total Nitrogen (TN)	>1.25	1.01 - 1.25	0.81 - 1.00	0.51 - 0.80	<0.51	3
C: N ratio	<10.1	10.1 - 15	15.1 - 20	20.1 - 25	>25	3
Total Phosphorus (TP)	>0.60	0.41 - 0.60	0.21 - 0.40	0.11 - 0.20	<0.11	3
Total Potassium (TK)	>0.1	0.076 - 0.1	0.051 - 0.075	0.026 - 0.050	<0.026	1
Total Sulphur (TS)	>0.5	0.5 - 0.4	0.4 - 0.3	0.3 - 0.2	<0.2	1

Table 2. The score value and weightage factor of various elements for calculating the clean index (CI).

Element	Score Index (*Sj*)						Weightage Factor (*Wj*)
	5	4	3	2	1	0	
Mn	<300	301 - 900	901 - 1200	1201 - 1500	1201 - 1400	>1500	1
B	<3.0	3.0 - 5.0	5.0 - 7.0	7.0 - 9.0	9.0 - 11.0	>11.0	1
Zn	<0.151	0.151 - 0.300	0.301 - 0.500	0.501 - 0.700	0.701 - 0.90	>0.90	1
Ti	<15	15.1 - 20	20.1 - 25	25.1 - 30	30.1 - 35	>35	1
Sn	<2	2.1 - 3	3.1 - 4	4.1 - 5	5.1 - 6	>6	1
Sr	<1	1.1 - 10	10.1 - 20	20.1 - 30	30.1 - 40	>40	1
Sb	<1	1.1 - 2	2.1 - 3	3.1 - 4	4.1 - 5	>5	2
Ba	<100	100 - 200	200 - 300	300 - 400	400 - 500	>500	2
Li	<2	2.1 - 4	4.1 - 6	6.1 - 8	8.1 - 10	>10	2
Be	<1	1.1 - 5	5.1 - 10	10.1 - 15	15.1 - 20	>20	2
Co	<10	10.0 - 20.0	20.1 - 30.0	30.1 - 40.0	40.1 - 50.0	>50	2
Mo	<2	2.1 - 4.0	4.1 - 6.0	6.1 - 8.0	8.1 - 10.	>10	2
Cu	<51	51 - 100	101 - 200	201 - 400	401 - 600	>600	2
V	<10	10.1 - 30	30.1 - 50	50.1 - 70	70.1 - 90	>90	2
Ni	<21	21 - 40	41 - 80	81 - 120	121 - 160	>160	2
Tl	<0.15	0.15 - 0.25	0.26 - 0.35	0.36 - 0.55	0.56 - 0.75	>0.75	2
Se	<0.5	0.5 - 1.5	1.6 - 2.5	2.6 - 3.5	3.6 - 7.5	>7.5	3
Pb	<100	100 - 150	150 - 200	200 - 250	250 - 300	>300	3
Cr	<51	50 - 100	100 - 150	150 - 200	200 - 250	>250	3
Cd	<0.3	0.3 - 0.6	0.7 - 1.0	1.1 - 2	2.0 - 4.0	>4.0	5
As	<4	4.0 - 8.0	8.1 - 12	12.1 - 16.0	16.1 - 22.0	>22	5
Hg	<0.025	0.025 - 1.0	0.1 - 0.2	0.21 - 0.3	0.31 - 0.4	>0.4	5

3. Results and Discussion

3.1. The pH and Electrical Conductivity of Soils Amended with Different Bio-Composts

The pre-plantation and post-harvest soils from the Yamuna floodplain exhibited alkaline pH, ranging from 7.66 to 8.56 before planting and 8.01 to 8.46 after harvesting. Kitchen and municipal waste compost-amended soil samples generally displayed the highest alkaline pH, persisting after the harvest of green amaranth, red amaranth, and spinach. Post-harvest pH values were comparable to or slightly higher than pre-plantation values. Bio-compost-amended soils had higher pH than chemical fertilizer amendments. Residential soil pH before plantation ranged from 8.15 to 8.62, with post-harvest values within a similar alkaline range (8.08 to 8.48). Post-harvest soil pH, on average, was slightly lower than pre-plantation (Figure 2). Chemical fertilizer-amended soil had a lower pH than leaf compost-amended but higher than other bio-compost-amended soils.

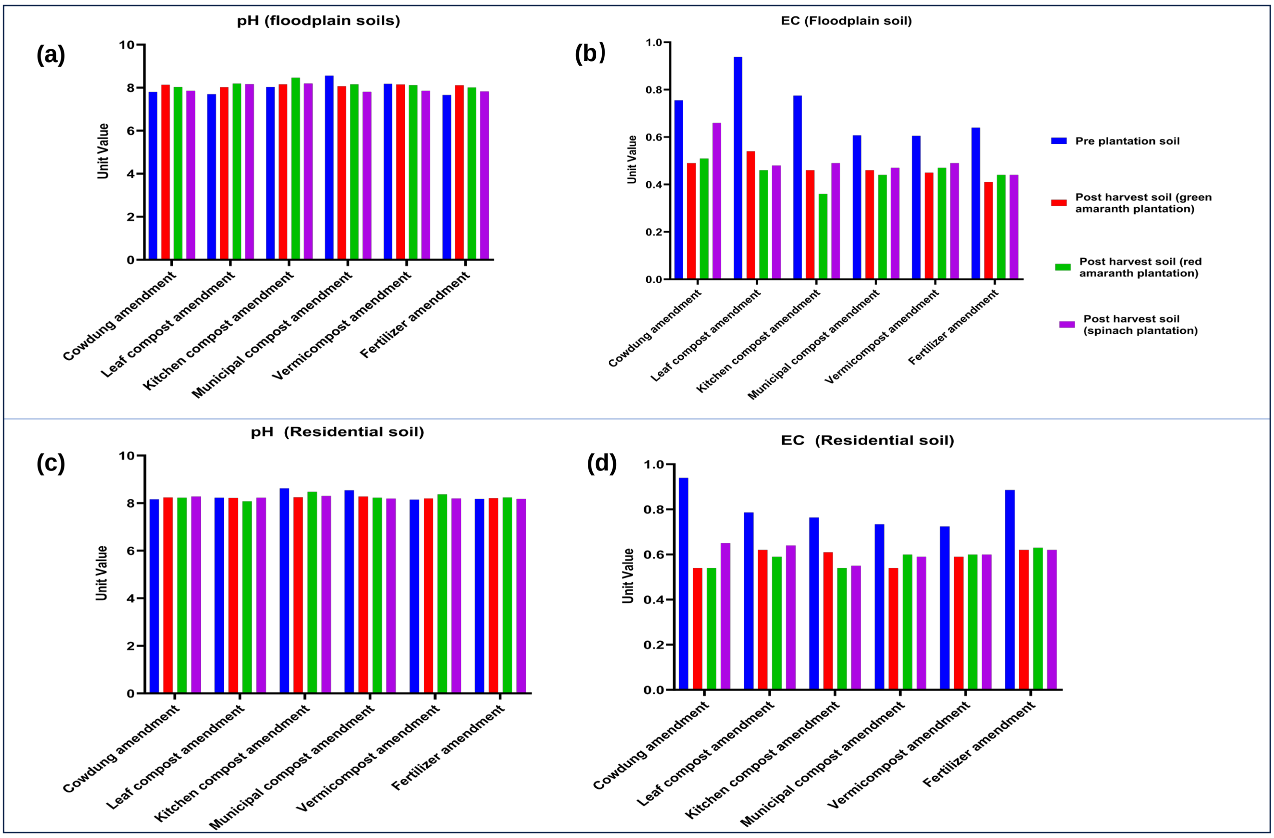


Figure 2. The pH and electrical conductivity (EC) of pre-plantation and post-harvest soils of various compost amendments and plantations.

Overall, pH variations across all samples were insignificant ($p > 0.05$), suggesting that crop cultivation and harvest minimally affected soil pH. Bio-compost amendments generally yielded higher pH than chemical fertilizers, except for leaf litter compost-amended soil, indicating amendment type influences pH. Despite slight decreases in post-harvest pH in residential soil, variations were statistically insignificant, highlighting consistent pH levels regardless of amendments or planting stages. Soil pH is integral to soil fertility, exerting a profound impact on key factors that govern plant growth and nutrient availability. The pH level directly influences the solubility and accessibility of essential nutrients, with optimal pH conditions ensuring plants can efficiently uptake nitrogen, phosphorus, potassium, and micronutrients. Microbial activity, vital for nutrient cycling and organic matter decomposition, is strongly influenced by soil pH, with an optimal range fostering a diverse and effective microbial community. Maintaining an appropriate pH also prevents aluminium and manganese toxicity in acidic soils, safeguarding root development and overall plant health. Furthermore, soil pH dictates the efficiency of biological processes, such as nitrogen fixation, and contributes to the buffering capacity of the soil, providing stability for crops. Recognizing the crop-specific pH preferences ensures tailored conditions for maximum yield and quality. Efficient fertilizer use is contingent upon maintaining the right pH, ensuring nutrients are effectively utilized by plants. In essence, soil pH is a critical determinant of soil fertility, guiding sustainable agricultural practices and optimizing conditions for robust plant growth.

The electrical conductivity (EC) values of soil samples collected from the Yamuna floodplain exhibited a range of 0.605 mS/cm to 0.938 dS/m prior to plantation and 0.36 dS/m to 0.66 dS/m post-harvest. Notably, soils amended with leaf compost and vermicompost demonstrated the highest and lowest EC levels, respectively, before plantation. Conversely, soils amended with cow dung manure and chemical fertilizer exhibited the highest and lowest EC levels after harvest. The observed reduction in EC values in post-harvest soil samples suggests a dynamic response to the growth cycle. Specifically, the bio-compost-amended soil samples displayed higher EC values than those amended with chemical fertilizer, though the differences were not statistically significant ($p > 0.05$). Residential soil samples, on the other hand, exhibited EC values ranging from 0.724 mS/cm to 0.939 mS/cm before plantation and 0.54 mS/cm to 0.65 mS/cm after harvest. The post-harvest period saw a significant decrease in EC values compared to pre-plantation soils ($p < 0.0001$). In the residential context, soil amended with chemical fertilizer showed a higher EC value than those amended with leaf compost and other bio-composts, although this difference was statistically insignificant (**Figure 2**). The reduction in EC values post-harvest may be attributed to nutrient uptake by plants during the growth phase or leaching of soluble salts from the soil. Utilizing organic bio-compost has the potential to enhance soil organic matter, thereby improving soil fertility and structure [19] [20] [21]. However, the specific impacts on EC values are contingent upon the composition and properties of the amendments employed.

Differences in EC values between bio-compost and chemical fertilizer amendments suggest that distinct nutrient sources can influence soil salinity. Chemical fertilizers typically supply readily available nutrients, whereas organic amendments release nutrients gradually over time. Given the significant implications of soil salinity on plant growth and crop productivity, prudent nutrient management becomes imperative for maintaining a balanced soil environment [22] [23] [24]. Consequently, organic amendments may exert varying effects on the electrical conductivity of soil, underscoring the need for a nuanced understanding of amendment composition and its impact on EC values. The observed reduction in EC after harvest underscores the potentially positive influence of plant growth and nutrient uptake on mitigating soil salinity.

Electrical conductivity (EC) plays a crucial role in assessing and managing soil fertility. It serves as a reliable indicator of soil salinity, helping identify potential challenges to plant growth by signaling the concentration of soluble salts [25]. EC measurements also provide insights into nutrient availability. Furthermore, EC values reflect soil texture and structure, aiding in tailoring soil management approaches based on composition. The assessment of organic matter content, influenced by EC, contributes to gauging overall soil health. Monitoring changes in EC over time facilitates the evaluation of the effectiveness of soil amendments, supporting sustainable practices [26].

3.2. Fertility Index (FI) and Mineralization Potential of Compost Amendments in the Soil

The leaf compost and other organic waste compost amendments had varied fertility index before plantation and post-harvest soils (**Table 3**). Notably, a general trend of decreased fertility indices was observed in the post-harvest soil samples compared to their pre-plantation counterparts. However, this trend was notably deviated in the case of the leaf compost amendment, where a marginal increase in the fertility index was observed. The vermicompost amendment had the highest fertility index before plantation at 3.375 to 3.938. On the other hand, the leaf compost amendment had the highest FI in the postharvest soil samples at 3.208 to 3.75. These findings highlighted the varied impact of different organic compost amendments on soil fertility, suggesting that their efficacy may vary depending on the specific amendment and the stage of soil development. Significantly, the fertility index of the soil samples treated with organic compost amendments consistently surpassed that of soil samples treated with chemical fertilizer across all plantations and soil types. This robust observation signifies a positive and overarching trend favouring the adoption of organic compost as a superior soil amendment. The implications extend beyond specific plantations and soil characteristics, emphasizing the broader applicability of organic compost in enhancing soil fertility (**Figure 3**).

Table 3. The fertility index (FI) of pre-planation and post-harvest soil samples with different organic compost amendments in two different soil types.

Yamuna floodplain soil samples	FI of Pre-plantation soils	FI of Post harvest soils			
		Green Amaranth plantation	Red Amaranth plantation	Spinach plantation	Mean FI of post-harvest soils
Cow dung amendment (YC)	3.000	2.438	2.813	3.188	2.813
Leaf compost amendment (YD)	3.063	2.813	2.813	4.000	3.208
Kitchen compost amendment (YK)	3.875	2.688	2.813	2.500	2.667
Municipal compost amendment (YM)	3.188	2.813	2.813	3.313	2.979
Vermicompost amendment (YV)	3.938	2.375	2.813	2.313	2.500
Chemical fertilizer amendment (YF)	2.250	2.188	2.563	2.750	2.500
Residential soil samples					
Cow dung amendment (NC)	2.813	2.938	3.500	2.875	3.104
Leaf compost amendment (ND)	2.938	3.688	3.250	3.188	3.375
Kitchen compost amendment (NK)	3.063	3.063	3.438	2.875	3.125
Municipal compost amendment (NM)	3.063	2.875	3.813	2.875	3.188
Vermicompost amendment (NV)	3.375	3.313	3.313	2.875	3.167
Chemical fertilizer amendment (NF)	2.813	2.875	2.938	2.500	2.771

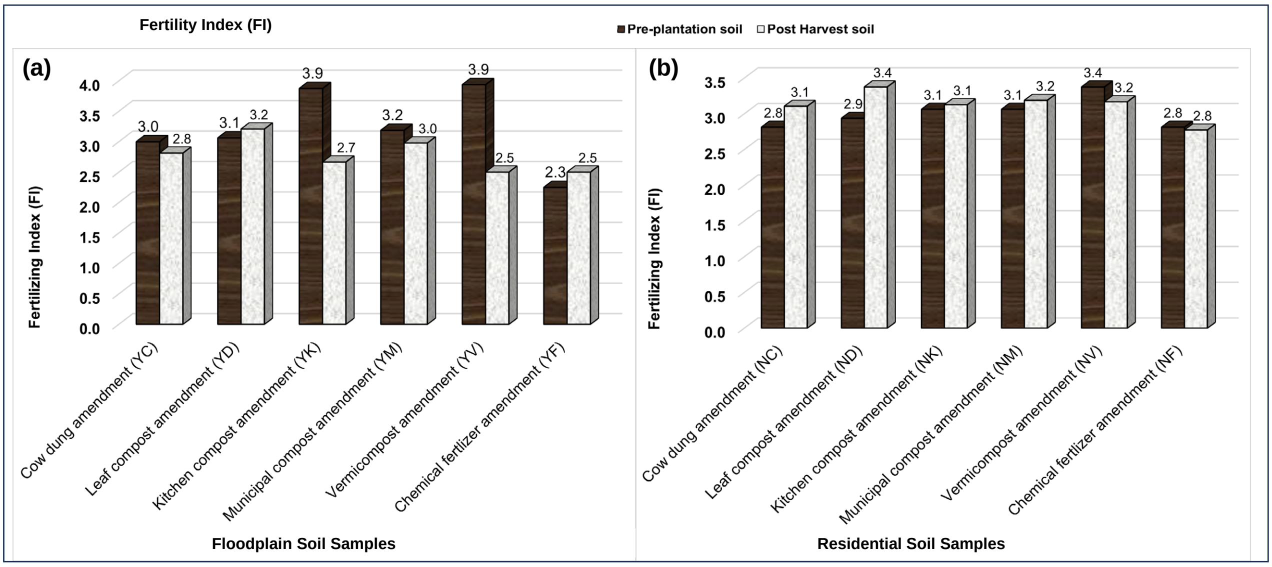


Figure 3. The mean fertility index (FI) of pre-planation and post-harvest soils with different organic compost amendments in two different soil types.

The carbon content of pre-plantation Yamuna floodplain soils, amended with leaf compost and chemical fertilizer, exhibited values of 6.7% and 2.3%, respectively. Other bio-compost amendments ranged from 3.7% to 6.6%. Pre-plantation residential soils, amended with leaf compost and chemical fertilizer, displayed carbon content of 2.69% and 1.40%, respectively. Chemical fertilizer-amended soil had the lowest carbon content in both Yamuna floodplain (2.3%) and residential soils (1.40%). Post-harvest Yamuna floodplain soils, amended with leaf compost, showed carbon content between 4.91% and 8.52%, while chemical fertilizer-amended soils ranged from 1.9% to 6.01%. Post-harvest residential soils, amended with leaf compost, had carbon content between 3.33% and 4%, while chemical fertilizer-amended soils ranged from 1.72% to 2.52%. Fertilizer-amended soil consistently exhibited lower carbon content than bio-compost-amended soils, with statistically significant variations ($p < 0.05$). The Dunnett test confirmed higher post-harvest carbon content than pre-plantation soils, particularly in residential and red amaranth plantations. Bio-compost-amended soils consistently had significantly ($p < 0.05$) higher carbon content than fertilizer-amended soils in both soil types, emphasizing the positive impact of bio-composts on soil carbon accumulation.

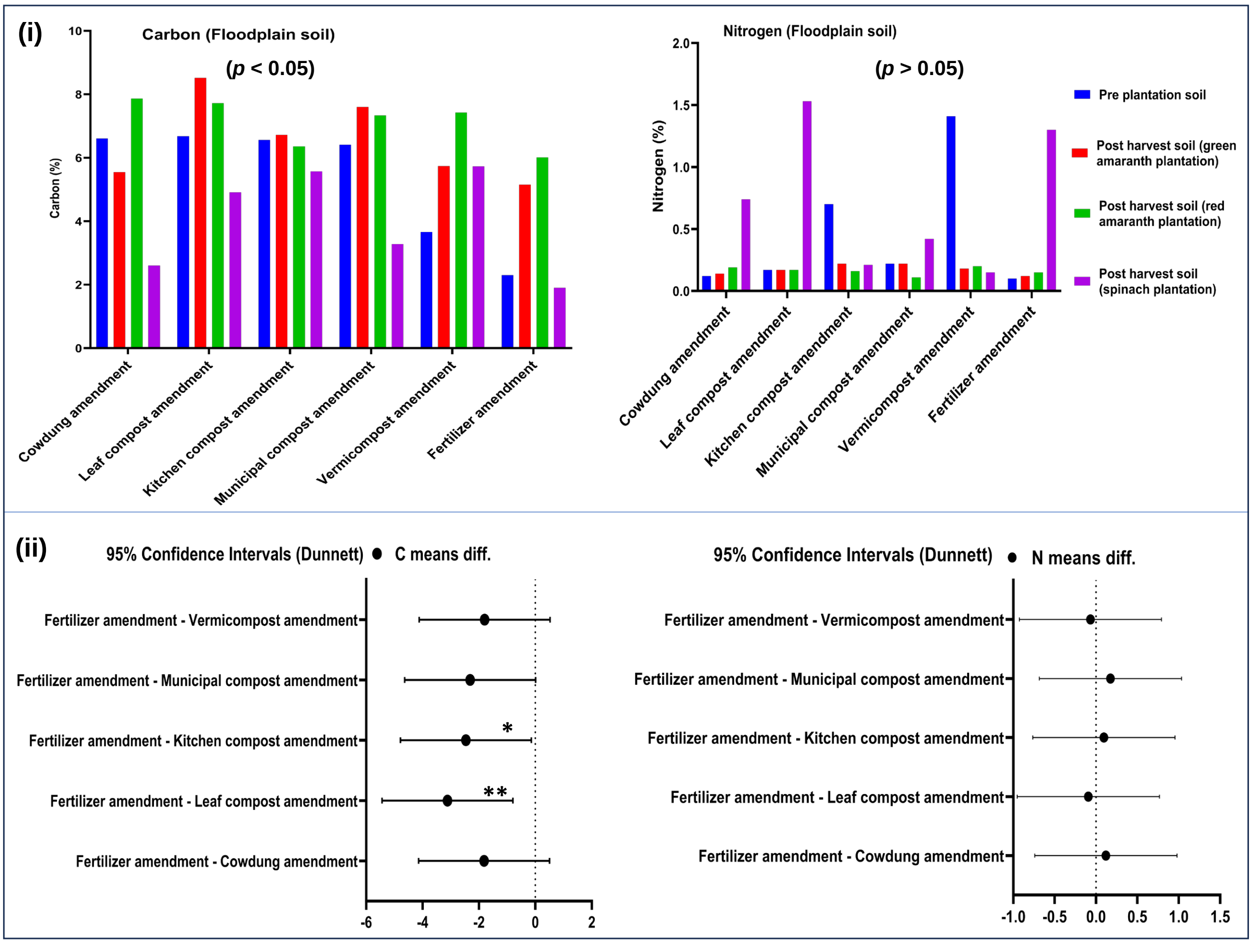
The carbon content of soils is a crucial factor in understanding soil fertility, nutrient cycling, and overall soil health. Soil organic carbon (SOC) is vital in soil structure, water-holding capacity, and nutrient availability, influencing plant growth and ecosystem functions [27] [28] [29]. The findings of the study revealed that the type of amendment applied to the soil significantly affects its carbon content. In both the Yamuna floodplain and residential soils, the carbon content was lowest in the soil amended with chemical fertilizer. This result suggested that chemical fertilizers might not contribute significantly to soil organic carbon accumulation. The results of our study were similar to previous studies that highlighted the limited impact of chemical fertilizers on SOC [30]. Bio-composts are rich in organic matter and provide a source of labile carbon that can support microbial activity and promote soil carbon sequestration [31]. The higher carbon content observed in bio-compost amended soils suggested that these organic amendments contributed to the accumulation of SOC and may have positive effects on soil fertility and ecosystem services. Overall, the results of this study suggest that incorporating bio-compost amendments, such as leaf litter compost, cow dung manure, kitchen waste compost, and vermicompost, could enhance soil carbon content and potentially improve soil fertility and ecosystem functions. These findings align with the growing interest in research emphasizing the benefits of organic amendments in promoting soil carbon sequestration and sustainable agriculture [32] [33] [34]. However, further research is needed to assess the long-term effects of these amendments on soil carbon dynamics and to evaluate their impacts on crop productivity and environmental sustainability.

The nitrogen concentrations within pre-plantation soil samples from the Yamuna floodplain exhibited a range of 0.10% to 1.41%, while residential soil samples displayed nitrogen levels spanning from 0.60% to 1.31%. Notably, vermicompost amendments manifested the highest nitrogen content in both soil types pre-plantation, registering at 1.41% for the Yamuna floodplains and 1.31% for residential areas. In contrast, fertilizer amendments resulted in the lowest nitrogen content within Yamuna floodplain soils, recording at 0.1%, while leaf compost amendments yielded the lowest nitrogen levels in residential soils, at 0.60%. Post-harvest, nitrogen levels witnessed a decline in Yamuna floodplain soils but experienced an increment in residential soils. However, the statistical insignificance ($p > 0.05$) of the difference in nitrogen levels between pre-plantation and post-harvest soil implies that the cropping cycle or harvest did not exert a discernible influence on nitrogen content. It is posited that factors such as nutrient uptake by crops, leaching, volatilization, or organic matter mineralization may have played pivotal roles in shaping nitrogen dynamics within the soil matrix (**Figure 4(a)** & **Figure 4(b)**). In juxtaposing bio-compost and chemical fertilizer amendments, both soil types demonstrated analogous nitrogen levels, with a marginal elevation observed in bio-compost amendments. This suggests that bio-compost amendments, encompassing vermicompost or leaf litter compost, have the potential to furnish nitrogen content on par with, or marginally surpassing, that supplied by chemical fertilizers—a corroboration consistent with antecedent research findings [35].

Nitrogen is a crucial element for plant growth and plays a fundamental role in soil fertility. It is a major component of amino acids, proteins, and chlorophyll, which are essential for plant structure, function, and photosynthesis [36]. Adequate nitrogen levels in the soil contribute to robust plant growth, increased crop yields, and overall agricultural productivity [37]. As a limiting factor in soil fertility, nitrogen availability exerts a discernible impact on an array of physiological and metabolic plant processes. Plants avidly assimilate nitrogen in the forms of nitrate (NO_3^-) and ammonium (NH_4^+), with these ionic species serving as primary nitrogen sources for plant nutrition. Nitrogen's involvement in enzymatic catalysis, nucleic acid synthesis, and hormonal regulation substantiates its pivotal role in modulating diverse facets of plant development and reproduction [38] [39].

Within the ambit of agricultural practices, nitrogen-containing fertilizers are routinely deployed to fortify soil fertility and stimulate plant growth. However, the judicious application of such fertilizers becomes imperative, as excessive usage may precipitate environmental ramifications, including water pollution via runoff and the emission of nitrogen oxides into the atmosphere [40]. Prudent soil management practices, inclusive of the incorporation of organic amendments such as bio-composts, emerge as instrumental strategies for maintaining optimal nitrogen levels, mitigating environmental impact, and fostering salubrious plant growth.

The phosphorus level in the pre-plantation soil samples of the Yamuna floodplain ranged from 0.56 mg/kg to 0.75 mg/kg. The chemical fertilizer amended soil had the lowest phosphorus level, while leaf litter compost-amended soil had the highest phosphorus content. The P level was slightly higher in the post-harvest



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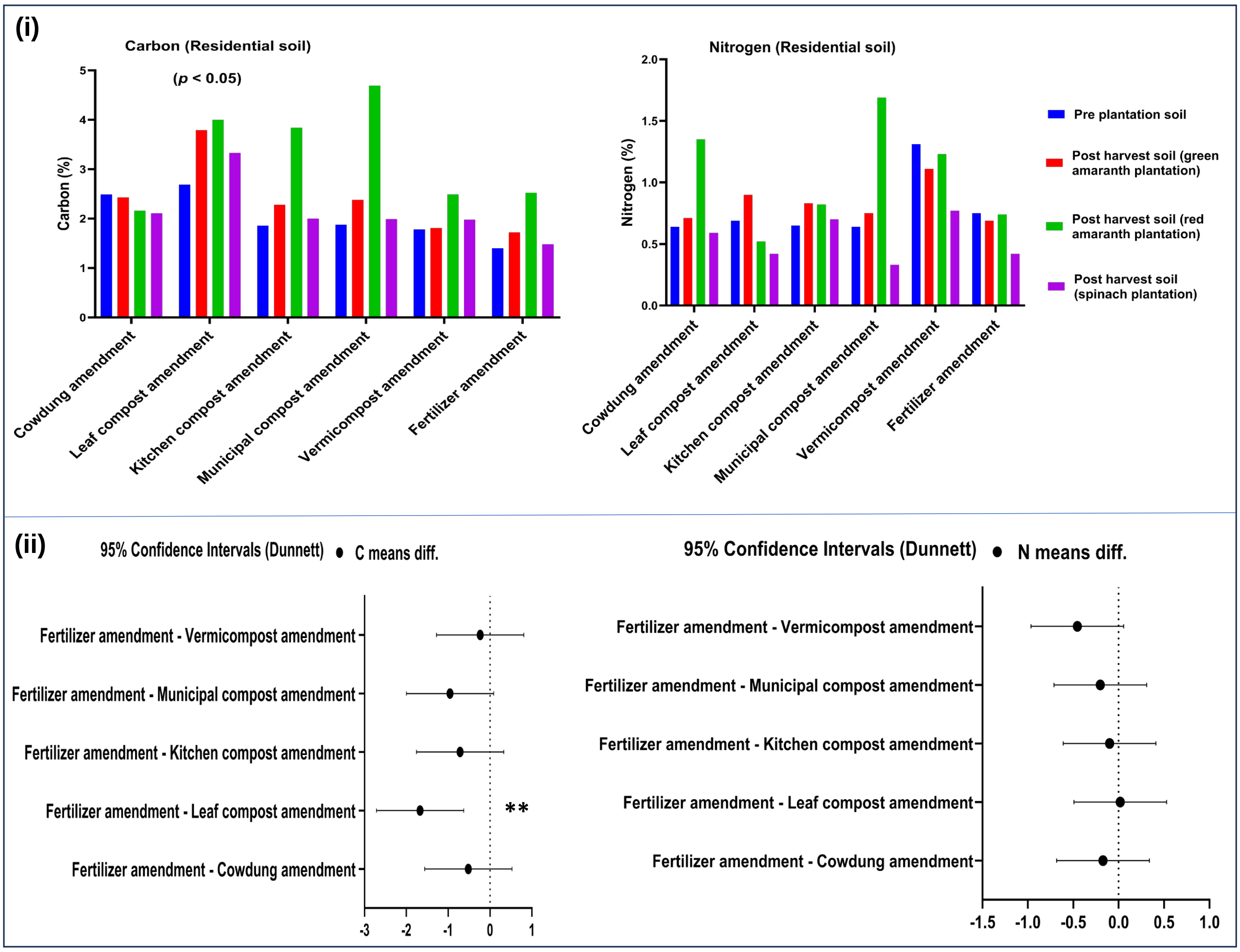

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Figure 4. (a) Mean level of Carbon and Nitrogen in the floodplain soils amended with different bio-composts and chemical fertilizer. The upper panel (i) of the graph shows the mean level of C and N in the pre-plantation and post-harvest soils of the Yamuna floodplain. The lower panel (ii) represents the mean differences of C and N between the chemical fertilizer amendment and the bio-compost amendments. * represented the statistical significance. (b) Mean level of Carbon and Nitrogen in the residential soils amended with different bio-composts and chemical fertilizer. The upper panel (i) graph shows the mean level of C and N in the pre-plantation and post-harvest soils of the residential soil. The lower panel (ii) illustrates the mean differences of C and N between the chemical fertilizer amendment and the bio-compost amendments. * represented the statistical significance.

soils than the pre-plantation soils, though the difference was not statistically significant ($p > 0.05$). The bio-compost-amended soil samples had higher P levels than the chemical fertilizer amended soil. The variation of P level in the leaf litter compost amended soil and chemical fertilizer amended soil was statistically significant ($p < 0.05$). Still, the variation was insignificant between the fertilizer amended soil and the other bio-compost amendments ($p > 0.05$). The residential soils had relatively lower phosphorus levels than the Yamuna floodplain soils. The pre-plantation residential soil samples ranged from 0.36 mg/kg to 0.56 mg/kg. The post-harvest soil samples had a higher level of P than the pre-plantation soils, and the bio-compost amendments had higher P levels than the chemical fertilizer amendment. However, the difference was not statistically significant. The variation in phosphorus level between the leaf litter compost-amended soil, and the chemical fertilizer-amended soil was statistically significant. This result signifies that the leaf litter compost amendment enriched the soil with phosphorus. Furthermore, it was observed that the residential soils had relatively lower phosphorus levels compared to the Yamuna floodplain soils. The post-harvest soil samples had a higher phosphorus level than the pre-plantation soils in both soil types, but this variation was insignificant. Phosphorus is an important macronutrient for soil health and plant growth, which could be enriched in the soil by adding bio-composts.

The potassium content in the pre-plantation Yamuna floodplain soil samples was highest in the municipal organic waste compost and cow dung manure amendments at 1093 mg/kg and 1067 mg/kg, respectively. At the same time, the leaf litter compost amendment and chemical fertilizer amendment had the lowest K level at 494 mg/kg and 547 mg/kg, respectively. The potassium level was significantly lower in the post-harvest soils ($p < 0.0001$). The lowest K content in the post-harvest Yamuna floodplain soil samples was observed in the chemical fertilizer amendment. At the same time, the highest level was seen in the municipal organic waste compost and cow dung manure amendment. Generally, the bio-compost amendments had a higher level of K than the chemical fertilizer amendment, but statistically higher only in the municipal organic waste compost and cow dung manure amendments ($p < 0.05$). The potassium level in the pre-plantation residential soil samples ranged from 579.7 mg/kg to 1012 mg/kg. The leaf litter compost amendment had the lowest level of K, while kitchen waste compost amended soil had the highest K content. The post-harvest residential soil samples had significantly lower levels of potassium ($p < 0.0001$). The bio-compost amendments had slightly lower levels of K than the fertilizer amendment, except in the cow dung manure amended soil, though the difference was statistically insignificant. Amendment of bio-composts such as cow dung manure, leaf litter compost, kitchen waste compost, municipal organic waste compost, and vermicompost, had higher enrichment of K in the soil in comparison to the chemical fertilizer in the case of the Yamuna floodplain soil samples. But the residential soil samples amended with bio-compost had a lower level of K than the fertilizer amendment. Also, the post-harvest soils had significantly lower levels of K in both soil types. Potassium is an essential plant macronutrient that promotes growth and development by controlling various metabolic pathways [41]. A deficiency of K could significantly affect plant growth and development [42]. Enrichment of K in the soil could be achieved through the appropriate application of soil amendments.

The pre-plantation Yamuna floodplain soil samples had sulphur content ranging from 0.1% to 4.7%, and the post-harvest soils had S of 0.06% to 0.29%. The cow dung manure amendment had the highest sulphur level, while the kitchen compost and vermicompost amendments had the lowest sulphur content before the plantation. While fertilizer amendment (0.06%) had the lowest S post-harvest, and the municipal organic waste compost amendment (0.29%) had the highest S among the post-harvest samples. The post-harvest soil samples had significantly lower levels of sulphur than the pre-plantation soil samples ($p < 0.05$). The soil samples amended with vermicompost, kitchen and leaf compost had similar levels of sulphur compared to the fertilizer amendment. The municipal organic waste compost and cow dung manure amendments had a higher sulphur level than the fertilizer amendment, though the variation was insignificant ($p > 0.05$). The residential soil samples had relatively lower levels of sulphur. The pre-plantation residential soil samples had a sulphur content of 0.04% to 0.22%. The fertilizer amendment had the lowest level, while the municipal organic waste compost amendment had the highest sulphur level. There was a significant reduction of sulphur in the post-harvest soils ($p < 0.05$). The sulphur level was slightly higher in the bio-compost-amended soil samples than in the fertilizer amendment but insignificant.

The Yamuna floodplain and residential soil samples of pre-plantation and post-harvest had sufficient micronutrients such as boron, cobalt, copper, manganese, molybdenum, and zinc. The boron levels in all the soil samples were above the suggested threshold limit of 1 to 2 mg/kg, according to the European Commission and Bureau of Indian Standards [43]. The post-harvest soil samples of the Yamuna floodplain had a lower B level than the pre-plantation soil, though the difference was not statistically significant ($p > 0.05$). On the other hand, the post-harvest samples of the residential soil had a significantly higher B content than the pre-plantation soil ($p < 0.05$). The bio-compost amended soil samples had a similar level of B to the fertilizer amendment in both soil types.

The post-harvest soil samples had more cobalt content than the pre-plantation soil in both types. The fertilizer amended soil had lower content of Co in the Yamuna floodplain soils but higher in the residential soils than the bio-compost amendments. However, the variation was not statistically significant ($p > 0.05$). The Yamuna floodplain soils had a higher content of copper than the residential soils. The Yamuna floodplain soil had Cu above the permissible limit of 50 mg/kg, according to the Central Pollution Control Board (CPCB), Govt. of India. The copper content in the post-harvest soil samples was higher in the Yamuna floodplain but lower in the residential soils than in the pre-plantation soil. However, the variation was not statistically significant ($p > 0.05$). The bio-compost amended soil samples had similar or slightly lower levels of Cu than the chemical fertilizer amendment in both soil types, except in the municipal organic waste compost amendment, where the Cu level was higher than the fertilizer amendment.

The manganese content in pre- and post-harvest soil types pre-plantation and post-harvest soils were above the permissible limit of 600 mg/kg, as per the CPCB. The pre-plantation soils of the Yamuna floodplain and residential soil had Mn ranging from 595 to 727 mg/kg and 681 to 710 mg/kg, respectively. The post-harvest soils had a slightly higher content of Mn than the pre-plantation soil. The bio-compost-amended soils had a higher level of Mn than the chemical fertilizer amended soil. Still, the variation of Mn content across the samples was not statistically significant ($p > 0.05$).

The molybdenum content was relatively higher in the Yamuna floodplain soils than in the residential soil. The pre-plantation soil samples of Yamuna floodplain and residential soil had Mo content of 2.81 to 4.94 mg/kg and 1.8 to 2.4 mg/kg, respectively, below the permissible limit of 10 mg/kg, as per the regulation of the World Health Organization (WHO). The post-harvest soil samples of the Yamuna floodplain had a slightly higher level of Mo than the pre-plantation. Also, the bio-compost-amended soil samples had a somewhat higher content of Mo than the chemical fertilizer amended soil, though the variation was not statistically significant ($p > 0.05$). In the residential soils, the post-harvest had a slightly higher content of Mo than the pre-plantation soil, except in the green amaranth plantation. The post-harvest soil of green amaranth plantation had a significantly lower level of Mo than the pre-plantation soil ($p < 0.05$). The bio-compost amended samples had a higher content of Mo in the Yamuna floodplain soils but lower in the residential soil samples than the chemical fertilizer amended sample. However, the variation of Mo among the soil samples was not statistically significant ($p > 0.05$).

The zinc contents in the pre-plantation soil samples of the Yamuna floodplain and residential ranged from 0.10 to 0.50 mg/kg and 0.13 to 0.26 mg/kg, respectively. The post-harvest soils had relatively higher levels of Zn than the pre-plantation soil though the variation was not statistically significant among the Yamuna floodplain soil samples. But this variation was statistically significant in the residential soils, in which the post-harvest soils had a significantly higher level of Zn ($p <0.05$). Dunnett's test revealed that the variation between the pre-and post-harvest soil of red amaranth plantation contributed to this variation. The bio-compost amended soils had Zn content slightly higher or almost similar to the chemical fertilizer amended soils in both the soil types. This study further provided insights into the micronutrient levels, such as B, Co, Cu, Mo, Mn, and Zn, in the Yamuna floodplain and residential soils and their variations before and after harvest. Understanding the levels of these micronutrients is essential for maintaining soil health and ensuring optimal plant growth since they play important roles in plant development [44] [45]. It has also been reported that micronutrients are essential for stress tolerance and plant innate immunity by being involved in the metabolic processes that regulate plant response to stressors [46]. The findings suggest the need for careful monitoring of copper levels in the Yamuna floodplain, as they exceeded the permissible limit. At the same time, the other micronutrients were at a sufficient level and below the safety threshold limit in all the amendments of both soil types.

3.3. Clean Index (CI) and Bioremediation Potential of Compost Amendments in Soil

The Clean Index (CI) of pre-plantation and post-harvest soils in Yamuna floodplain and residential areas was evaluated based on different organic amendments and chemical fertilizers (**Table 4**). In the Yamuna floodplain, the post-harvest soil's mean CI was calculated for each amendment. Cow dung amendment (YC) and leaf compost amendment (YD) exhibited similar CI values of 3.253 and 3.047, respectively. Kitchen compost (YK) and municipal compost (YM) showed mean CI values of 3.040 and 2.873, while vermicompost (YV) and chemical fertilizer (YF) had a mean CI of 3.147 and 2.780, respectively. In residential soil samples, cow dung (NC) and leaf compost (ND) amendments had higher mean CI values of 3.453 and 3.547, while kitchen compost (NK) and municipal compost (NM) showed mean CI values of 3.340 and 3.187. Vermicompost (NV) and chemical fertilizer (NF) amendments had mean CI values of 3.400 and 3.200. Overall, the results suggest that different organic amendments influence the Clean Index differently, with cow dung and leaf compost amendments generally showing higher CI values in both floodplain and residential soils. Remarkably, the organic compost amendments had higher CI as compared to the chemical fertilizer amendment, across all the soil samples irrespective of the soil types and plantation (**Figure 5**). This indicates the potential of these amendments in enhancing soil quality and sustainability.

The arsenic content in the pre-plantation Yamuna floodplain soil samples ranged from 8.22 to 14.71 mg/kg. The leaf litter compost-amended soil had the lowest level of As, while the chemical fertilizer amended soil had the highest level of As. The arsenic concentration in all the soil samples, except the leaf litter compost amendment, was above the permissible limit of 10 mg/kg for the agricultural land, according to the Central Pollution Control Board (CPCB) regulation [43]. The post-harvest soils had slightly higher levels of As than the pre-plantation soil. Among the post-harvest soil samples, the chemical fertilizer amended soil had the highest level of As. In contrast, the leaf litter compost and vermicompost amended soils had the lowest level of As. The bio-compost-amended soils had less As than the chemical fertilizer amended soil. Still, the As variation among different soil samples amended with different bio-compost and fertilizer was not statistically significant ($p > 0.05$). The arsenic level was slightly higher in the residential soil samples than in the Yamuna floodplain soils.

The pre-plantation residential soils had As levels from 14.82 to 20.05 mg/kg. The chemical fertilizer amended soil had the highest level of As, and the municipal organic waste and kitchen waste compost-amended soils had the lowest level of As among the pre-plantation soils. The post-harvest soils had a lower level of As than the pre-plantation soils. The highest reduction of As in the post-harvest soils was seen in the vermicompost and leaf litter compost amendments, in which there was a reduction of about 62% to 74% in the vermicompost amendment and 37% to 60% in the leaf litter compost amendment. The bio-compost-amended soil had a significantly lower As than the chemical fertilizer amended soil ($p < 0.05$). A post hoc analysis through Dunnett's test revealed significant variation between the chemical fertilizer and kitchen waste compost amendments (**Figures 6(a)** & **Figures 6(b)**).

Table 4. The clean index (CI) of pre-planation and post-harvest soil samples with various organic compost amendments in two different soil types.

Yamuna floodplain soil samples	CI of Pre-plantation soils	CI of Post harvest soils			
		Green Amaranth plantation	Red Amaranth plantation	Spinach plantation	Mean CI of post-harvest soils
Cow dung amendment (YC)	3.28	3.24	3.28	3.24	3.253
Leaf compost amendment (YD)	3.22	2.96	3.22	2.96	3.047
Kitchen compost amendment (YK)	2.96	3.08	2.96	3.08	3.040
Municipal compost amendment (YM)	2.98	2.82	2.98	2.82	2.873
Vermicompost amendment (YV)	2.9	3.18	3.08	3.18	3.147
Chemical fertilizer amendment (YF)	3.08	2.72	2.9	2.72	2.780
Residential soil samples					
Cow dung amendment (NC)	3.34	3.44	3.26	3.66	3.453
Leaf compost amendment (ND)	3.58	3.34	3.5	3.8	3.547
Kitchen compost amendment (NK)	3.38	3.42	3.08	3.52	3.340
Municipal compost amendment (NM)	3.04	3.28	3.14	3.14	3.187
Vermicompost amendment (NV)	3.08	3.2	3.4	3.6	3.400
Chemical fertilizer amendment (NF)	2.82	2.96	3.26	3.38	3.200

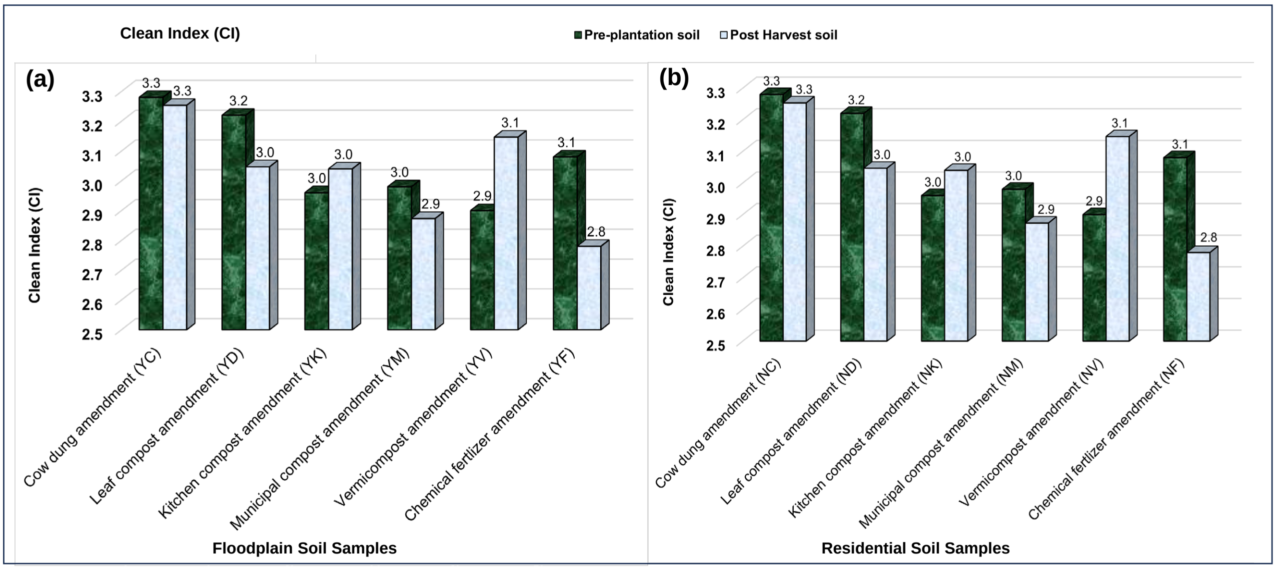
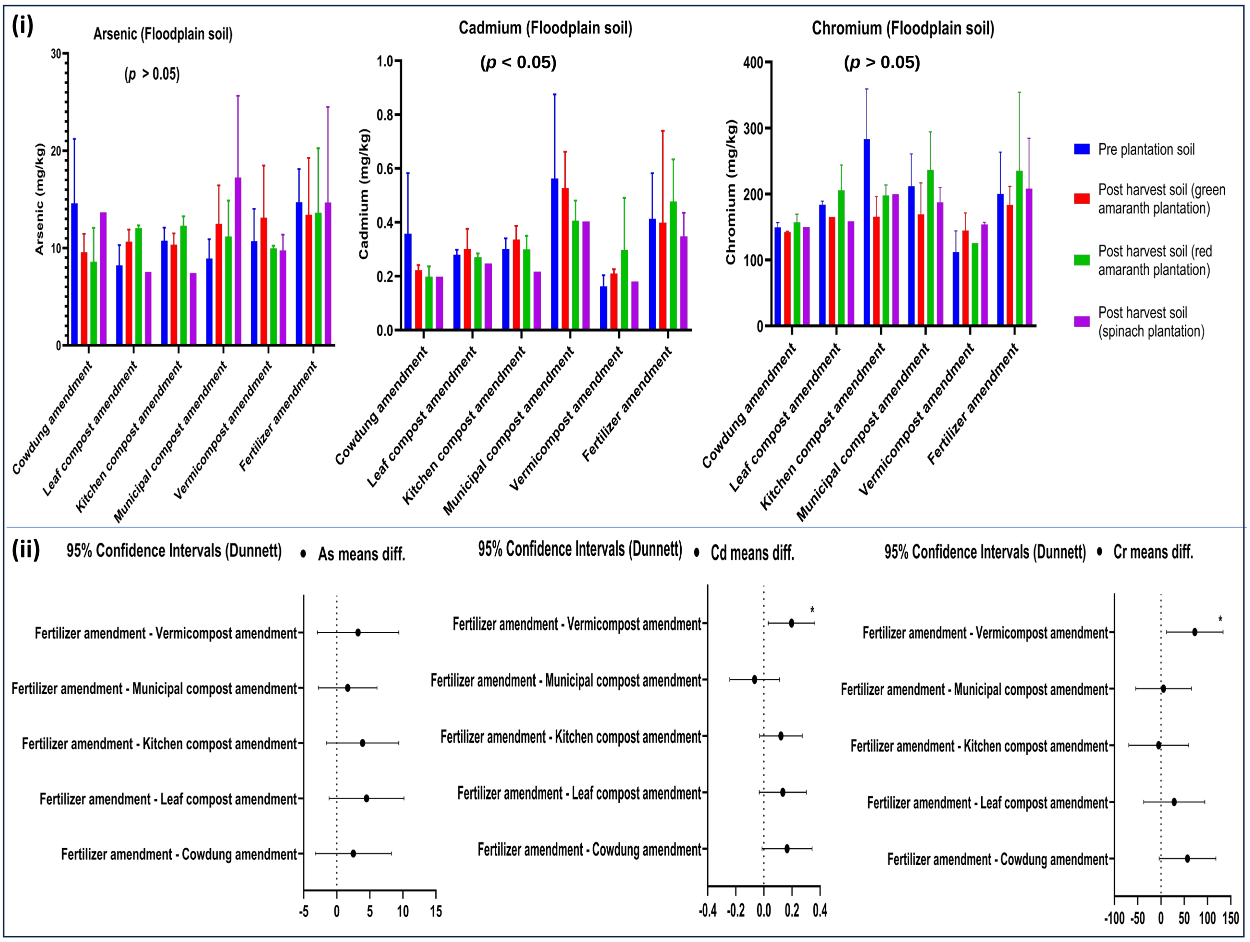


Figure 5. The clean index (CI) of pre-planation and post-harvest soils with different organic compost amendments in two different soil types.

The cadmium content in the pre-plantation soils of the Yamuna floodplain ranged from 0.16 to 0.55 mg/kg, below the permissible limit of 1.00 mg/kg, as per the CPCB regulation. The vermicompost and leaf litter compost amended soils had the lowest level of Cd at 0.16 mg/kg and 0.28 mg/kg, respectively. At the same time, the municipal organic waste compost and chemical fertilizer amended soils had the highest level of Cd at 0.55 mg/kg and 0.41 mg/kg, respectively. The post-harvest soils had a lower mean level of Cd than the pre-plantation soil, though the difference was not statistically significant ($p > 0.05$). The highest reduction was seen in the cow dung manure amendment. In general, the bio-compost amendments had significantly lower levels of Cd than the chemical fertilizer amendment, except for the municipal organic waste compost amendment, in which the Cd content was slightly higher than the chemical fertilizer amendment. Dunnett's test showed that the vermicompost amendment significantly contributed to the variation. The residential soil had lower content of Cd than the Yamuna floodplain soil. The pre-plantation residential soil had Cd ranging from 0.07 to 0.405 mg/kg. The leaf litter compost (0.07 mg/kg) and vermicompost (0.11 mg/kg) amended soil had the lowest level of Cd, while the municipal amended soil had the highest level of Cd (0.405 mg/kg). The post-harvest soils had a lower level of Cd than the pre-plantation soils, except in the red amaranth plantation of kitchen waste compost amendment, where there was a slight increment. Cd was significantly reduced in the post-harvest soil of the green amaranth plantation ($p < 0.05$). The most significant reduction of Cd in the post-harvest soil was seen in the vermicompost amendment and leaf litter compost amendment, with a decrease of about 66% to



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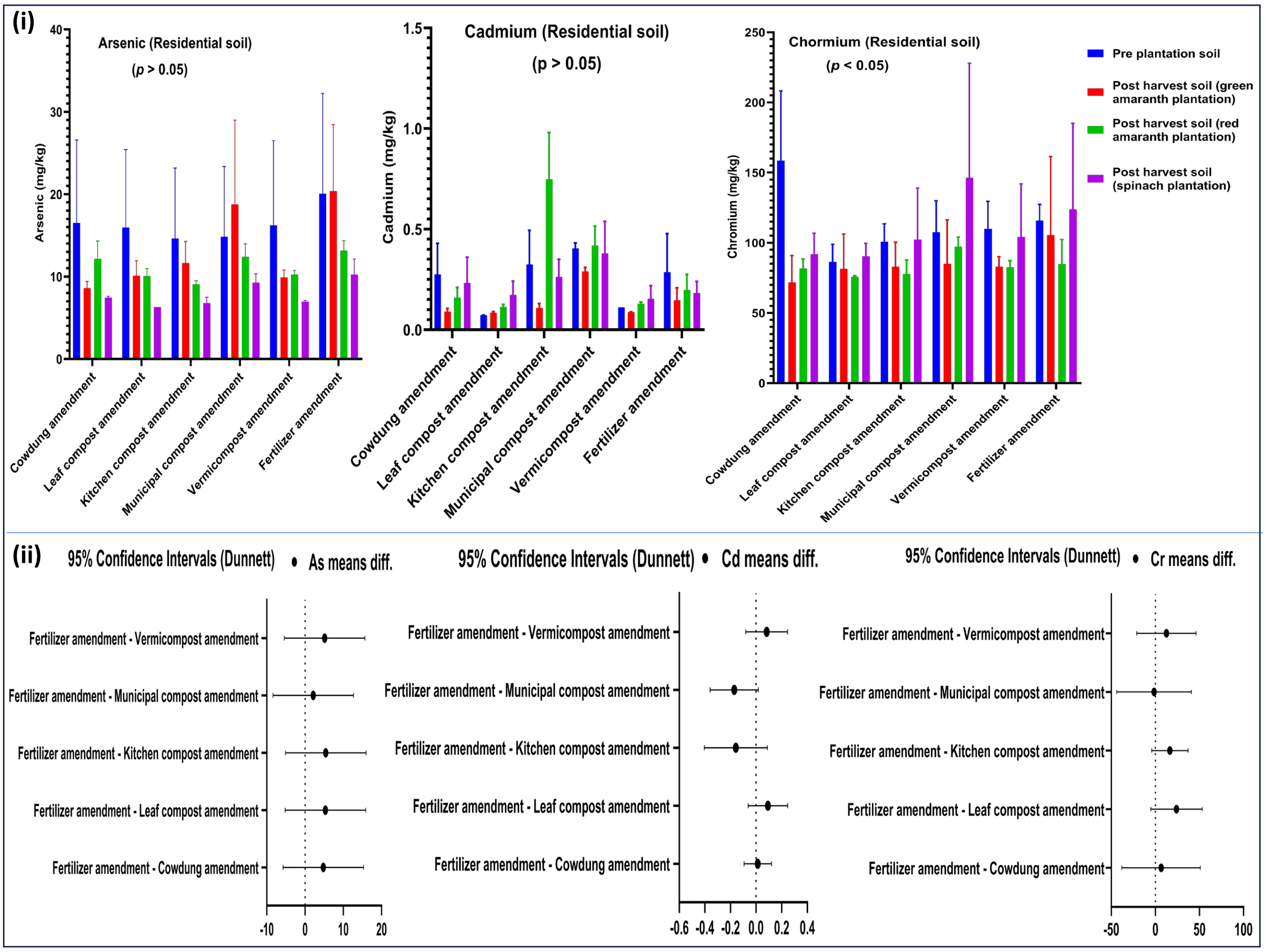

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Figure 6. (a) Mean levels of As, Cd and Cr in the floodplain soils amended with different bio-composts and chemical fertilizer. The graph panel (i) shows the mean levels of As, Cd, and Cr in pre-plantation and post-harvest soils amended with different composts and planted with different vegetables. The graph panel (ii) represents the mean differences of the parameters between the chemical fertilizer amendment and the bio-compost amendments. * represented the statistical significance. (b) Mean levels of As, Cd, and Cr in the residential soils amended with different bio-composts and chemical fertilizer. The graph panel (i) shows the mean levels of As, Cd, and Cr in the pre-plantation and post-harvest soils of the residential soils. The graph panel (ii) represents the mean differences of As, Cd, and Cr between the chemical fertilizer amendment and the bio-compost amendments of the residential soil samples. * represented the statistical significance.

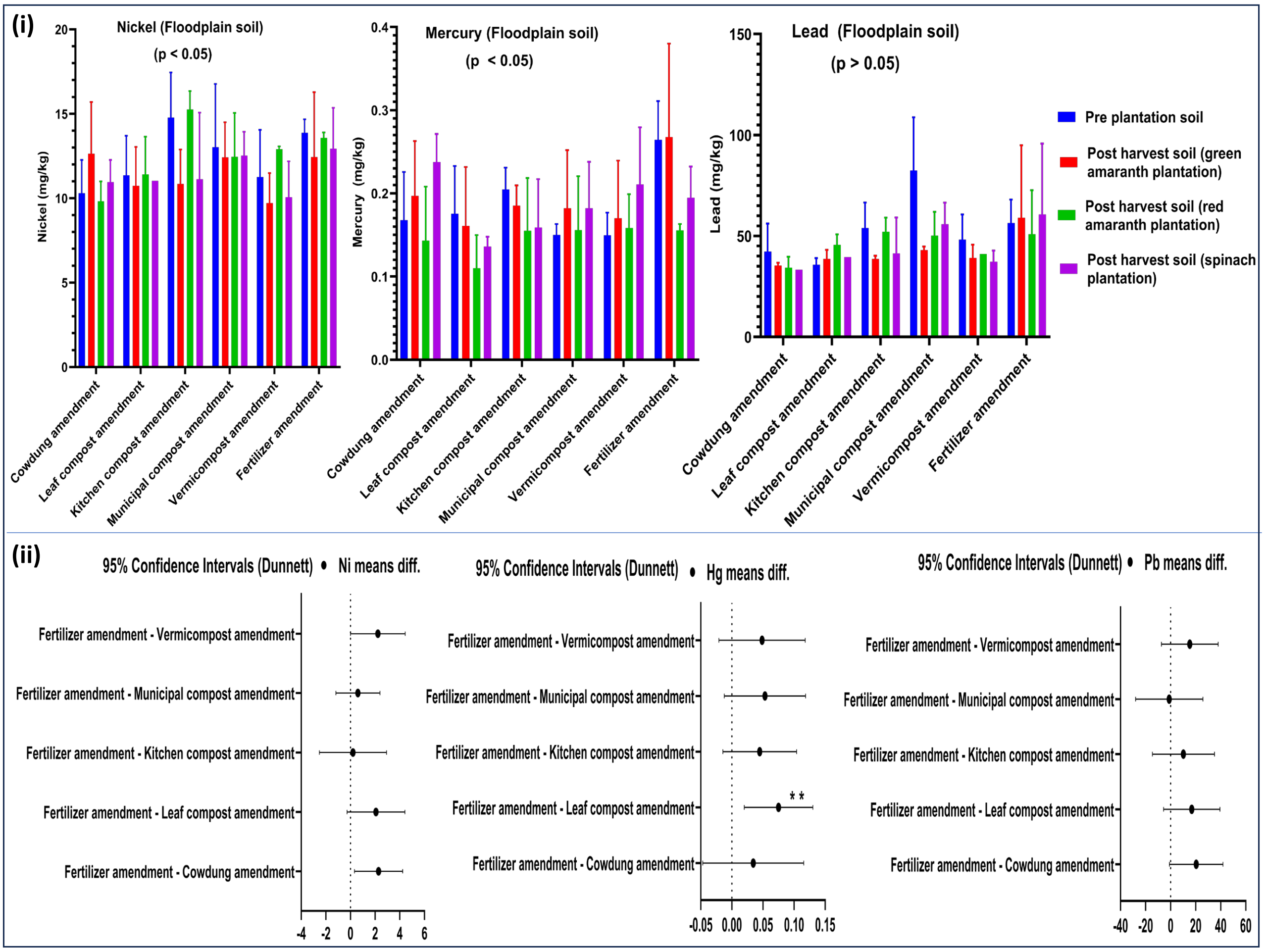
81% and 44% to 73%, respectively. Compared with the chemical fertilizer amendment, the cow dung manure, leaf litter compost, and vermicompost amendments had a lower level of Cd. In contrast, the municipal organic waste and kitchen waste compost amendments had higher levels of Cd. But, the variation of Cd among the chemical fertilizer amendment and bio-compost amendments was not statistically significant.

The chromium content in the Yamuna floodplain soil samples of all the amendments was high, ranging from 111.84 to 282.92 mg/kg, above the safety threshold value of 100 mg/kg. The lowest content was observed in the vermicompost amendment and the highest in the kitchen waste compost amendment. The post-harvest soils had relatively lower mean levels of Cr, except in the red amaranth plantation soil, where there was a slight increment of Cr in the post-harvest soil. But the variation of Cr among pre-plantation and post-harvest soil samples was not statistically significant ($p > 0.05$). The bio-compost-amended soil samples had lower content of Cr than the chemical fertilizer amended soil. Dunnett's test revealed that the difference was significant in the vermicompost and chemical fertiliser amendments ($p < 0.05$). Still, the difference was insignificant between the chemical fertilizer amendment and other bio-compost amendments ($p > 0.05$). The residential soil samples had Cr ranging from 86.27 to 158.43 mg/kg. The lowest Cr content was seen in the leaf litter compost amendment and the highest in the kitchen waste compost amendment. The post-harvest soil had Cr levels significantly lower than the pre-plantation soils ($p < 0.01$). The maximum reduction of Cr in the post-harvest soil was seen in the cow dung manure amendment at about 42% to 55% and the vermicompost amendment at about 8% to 27%. The bio-compost-amended soils had a lower Cr than the chemical fertilizer amendment, but the difference was insignificant. The most significant difference in Cr content concerning the chemical fertilizer amendment was in the leaf and kitchen waste compost amendments.

The pre-plantation soil of the Yamuna floodplain had a Nickel content of 11.26 to 14.78 mg/kg, which is below the safety threshold value of 50 mg/kg. The vermicompost amendment had the lowest Ni content, and the kitchen waste compost amendment had the highest Ni content. The post-harvest soils had a lower level of Ni than the pre-plantation soils, but the difference was insignificant ($p > 0.05$). The bio-compost-amended soils had a significantly lower level of Ni than the chemical fertilizer amended soil ($p < 0.05$). Dunnett test showed significant variation in the vermicompost and cow dung manure amendments. The residential soil had a lower level of Ni than the Yamuna floodplain soils, ranging from 9.17 to 10.32 mg/kg. The post-harvest soils had a slightly lower value of Ni than the pre-plantation soils. The bio-compost amended soil samples such as leaf compost, vermicompost, and cow dung manure, had lower content of Ni than the chemical fertilizer amended soil, except in the municipal organic and kitchen waste compost-amended soils. However, the variation of Ni across all the samples was not statistically significant.

The mercury content in pre-plantation soils of the Yamuna floodplain ranged from 0.15 to 0.26 mg/kg. The fertilizer amended soil had a higher content of Hg, while the vermicompost and municipal organic waste compost-amended soil had the lowest value of Hg. The post-harvest soils had a higher level of Hg, except in the red amaranth plantation, though the variation was insignificant. The bio-compost amendments had a lower level of Hg than the chemical fertilizer amendment. The Dunnett test revealed that the Hg level was significantly lower in the leaf litter compost amendment than in the chemical fertilizer amendment ($p < 0.01$). The pre-plantation residential soil had a Hg level ranging from 0.12 to 0.46 mg/kg. The leaf litter compost amendment had the lowest Hg value, while the chemical fertilizer amended soil had the highest value of Hg. The Hg level in the post-harvest soils was reduced, though the reduction was not significant. Also, the bio-compost-amended soils had a lower level of Hg than the chemical fertilizer amended soil, except in the municipal organic waste compost amendment. However, the variation of Hg contents in the bio-compost amendments and chemical fertilizer amendment was not statistically significant.

The lead content in the pre-plantation Yamuna floodplain and residential soil raged from 35.80 to 79.91 mg/kg and 20.81 to 35.51 mg/kg, respectively. The leaf litter compost amendment had the lowest Pb content. In contrast, the municipal organic waste compost and chemical fertilizer amendment had the highest Pb content in both the pre-plantation soil types. The post-harvest Yamuna floodplain soil had a lower level of Pb, while the post-harvest residential soil had a higher level of Pb. Nonetheless, the variation of Pb among all the soil samples was not statistically significant ($p > 0.05$). Compared with the chemical fertilizer amendment, the bio-compost amendments had a lower level of Pb, except in the municipal organic waste compost amendment, in both the soil types (Figure 7(a) & Figure 7(b)).



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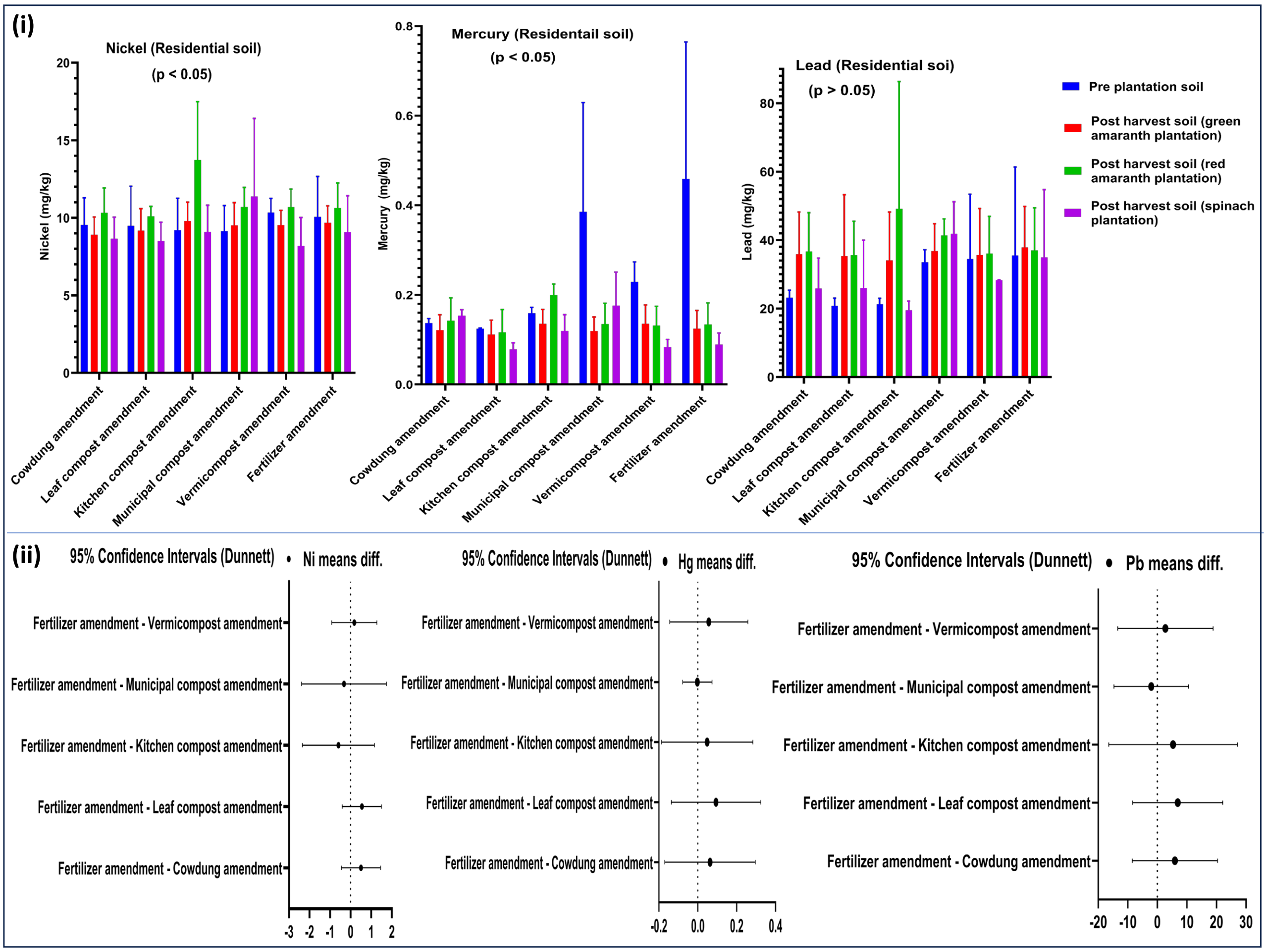

(b)

Figure 7. (a) Mean levels of Ni, Hg, and Pb in the floodplain soils amended with different bio-composts and chemical fertilizer. The graph panel (i) shows the mean levels of Ni, Hg, and Pb in the pre-plantation and post-harvest soils of the floodplain soil. The graph panel (ii) represents the mean differences of Ni, Hg, and Pb between the chemical fertilizer amendment and the bio-compost amendments of the floodplain soil samples. * represented the statistical significance. (b) Mean levels of Ni, Hg, and Pb in the residential soils amended with different bio-composts and chemical fertilizer. The graph panel (i) shows the mean levels of Ni, Hg, and Pb in the pre-plantation and post-harvest soils of the residential soil. The graph panel (ii) represents the mean differences of Ni, Hg, and Pb between the chemical fertilizer amendment and the bio-compost amendments of the residential soil samples. * represented the statistical significance.

The lithium content in the pre-plantation soil of the Yamuna floodplain varied from 9.86 to 14.81 mg/kg. The lowest and highest content was observed in the leaf litter compost and chemical fertiliser amendments, respectively. The post-harvest soil had a lower level of Li than the pre-plantation soils, except in the red amaranth plantation, but the difference was not statistically significant. The variation of Li in different amendments was statistically significant ($p < 0.01$). The bio-compost-amended soil had a lower level of Li than the chemical fertilizer amended soil, except in the vermicompost amendment. Dunnett's test showed that the Li level was significantly lower in the kitchen waste compost, leaf litter compost, and cow dung manure amendments than in the chemical fertilizer amendment ($p < 0.05$). The pre-plantation residential soil samples had slightly lower levels of Li than the Yamuna floodplain soil, ranging from 10.47 to 13.15 mg/kg. The lowest level was observed in the municipal organic waste compost amendment and the highest in the chemical fertilizer amendment. In general, the post-harvest soil samples had significantly higher levels of Li than the pre-planation soils ($p < 0.05$). Dunnett test revealed that significant variation was observed only in the red amaranth planted soil. The bio-compost-amended residential soils had lower content of Li than the fertilizer amended soil, though the variation was not statistically significant.

Potentially toxic elements in agricultural soil are an exceptional concern for food safety and human health since they can enter the food chain and cause plant and human health hazards [29] [47] [48]. This study analysed the dynamic of PTEs such as As, Cd, Cr, Li, Ni, Hg, and Pb and their bioremediation in the soil due to bio-compost amendment. Arsenic accumulation in soil can adversely affect plant growth and crop productivity [49]. Plants take up arsenic which can accumulate in their edible parts, contaminating food crops [50]. Consuming crops contaminated with arsenic can pose health risks to humans and animals. Long-term exposure to arsenic could lead to numerous health problems, including cancer, cardiovascular diseases, and reproductive issues [51] [52]. The higher levels of arsenic in the chemical fertilizer amended soils indicated the potential contribution of synthetic fertilizers to arsenic contamination. The use of organic amendments, such as leaf litter compost, vermicompost, and bio-compost, has been shown to reduce arsenic levels in the soil. These amendments could enhance soil quality, increase nutrient availability, and promote microbial activity, thereby mitigating arsenic toxicity.

Cadmium (Cd) toxicity is a significant concern for human health and the environment. The Cd levels in the soils in this study were below the permissible limit in all the samples. Cadmium could accumulate in the soil through various sources, such as industrial activities, agricultural practices, and waste disposal. Exposure to Cd can occur through the consumption of contaminated food, particularly crops grown in Cd-contaminated soil. When Cd enters the human body, it can have detrimental effects on various organs and systems. Some of the critical health concerns associated with Cd toxicity include kidney damage, respiratory problems, reproductive and developmental disorder, and carcinogenicity [53] [54]. The use of certain soil amendments, such as leaf litter compost and vermicompost, resulted in lower levels of Cd in the soil compared to chemical fertilizer amendment. This is an encouraging observation because using Cd-contaminated soil amendments can potentially increase the Cd content in crops, posing a greater risk to human health.

High chromium levels in the soils are another cause of concern as they may negatively affect plant growth and development. The vermicompost amendment had the lowest chromium content among the different amendments used. In contrast, the kitchen waste compost amendment had the highest level, suggesting that the source of organic material used in amendments can significantly impact the chromium levels in the soil. Comparing different types of amendments, the bio-compost amended soil samples had lower chromium content than those amended with chemical fertilizers. This indicated that the use of bio-compost amendments may help reduce chromium levels in the soil, potentially mitigating the risk of chromium toxicity in plants. Elevated levels of Cr could lead to plant toxicity which could hamper the nutrient uptake by the plants, stunt their growth, and thereby affect the overall plant health [55] [56]. Chromium can also accumulate in plant tissues, potentially posing a risk to human health if these plants are consumed since Cr is known to be carcinogenic and causes other health hazards [57]. Therefore, it is important to ensure that chromium levels in soil amendments and plants are within safe limits defined by regulatory authorities.

Plants use Nickel (Ni) as a micronutrient at a minute level, but it could become toxic when present in unwarranted amounts. Both plant and human health can be affected by Ni toxicity. High levels of Ni in the soil can inhibit plant growth and development. It can reduce root and shoot growth, chlorosis, and overall stunted plant growth [58] [59]. Certain plant species, such as leafy vegetables, grains, and legumes, have a higher tendency to accumulate Ni. When humans consume plants that have accumulated high levels of Ni, there is a potential for Ni exposure. Long-term exposure to high levels of Ni has been associated with potential carcinogenic effects [60]. This study highlighted the effects of different amendments on Nickel content in the soil. All the soil samples analysed had the Ni content below the safety threshold value of 50 mg/kg according to the United Nation Environmental Programme guideline 2013 [43] [61]. Vermicompost amendment resulted in the lowest Nickel levels, while kitchen waste compost amendment had the highest. The use of bio-compost amendments generally led to lower Nickel content compared to chemical fertilizer amendments. These findings provide valuable insights for sustainable agricultural practices and the potential remediation of Nickel on soil and plant health due to bio-compost amendment.

Mercury is another potentially toxic element. Mercury toxicity can have detrimental effects on plant growth and development, as well as pose risks to human health [3]. Our study indicated that the fertilizer-amended soils had higher levels of Hg compared to soils amended with vermicompost and municipal organic waste compost. Also, the leaf litter compost amendment had significantly lower levels of Hg compared to the chemical fertilizer amendment in both pre-plantation and post-harvest soils. These results suggested that the use of chemical fertilizers might contribute to increased Hg contamination in soils. This finding highlighted the potential of organic waste bio-compost as a sustainable approach to bioremediating Hg contamination in soils and mitigating associated health risks for plants and humans.

The effects of different compost amendments on Pb contents in the soils showed that the bio-compost amendments generally resulted in lower Pb content than the chemical fertilizer amendment. These findings suggested that compost amendments, such as leaf litter, vermicompost, and kitchen waste compost, could potentially bioremediate Pb content in the soil. However, the municipal organic waste compost amendment used in this study did not show a significant reduction in Pb content. It is essential to further investigate the composition and quality of the compost amendments and their potential interactions with soil properties to understand their impact on Pb bioremediation better.

Overall, this study indicated that the choice of soil amendments, such as bio-composts or chemical fertilizer could significantly affect both total nutrient levels and total PTEs in soils and cultivars. Bio-compost amendments generally resulted in higher total nutrient levels in both soils and cultivars while also lowering the levels of potentially toxic elements. The leaf litter bio-compost amendment had a similar nutrient enrichment level to that of the chemical fertilizer amendment, though slightly lower than the other bio-compost amendments in pre-plantation as well as post-harvest soil samples. But remarkably, the cultivars of the leaf litter compost amendment of both the soil types had higher levels of total nutrients than those of the chemical fertilizer amendment and the other bio-compost amendments. Similarly, the PTEs content was lower in the leaf litter compost amended soil than in the chemical fertilizer and other bio-composts amended soils. The cultivars of the leaf litter compost amendment had slightly higher levels of PTEs than the cultivars of the other bio-compost amendments but lower than those of the chemical fertilizer amendment. These findings highlighted the potential benefits of leaf litter and other organic waste bio-compost amendments in promoting soil fertility and reducing the risk of PTE accumulation in agricultural systems. The leaf litter compost and other organic waste bio-compost, such as kitchen waste compost and vermicompost, were reported to have high fertilizing potential with low PTEs contamination [10]. Different organic waste bio-composts had varying impacts on nutrient enrichment and bioremediation of PTEs. A mixture of different bio-composts can be formulated to be used as a soil amendment to harness the optimal potential of bio-compost for nutrient enrichment and bio-remediation of potentially toxic elements, promoting sustainable productivity and food safety.

4. Conclusion

The study showed that leaf litter compost and other organic waste compost amendments could increase total nutrient levels while reducing potentially toxic element concentrations in soils and cultivars. This highlighted the potential benefits of leaf litter compost and other organic waste bio-composts in promoting soil fertility and minimizing the risk of PTE accumulation in agricultural systems. Therefore, incorporating leaf litter compost and different organic waste composts as soil amendments could be a promising approach for sustainable productivity, promoting healthier soils, while mitigating the risks associated with PTE accumulation which enhanced the environmental safety. Further research and practical implementation of bio-compost amendments is warranted to validate and expand upon these positive outcomes.

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Authors Contribution

Sarita Nanda—Methodology, conceptualisation, experimental design, and supervision. Sophayo Mahongnao and Pooja Sharma—Methodology, Data generation, data curation, formal analysis, and original drafting; Arif Ahamad—Methodology, conceptualisation, experimental design, and review. All the authors reviewed and approved this manuscript.

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Ethical approval is not applicable.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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