

Synergistic remediation of e-waste contaminated soil using thermally treated sludge residue and *Lolium perenne* L.

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Abstract

Electronic waste (e-waste) generation has significantly increased because of the widespread use of electronic products, and thermally treated sludge residue improves e-waste-contaminated soil by synergizing with *Lolium perenne* L. This study investigated the effects of different doses of thermally treated sludge residue (0% and 5%) in synergy with *L. perenne* L. on organic matter, nutrients, heavy metal morphology, and heavy metal uptake and transport by *L. perenne* L. in e-waste-contaminated soil using pot experiments. The results showed that the thermally treated sludge residue improved soil quality and significantly increased soil conductivity, cation exchange, organic matter, effective phosphorus, and fast-acting potassium content. New heavy metal crystalline phases were detected, and soil solubility humus components were found. Sludge fermentation residue significantly increased dissolved organic matter content, whereas sludge pyrolysis residue showed no significant effect. The combination of thermally treated sludge residue and *L. perenne* L. increased steady-state proportions of Cu, Zn, Pb, and Cd. The thermally treated sludge residue promoted *L. perenne* L. growth, increasing fresh weight, plant height, phosphorus uptake, and potassium uptake of *L. perenne* L.; it significantly reduced *L. perenne* L. response to Cu, Zn, Pb, and Cd. In addition, *L. perenne* L. promoted the activity of microorganisms in thermally treated sludge residue and improved its ability to reduce heavy metals. This approach has the potential for ecological remediation of contaminated sites, providing a new method for the remediation of e-waste-contaminated soil.

1 Introduction

In recent years, the generation of electronic waste (e-waste) has significantly increased because of the widespread use of electronic products (Zhang. 2020). Improper dismantling of e-waste leads to random disposal or landfilling, resulting in soil and groundwater contamination in the vicinity of dismantling sites. Studies have shown that e-waste dismantling sites are subject to contamination by multiple heavy metals and organic pollutants, leading to the destruction of vegetation (Zhang et al. 2017). For example, Zhang et al. (2017) calculated the heavy metal pollution index in the soil of an e-waste recycling site in Taizhou, Zhejiang Province, China. They found heavy contamination with Cd, Cu, Pb, and Zn. Furthermore, Gu et al. (2019) quantified polycyclic aromatic hydrocarbons in the soil of an e-waste dismantling site and the risk to human health, and identified a serious environmental risk.

Owing to excessive pollutant concentrations and poor soil nutrient conditions, natural vegetation recovery at these sites is difficult without artificial measures during the pre-vegetation stage, where increasing nutrient content is crucial for soil vegetation recovery.

Aerobic sludge fermentation is a method used to stabilize and treat sludge. It involves the decomposition and conversion of organic matter in sludge into humus through the action of microorganisms (Wei et al. 2020). During this process, the organic matter in the sludge is mineralized and decomposed, the humus is formed in large quantities, and the biological effects of heavy metals are reduced (Wang et al. 2019). Sludge pyrolysis, an emerging technology for sound disposal, is a process in which sludge

decomposition occurs at relatively low temperatures in an inert atmosphere to form carbon-rich products (Jiang et al. 2021). During this process, the carbon content of the sludge increases, a porous carbonaceous residue is obtained, and the stability of the heavy metals improves. Thermally treated sludge residues (fermentation residues and pyrolysis residues) are rich in nutrients, such as nitrogen, phosphorus, and potassium. The special structure and oxygen-containing functional groups of both residues improve soil properties and stabilize soil heavy metals, providing favorable conditions for accelerated vegetation recovery. Studies have been conducted to quantitatively evaluate plant germination rate, biomass, chlorophyll content, and other indicators from pot or site tests and have found that thermally treated sludge residue significantly promote plant growth (Han et al. 2004; Chu et al. 2017). Therefore, the use of thermal sludge treatment slag as a soil amendment or remediation agent is a win-win option for achieving resourceful sludge utilization and soil vegetation restoration.

Phytoremediation techniques for heavy metal-contaminated soils include phytoextraction and phytostabilization. Phytoextraction involves the acidification and uptake of plant roots for heavy metal reduction remediation and is suitable for low- to moderately-contaminated soils. Conversely, phytostabilization mainly uses plant roots for the chelation and precipitation of heavy metal stabilization and remediation and is suitable for heavily contaminated soil (Chen and Hu. 2014). Although scholars have conducted relevant studies on the ecological remediation of mining sites, few have reported on the remediation of high-concentration and multi-species heavy metal-contaminated soils at e-waste dismantling sites. *Lolium perenne* L. is a perennial plant with the advantages of high biomass, well-developed root system, adaptability, short growth cycle, and high economic value. It can serve as a pioneer plant for revegetation of contaminated soil (Dudai et al. 2018).

Therefore, this study was conducted to analyze the effects of adding thermally treated sludge residue on soil properties, heavy metal migration transformation, as well as the growth of *L. perenne* L. through potting tests. It aims to provide a theoretical basis and practical guidance for the application of thermally treated sludge residue in the ecological remediation of e-waste dismantling contaminated soil. We anticipate that our findings will offer valuable insights into the potential use of thermally treated sludge residue as a solution for the ecological remediation of e-waste-contaminated soil. By contributing to the development of effective and sustainable remediation techniques, our research will promote soil health, facilitate vegetation recovery, and mitigate heavy metal pollution, thereby fostering a safer and more sustainable environment.

2 Materials and Methods

2.1 Sample source and pretreatment

Soil samples were collected from an abandoned workshop-type e-waste dismantling site located in Taizhou, Zhejiang Province, China. Following the guidelines outlined in the Technical Specification for Soil Environmental Monitoring (HJ/T 166–2004), the site was divided into six equal units using the "3×2"

method. A total of 50 kg of surface soil (0–20 cm) was collected from each unit. Subsequently, the samples were sieved to a particle size of < 2 mm and stored at room temperature.

The sludge used in this experiment was obtained from a wastewater treatment plant located in Changzhou, Hebei, China. A portion of the sludge was used to prepare the high-temperature aerobic fermentation sludge. This involved mixing the sludge with straw and other raw materials at a certain ratio, forming a pile in a high-temperature reactor, and subjecting it to a 7-day cycle of turning. After 49 days (Yang. 2018), the fermentation sludge was obtained. The fermentation sludge was crushed and sieved to a particle size of < 2 mm using a crusher and stored at room temperature for backup. Another portion of the sludge was used to prepare the pyrolysis slag, which was placed in an oven at 105°C for 24 h, cooled, ground, passed through a 100-mesh sieve, placed in a tube furnace, pyrolyzed under a nitrogen atmosphere at a heating rate of 10°C/min, a final pyrolysis temperature of 600°C, and a residence time of 60 min, cooled to room temperature, and then stored for backup (Gu et al. 2022). The basic physicochemical properties and heavy metal contents of the soil and sludge thermally treated residues are listed in Table 1. The *L. perenne* L. seeds used in the experiment were purchased from a company in Cangzhou, Hebei, China.

Table 1
Basic physicochemical properties of soil and thermally treated sludge residue

Property	Soil	Sludge fermentation residue	Sludge pyrolysis sludge
pH	7.95	6.58	7.90
Moisture content / %	/	32.4	/
Conductivity / (mS cm ⁻¹)	0.38	4.87	1.1
Organic matter / (g kg ⁻¹)	7.06	971	485
Hydrocarbon ratio	4.58	6.33	31.2
Available phosphorus / (mg kg ⁻¹)	8.30	830	277
Available potassium / (mg kg ⁻¹)	52.9	1246	416
Total nitrogen / (g kg ⁻¹)	0.36	5.01	1.03
Copper / (mg kg ⁻¹)	2877	287	597
Zinc / (mg kg ⁻¹)	15255	982	1448
Cadmium / (mg kg ⁻¹)	39.1	0.2	1.52
Lead / (mg kg ⁻¹)	2950	36	70
Nickel / (mg kg ⁻¹)	182	13	115
Chromium / (mg kg ⁻¹)	294	45	148

2.2 Pot experiment

The experiment was conducted in a greenhouse at the Shanghai Polytechnic University from April 5 to May 20, 2021. Soil samples (1 kg) were placed in plastic pots 12 cm in diameter and 18 cm in height. The sludge fermentation and pyrolysis residues were then mixed evenly with soil at a ratio of 0% and 5% of fresh weight and labeled CK (0%), TS (5% fermentation residue), and TB (5% pyrolysis residue), respectively, with three replicates for each treatment. Deionized water was first added to maintain soil moisture in pots at approximately 80% of field holding capacity, and seeds were sown (0.5 g per pot) after 15 d. After 5 d of seed germination, 50 seedlings per pot were retained, and plants were harvested after 25 d. Deionized water was supplemented regularly during the growth period of *L. perenne* L. to maintain soil moisture at approximately 80% of the field water-holding capacity.

Lolium perenne L. was harvested with as much root integrity as possible, and plant height was measured with a straight edge while the soil was collected from each pot. The plant samples were washed

successively with tap water and deionized water and then dried using sterile cotton. One part was used to determine the chlorophyll content, and the other was dried at 65°C after sterilization at 105°C for 10 min to determine the contents of heavy metals (Cu, Zn, Pb, and Cd), phosphorus uptake, and potassium uptake. Soil samples were air-dried indoors, crushed, and passed through a 2 mm sieve to determine their pH, conductivity, cation exchange, fast-acting potassium, effective phosphorus, organic carbon, heavy metal forms, fluorescein diacetate enzyme activity, and the spectral characterization of dissolved organic matter.

2.3 Analytical test methods

The heavy metal, potassium, and phosphorus contents in *L. perenne* L. samples were determined according to GB/T 30376 – 2013. The chlorophyll content was determined according to NY/T 3082 – 2017. The soil pH was determined according to HJ 962–2018. The electrical conductivity was determined according to HJ 802–2016. The cation exchange was determined according to HJ 889–2017. The effective phosphorus content was determined according to HJ 704–2014. The fast-acting potassium content was determined according to LY/T 1234–2015. The organic carbon content was determined according to HJ 615–2011. Fluorescein diacetate enzyme activity was determined by using the methods outlined in the experimental section of Environmental Soil Science (Jia. 2016). Heavy metal forms were determined according to GB/T 25282 – 2010.

The soil samples were added to ultrapure water at a ratio of 1 g:20 mL and extracted by shaking at 23°C and 180 rpm for 24 h. The suspension was centrifuged at 4°C and 10,000 r/min for 20 min, the supernatant was passed through a 0.45 µm filter membrane, and the organic matter in the resulting filtrate was dissolved organic matter (DOM). Fluorescence characterization of a portion of the DOM was carried out using a HORIBA Fluoro Max molecular fluorescence spectrometer under the following conditions: excitation wavelength (Ex) from 220 to 450 nm in steps of 5 nm; emission wavelength (Em) from 290 to 550 nm in steps of 1 nm; slit width of both Ex and Em of 5 nm; integration time of 0.02 s. The instrument system automatically deducted the blank for Rayleigh effect and Raman scattering. A portion of the DOM was used to determine the UV spectra with a scanned wavelength of 226–400 nm and a scanning interval of 0.5 nm. The remaining portion of the DOM was used to determine its content using a total organic carbon analyzer (Multi N/C 2100).

Mineral characterization of the soil was performed using an X-ray diffractometer (D8 Advance) under the following test conditions: scanning angle of 10°–80°, step of 0.1°, and integration time of 0.02 s.

2.4 Calculation methods of heavy metal-related indicators

2.4.1 Heavy metal steady-state ratios (FS)

The proportions of the weak acid-extractable (F1), reducible (F2), oxidizable (F3), and residual (F4) states of the heavy metals were determined with reference to GB/T 25282 – 2010. According to Liu et al. (2021), the sum of F3 and F4 can be used as the FS to evaluate the stability of heavy metals in soil. The larger the FS value, the more stable the heavy metals and the lower their biological effectiveness.

2.4.2 Plant heavy metal enrichment (BC)

The BC value is the sum of the heavy metal content in the lower part of the plant (C1) and the aboveground content (C2), and indicates the enrichment of heavy metals in the plant. The greater the BC value, the greater the absolute content of heavy metals in the plant (Liu et al. 2020).

2.4.3 Plant heavy metal transport coefficient (TF)

TF is the ratio of C2 to C1, which is used to evaluate the ease of migration of heavy metals from the lower part of the ground to the aboveground part of the plant. The larger the TF value, the easier it was for heavy metals to accumulate in the aboveground parts of the plant.

2.5 Data Statistics and Analysis

Microsoft Excel was used for data collection, SPSS (version 23.0) for analysis of variance (ANOVA) and Tukey's test, and Origin 9.1 for plotting the data.

3 Results and Discussion

3.1 Effect of thermally treated sludge residue on soil chemical and biological properties

Figure 1 shows the changes in the chemical and biological properties of the soil after the application of the two thermally treated sludge residue. Compared to CK, the application of fermentation sludge (TS) significantly ($P < 0.05$) increased electrical conductivity (191–218%), cation exchange (52–84%), organic matter content (21–36%), effective phosphorus content (154–178%), fast-acting potassium content (69–96%) and FDA enzyme activity (67 to 124%) in all soils, and significantly ($P < 0.05$) reduced the pH of the soil planted with *L. perenne* L. (0.4 units).

Compared to CK, the application of pyrolysis residue (TB) significantly ($P < 0.05$) increased the effective phosphorus (142%–245%) and fast-acting potassium (40%–46%) content of all soils, significantly ($P < 0.05$) increased the electrical conductivity of *L. perenne* L.-grown soils (32%), significantly ($P < 0.05$) increased the cation exchange of *L. perenne* L.-grown soils (37%), significantly ($P < 0.05$) increased the organic matter content of *L. perenne* L.-grown soils (17%); however, increase in the FDA enzyme activity and decrease in the pH of all soils were not significant ($P < 0.05$).

The pH of both thermally treated sludge residue was lower than that of the original sampled soil (Table 1), which may have caused a decrease in soil pH after application; however, the decrease was not significant ($P < 0.05$) overall. Application of fermentation sludge significantly ($P < 0.05$) increased soil conductivity, which may be influenced by the high conductivity of the sludge itself ($4.87 \text{ mS}\cdot\text{cm}^{-1}$, Table 1). When soil conductivity is higher than $2 \text{ mS}\cdot\text{cm}^{-1}$, it can cause salt stress in plants (Luo et al. 2016). Since the soil conductivity in this study reached up to $1.97 \text{ mS}\cdot\text{cm}^{-1}$, the amount of fermentation

residue applied needs to be controlled in practice. Soil cation exchange, organic matter, effective phosphorus, and fast-acting potassium content are the indexes of soil fertility, and the application of both thermally treated sludge residue improved soil fertility. On the one hand, the thermally treated sludge residues are rich in soil nutrients. On the other hand, because of the large number of negatively charged functional groups and large surface area, they have a strong adsorption capacity for cations (such as K^+ , Ca^{2+} , Mg^{2+}) (Xu et al. 2013), thus increasing soil cation exchange and fast-acting potassium content. It has been shown that the carboxyl groups of humus can reduce phosphorus adsorption by iron and aluminum oxides through the adsorption of phosphate (Yang et al. 2013) and that organic acids and phenolics in humus can react with phosphate mineral surfaces, thus increasing the effective soil phosphorus content (Hua et al. 2008). In addition, pyrolytic carbon can increase soil phosphorus content by adsorbing phosphate from the soil to promote the mineralization of organic phosphorus (Zhou et al. 2020).

Soil enzyme activity is an important indicator of soil microbial activity, and its levels reflect the strength of soil fertility and elemental biogeochemical cycles. In recent years, it has been proposed that fluorescein diacetate enzyme activity can be used to characterize the magnitude of total soil enzyme activity and examine the overall inhibition of microorganisms by pollutants (Liu et al. 2021). The application of both thermally treated sludge residue increased the activity of soil fluorescein diacetate enzyme, indicating increased activity of soil microorganisms. In conclusion, both thermally treated sludge residue increased the soil nutrient content and further improved the ecological function of the soil.

3.2 Effect of thermally treated sludge residue on soil-dissolved organic matter

Figure 2 shows the changes in the three-dimensional fluorescence spectra of soil-dissolved organic matter (DOM) after the application of the two thermally treated sludge residue. According to the division of the spectra by Chen et al. (2015): region I ($Ex < 250$ nm, $Em < 330$ nm) and region II ($Ex < 250$ nm, 330 nm $< Em < 380$ nm) represent tryptophan-like and tyrosine-like, respectively; region III ($Ex < 250$ nm, $Em > 380$ nm) represents fulvic acid-like; region IV ($Ex > 250$ nm, $Em < 380$ nm) represents soluble microbial metabolites; region V ($Ex > 250$ nm, $Em > 380$ nm) represents humic acid-like. Compared with CK, the application of the two thermally treated sludge residue resulted in new fluorescence peaks in spectral region V, indicating the presence of humic acid-like substances in the soil. However, the peak positions corresponding to the two thermally treated sludge residue were different, indicating differences in composition, which require further investigation. In general, the application of thermally treated sludge residue involves introducing humus components into the soil, which is beneficial for improving soil properties and stabilizing heavy metals.

Table 2 shows the changes in soil DOM content and its spectral parameters after the application of the two thermally treated sludge residue. The $S_{226\sim400}$ value is the integral value of the UV absorbance of DOM in the wavelength range of 226–400 nm, which characterizes the relative amount of organic matter with unsaturated bonded functional groups (especially aromatic ring structures) (Li et al. 2010). The

humification index is the ratio of the sum of the fluorescence intensity at an excitation wavelength of 254 nm, emission wavelength of 435–480 nm, and emission wavelength of 300–345 nm, which can be used to characterize the humification degree of organic matter (Xu et al. 2020). The application of fermentation residue (TS) significantly ($P<0.05$) increased the dissolved organic matter content of all soils (34% to 50%) compared to the CK. In contrast, the application of pyrolysis residue (TB) was not significant ($P<0.05$), probably because of the higher organic matter content of the fermentation residue itself (Table 1), resulting in a higher dissolved organic matter content released in the soil. In addition, fermentation residue significantly ($P<0.05$) increased the $S_{226\sim400}$ values (123%–277%) and humification index (11%–25%) of all soil DOM, whereas the effect of pyrolysis residue (TS) remained insignificant ($P<0.05$), indicating that soil DOM treated with fermentation residue had more aromatic-electron systems, higher humification of DOM, higher molecular weight, and a more complex structure.

Table 2
Soil-dissolved organic matter spectral parameters

Processing	Dissolved organic matter content (mg kg ⁻¹)	$S_{226-400}$ Values	Humification index
CK	57.9 ± 4.1b	1.36 ± 0.12b	2.34 ± 0.00b
TS	86.8 ± 8.2a	3.49 ± 0.17a	2.59 ± 0.07a
TB	61.6 ± 3.9b	1.66 ± 0.31b	2.25 ± 0.11b

3.3 Effect of thermally treated sludge residue on soil mineral and heavy metal steady state

Figure 3 shows the changes in soil heavy metal minerals after the application of the two thermally treated sludge residue. $Cu_5O_2(PO_4)_2$ and PbO_2SO_4 crystalline phases were detected in the soil planted with *L. perenne* L. after the application of fermentation slag (TS) compared to CK, and $NaCaCu_5(PO_4)_4Cl$, $ZnMoO_4 \cdot 0.8H_2O$ and $AlCaCu(Si_2O_6)(OH)_3$ crystalline phases were detected in the soil planted with *L. perenne* L. after the application of pyrolysis slag (TB) compared to CK.

Table 3 shows the changes in the proportion of the soil heavy metal steady state after the application of the two thermally treated sludge residue. Compared with CK, the application of fermentation slag (TS) increased the steady-state proportions of Cu, Zn, Cd, and Pb by 14–16%, 9–12%, 10–16%, and 6–8%, respectively, while the stable ratios of Cu, Zn, Cd, and Pb were increased by 16–20%, 14–20%, 11–18% and 8–11% respectively, using pyrolysis slag (TB).

Table 3
Effects of thermally treated sludge residue on the proportion
of heavy metal steady state in soil

Processing	Proportion of heavy metal steady state (%)			
	Cu	Zn	Cd	Pb
CK	47	42	39	51
TS	62	51	51	59
TB	67	56	57	63

Note: CK = control; TS = application of sludge fermentation residue; TB = sludge pyrolysis residue. The steady-state proportions of Cu, Zn, Cd, and Pb in the original soil samples were 38, 33, 30, and 38%, respectively.

When soils are contaminated with heavy metals, plants can alter the inter-root soil pH by secreting OH⁻ or specific proteins from the root system, thus improving the stability of heavy metals (Pignattelli et al. 2012). Heavy metal contamination of the test soils may have triggered the phytostabilizing remediation mechanism. Compared with the original sampled soil (Table 1), the pH and proportion of the heavy metal steady state (Table 2) increased in all CK treatments, indicating that the remediation of heavy metals by *L. perenne* L. was in the form of stable remediation, which is similar to the results of Chen et al. (2017). Compared with CK, the application of the two thermally treated sludge residue further increased the proportion of the soil heavy metal steady state, indicating that the thermally treated sludge residue and *L. perenne* L. synergistically stabilized heavy metal remediation by a mechanism that can be summarized in the following four aspects (Sevilla-Perea and Mingorance. 2015; Yang et al. 2021; Keiluweit and Kleber. 2009) (Fig. 4): (1) the ion exchange effect. Many negatively charged functional groups in thermally treated sludge residue can adsorb K/Ca/Na/Mg ions, which can be replaced with heavy metal ions; (2) the coordination effect. The oxygen-containing functional groups of thermally treated sludge residue can form stable complexes or chelates with heavy metals; and (3) the cation- π -bonding interactions. The aromatic ring π -electron structure of the thermally treated sludge residue can form a tight covalent electron cloud structure with heavy metal ions; and (4) physical adsorption. Heavy metal ions are mainly attracted to the surface of the thermally treated sludge residue via hydrogen bonding, electrostatic attraction, and van der Waals forces, which facilitate subsequent chemisorption. In addition, soil heavy metals can combine with groups in pyrolytic carbon to form precipitates such as hydroxides, carbonates, silicates, and phosphates (Liu et al. 2021), and heavy metal ions can also form more stable "ionic bridges" between the negatively charged mineral surfaces and the negatively charged functional groups of humic substances, affecting the migration of heavy metals (Li et al. 2005). In this study, $\text{Pb}_4(\text{S}_2\text{O}_3)\text{O}_2(\text{OH})_2$, $\text{AlCaCu}(\text{Si}_2\text{O}_6)(\text{OH})_3$, $\text{KZn}_3\text{Mn}_2\text{Si}_2\text{O}_{30}$, $\text{NaCaCu}_5(\text{PO}_4)_4\text{Cl}$, and other crystalline phases were detected in the soil treated with thermal treatment slag, which may be related to the above effect. In conclusion, the thermally treated sludge residue promoted the conversion of soil heavy metals to a steady state.

3.4 Effect of sludge heat treatment slag on the growth, uptake, and transport of heavy metals in *L. perenne* L.

Figure 5 shows the changes in plant growth after the application of the two thermally treated sludge residue. Compared to CK, the application of fermentation residue (TS) significantly ($P < 0.05$) increased the fresh weight (36%) and plant height (18%) of *L. perenne* L. Additionally, it significantly ($P < 0.05$) increased phosphorus uptake (48%) and significantly ($P < 0.05$) increased potassium uptake (45%) of vetiver grass. Conversely, the application of pyrolysis residue (TB) significantly ($P < 0.05$) increased the fresh weight (35%) and plant height (20%) of *L. perenne* L. Additionally, it significantly ($P < 0.05$) increased phosphorus uptake (33%) and significantly ($P < 0.05$) increased potassium uptake (33%) in *L. perenne* L. However, both sludge treatments did not significantly ($P > 0.05$) increase chlorophyll content in *L. perenne* L.

Tables 4 and 5 show the changes in total plant heavy metal enrichment and transport coefficients after the application of the two thermally treated sludge residue, respectively. The application of fermentation slag (TS) significantly ($P < 0.05$) reduced Cu (25%) and Zn (5%) enrichment and reduced Cu, Zn, Cd, and Pb migration coefficients in *L. perenne* L. compared to CK. The application of pyrolysis residue (TB) significantly ($P < 0.05$) reduced Cu (34%), Zn (6%), and Pb (32%) enrichment and reduced Cu, Zn, Pb, and Cd migration coefficients in *L. perenne* L. compared to CK.

Table 4

Effect of thermally treated sludge residue on the total heavy metal enrichment of *Lolium perenne* L.

Processing	Total enrichment of heavy metals (mg kg ⁻¹)			
	Cu	Zn	Cd	Pb
CK	293 ± 17a	794 ± 9a	3.6 ± 1.0a	112 ± 13a
TS	219 ± 5b	758 ± 4b	2.0 ± 0.8a	92.3 ± 7a
TB	194 ± 12c	750 ± 10b	1.9 ± 0.2a	76.5 ± 4b
Note: CK = control; TS = application of sludge fermentation residue; TB = sludge pyrolysis residue. Different lowercase letters in the same column indicate significant differences between the treatment groups ($P < 0.05$).				

Table 5
Effect of thermally treated sludge residue on heavy metal migration coefficient of
Lolium perenne L.

Processing	Total enrichment of heavy metals (mg kg ⁻¹)			
	Cu	Zn	Cd	Pb
CK	0.052	0.080	0.158	0.018
TS	0.042	0.078	0.136	0.017
TB	0.041	0.066	0.146	0.014
Note: CK = control; TS = sludge fermentation residue; TB = sludge pyrolysis residue.				

The total heavy metal enrichment of *L. perenne* L. decreased after the application of both thermally treated sludge residue (Table 4), mainly because of an increase in the proportion of soil heavy metals in the steady state (Table 3). The total heavy metal enrichment of *L. perenne* L. in all treatments ranged from the largest to the smallest: Zn, Cu, Pb, and Cd, which was influenced by the difference in the content of each heavy metal in the soil background values. The heavy metal transport coefficients of *L. perenne* L. in all treatments were less than 1 (Table 5), indicating that heavy metals were less likely to be transported aboveground after being absorbed by *L. perenne* L. roots, and the results were similar to those of Song et al (2019). *Lolium perenne* L. retains or fixes most of the heavy metals in its roots, which can reduce the toxic effects of heavy metals on sensitive aboveground organs (Rui et al. 2012).

Chlorophyll is the main pigment for photosynthesis in plants, phosphorus affects root development, and potassium affects leaf growth (Du et al. 2020). The application of thermally treated sludge residue increased the soil nutrient content and improved phosphorus and potassium uptake by plants, thus increasing plant fresh weight and plant height. In addition, because heavy metals inhibit plant chlorophyll synthesis (Liang and Pardee. 1992), the soil heavy metal steady-state ratio increased after the application of thermally treated sludge residue, which reduced the heavy metal content in plants and increased chlorophyll content, promoting plant growth.

4 Conclusion

The application of thermally treated sludge residue increased the soil nutrient content and enzyme activity and controlled the leaching risk of soil heavy metals. The new crystalline phase of heavy metals may stabilize heavy metals in soil to some extent and reduce their toxicity and bioavailability in soil, whereas the detection of humus components in soil-dissolved organic matter can improve soil fertility and ecosystem health status. Furthermore, we found that the application of thermally treated sludge residue suppressed the enrichment of *L. perenne* L. with heavy metals and promoted the growth of *L. perenne* L. In addition, the nutrient content and soil improvement effect of sludge fermentation slag was better than that of sludge pyrolysis slag, which can be promoted in the field of environmental remediation of e-waste dismantling contaminated soil as a priority; however, attention should be paid to the application amount to avoid inhibiting *L. perenne* L. growth due to high electrical conductivity.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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Data availability All data generated or analyzed during this study are included in this article.

Author Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Weihua Gu and Jianfeng Bai. The first draft of the manuscript was written by Weihua Gu and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

References

1. Chen W, Westerhoff P, Leenheer JA et al (2003) Fluorescence excitation-emission matrix regional integration to quantify spectra for dissolved organic matter. *Environmental Science & Technology*, 2015, 37(24): 5701–5710
2. Chu SS, Wu DM, Liang LY et al (2017) Municipal sewage sludge compost promotes *Mangifera persiciforma* tree growth with no risk of heavy metal contamination of soil. *Sci Rep* 7(1):13408
3. Chen L, Hu MY (2014) Research progress of phytoremediation technology for heavy metal contaminated soil. *Chem Biol Eng* 31(4):596–602
4. Chen YY, Lu S, Hui HX et al (2017) Remediation efficacy and action pathways of Indian mustard and vetiver on Pb-contaminated soil. *Environ Sci Res* 30(9):1365–1372
5. Du J, Guo ZY, Li RH et al (2020) Screening of Chinese mustard (*Brassica juncea* L.) cultivars for Cd/Zn phytoremediation and research on physiological mechanisms. *Environ Pollut* 261:114213
6. Dudai N, Tsion I, Shamir SZ et al (2018) Agronomic and economic evaluation of Vetiver grass (*Vetiveria zizanioides* L.) as means for phytoremediation of diesel polluted soils in Israel. *J Environ Manage* 211:247–255
7. Gu WH, Yao HY, Bai JF et al (2019) Risk assessment of soil polycyclic aromatic hydrocarbons pollution in a typical e-waste dismantling area in Taizhou, Zhejiang. *China Environ Manage* 11(1):67–71
8. Gu WH, Guo JS, Bai JF et al (2022) Co-pyrolysis of sewage sludge and $\text{Ca}(\text{H}_2\text{PO}_4)_2$: heavy metal stabilization, mechanism, and toxic leaching. *J Environ Manage* 305:114292

9. 30376 – 2013 GB/T Determination of iron, manganese, copper, zinc, calcium, magnesium, potassium, sodium, phosphorus, sulfur in tea-inductively coupled plasma atomic emission spectrometry. Beijing: All-China Federation of Supply and Marketing Cooperatives
10. GB/T 25282 – 2010. Soil and sediment-sequential extraction procedure of speciation of 13 trace elements. Beijing: China National Standardization Administration Committee
11. Han SH, Lee JC, Jang SS et al (2004) Composted sewage sludge can improve the physiological properties of *Betula schmidtii* grown in tailings. J Plant Biology 47(2):99–104
12. HJ/T 166–2004. Technical specification for soil environmental monitoring. Beijing: China Environmental Science Press
13. HJ 962–2018. Soil-determination of pH-potentiometry. Beijing: China Environmental Science Press
14. HJ 802–2016. Soil quality-determination of conductivity-electrode method. Beijing: China Environmental Science Press
15. HJ 889–2017. Soil quality-determination of cation exchange capacity (CEC)-hexamminecobalt trichloride solution/spectrophotometric method. Beijing: China Environmental Science Press
16. HJ 704–2014. Soil quality-determination of available phosphorus-sodium hydrogen carbonate solution-Mo-Sb anti spectrophotometric method. Beijing: China Environmental Science Press
17. HJ 615–2011. Soil-determination of organic carbon-potassium dichromate oxidation spectrophotometric method. Beijing: China Environmental Science Press
18. Hua QX, Li JY, Zhou JM et al (2008) Enhancement of phosphorus solubility by humic substances in Ferrosols. Pedosphere 18(4):533–538
19. Jiang YY, Wang Y, Duan WY et al (2021) Assessment of heavy metal migration characteristics and environmental effects during municipal sludge pyrolysis. Environ Sci 42(6):2966–2974
20. Jia JL (2016) Environmental soil science. Chemical Industry Press, Beijing
21. Keiluweit M, Kleber M (2009) Molecular-level interactions in soils and sediments: the role of aromatic pi-systems. Environ Sci Technol 43(10):3421–3429
22. LY/T 1234–2015. Potassium determination methods of forest soils. Beijing: State Forestry Administration
23. Liu LH, Huang L, Huang R et al (2021) Immobilization of heavy metals in biochar derived from co-pyrolysis of sewage sludge and calcium sulfate. J Hazard Mater 403:123648
24. Liu G, Meng J, Huang Y et al (2020) Effects of carbide slag, lodestone and biochar on the immobilization, plant uptake and translocation of As and Cd in a contaminated paddy soil. Environ Pollut 266:115194
25. Luo YM (2016) Remediation mechanism and technology development of heavy metal contaminated soil. Science and Technology Press, Beijing, p 290
26. Liu QM, Wang YT, Li JW et al (2021) Effect of remediation conditions on enhanced microbial remediation of petroleum-contaminated soil with mineralized waste. Environ Sci Technol 34(4):40–45

27. Li MX, He SS, Liu J et al (2010) Characterization of water-soluble organic matter in chicken manure compost by UV absorption spectroscopy. *Spectrosc Spectr Anal* 30(11):3081–3085
28. Liu ZG, Xia Y, Meng YH et al (2021) Progress in remediation of heavy metal contaminated soil with biomass carbon materials: Analysis of remediation mechanism and research hotspots. *J Environ Eng* 15(4):1140–1148
29. Li AM, Ran W, Dai JY (2005) Progress in the study of adsorption between natural organic matter and minerals and its environmental effects. *J Rock Mineralogy* 06:671–680
30. Liang P, Pardee A (1992) Differential display of eukaryotic messenger RNA by means of the polymerase chain reaction. *Science* 257(5072):967
31. NY/T 3082 – 2017. Determination of chlorophyll content in fruits, vegetables and derived products-spectrophotometry method. Beijing: Ministry of Agriculture of the People's Republic of China
32. Pignattelli S, Colzi, Bucciante A et al (2012) Exploring element accumulation patterns of a metal excluder plant naturally colonizing a highly contaminated soil. *J Hazard Mater*, 227–228(15): 362–369
33. Rui H, Sun K, Xue S et al (2012) Physiological responses and tolerance mechanisms to Pb in two xerophils: *Salsola passerina Bunge* and *Chenopodium album L.* *J Hazard Mater* 205–206:131–138
34. Sevilla-Perea AMD, Mingorance (2015) Field approach to mining-dump revegetation by application of sewage sludge co-compost and a commercial biofertilizer. *J Environ Manage* 158(1):95–102
35. Song QM, Cai XD, Wu YX et al (2019) Study on the stress response of vetiver grass to heavy metal fractions in the water-soluble state of contaminated soil. *J Agricultural Environ Sci* 38(12):2715–2722
36. Wei L, Zhu F, Li Q et al (2020) Development, current state and future trends of sludge management in China: Based on exploratory data and CO₂-equivalent emissions analysis. *Environ Int* 144:106093
37. Wang L, Li Y, Prasher SO et al (2019) Organic matter, a critical factor to immobilize phosphorus, copper, and zinc during composting under various initial C/N ratios. *Bioresour Technol* 289:121745
38. Xu JX, Wang C, Yao DJ et al (2020) Spectral characterization of soil dissolved organic matter in Dongtan wetland. *Chongming Environ Eng* 38(11):218–225
39. Xu H, Yan Z, Cai H et al (2013) Heterogeneity in metal binding by individual fluorescent components in a eutrophic algae-rich lake. *Ecotoxicol Environ Saf* 98(1):266–272
40. Yang K (2018) Research on heavy metal transformation pattern of aerobic fermented sludge and its fertilization plant efficacy. Heilongjiang, Harbin Institute of Technology
41. Yang S, Zhang Z, Cong L et al (2013) Effect of fulvic acid on the phosphorus availability in acid soil. *J Soil Sci Plant Nutr* 13(3):526–533
42. Yang F, Tang CY, Antonietti M (2021) Natural and artificial humic substances to manage minerals, ions, water, and soil microorganisms. *Chem Soc Rev* 50(10):6221
43. Zhang XY (2020) Global e-waste is growing rapidly. *Ecol Econ* 36(10):1–4

44. Zhang JL, Ding JF, Lin HZ et al (2017) Pollution of heavy metals and polychlorinated biphenyls by improper e-waste dismantling activities and its ecotoxicological effect. *J Agro-Environment Sci* 36(5):891–899
45. Zhang Y, Hu JL, Bai JF et al (2017) Contamination assessment and genesis analysis of heavy metals in farmland soils around a waste electrical and electronic equipment disassembling area. *Ecol Environ Sci* 26(7):1228–1234
46. Zhou HH, Yuan XY, Xiong YT et al (2020) Influence of biochar input on changes in the effective state of soil nutrients in different riparian zones. *Environ Sci* 41(2):914–921

Figures

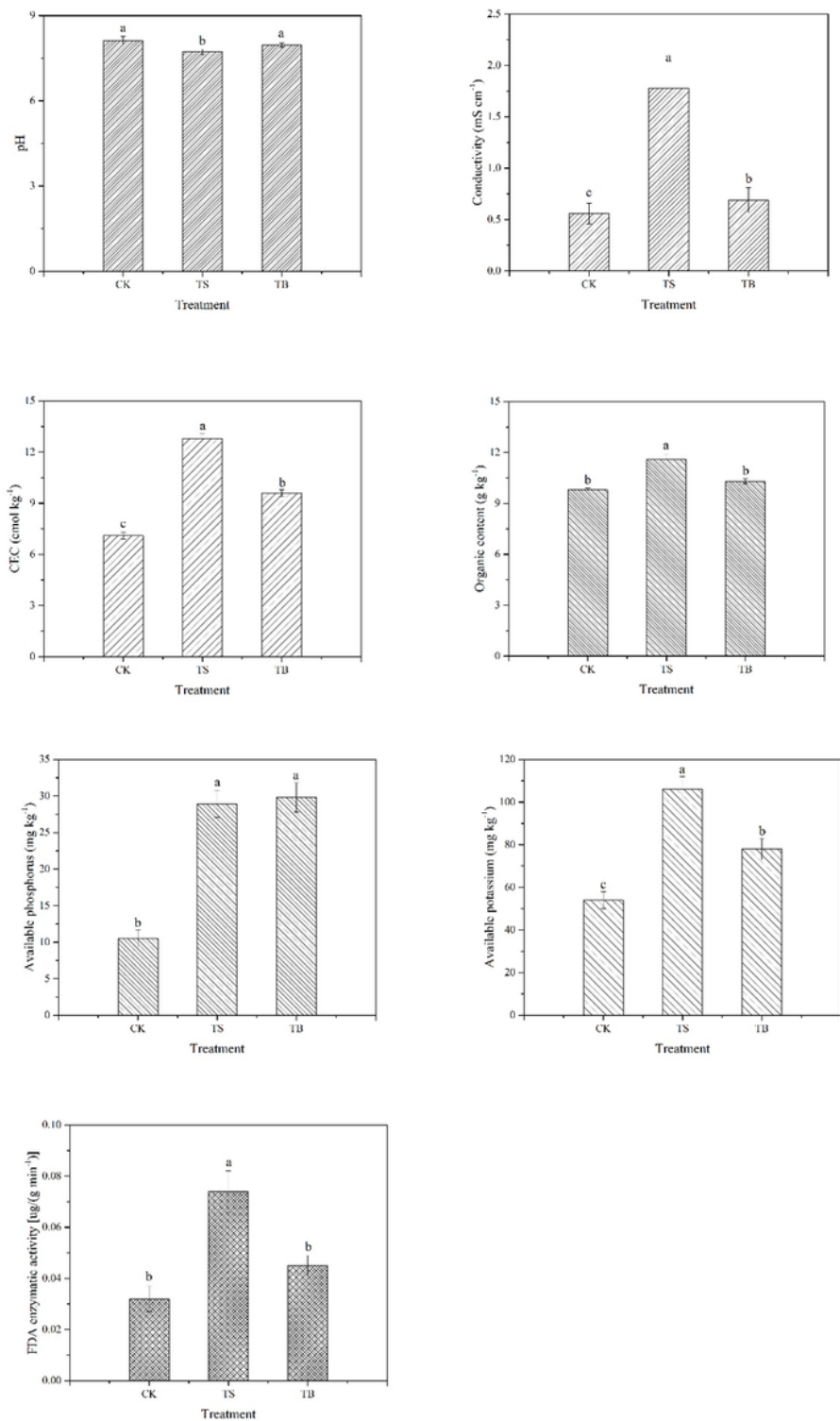


Figure 1

Effect of thermally treated sludge residue on soil chemical and biological properties (CK indicates control, TS indicates the application of sludge fermentation residues, and TB indicates the application of sludge pyrolysis residues. Different lowercase letters indicate significant differences between treatment groups P < 0.05)

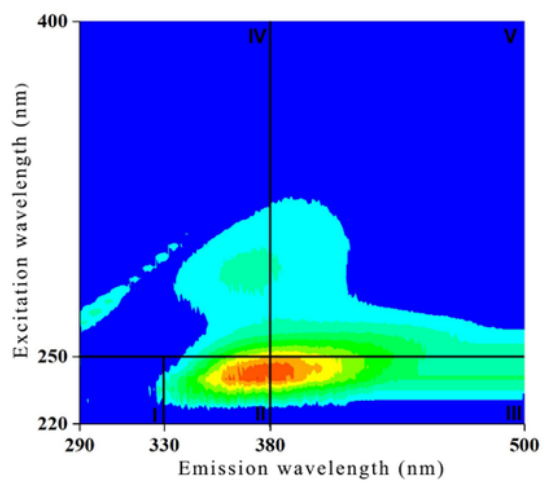
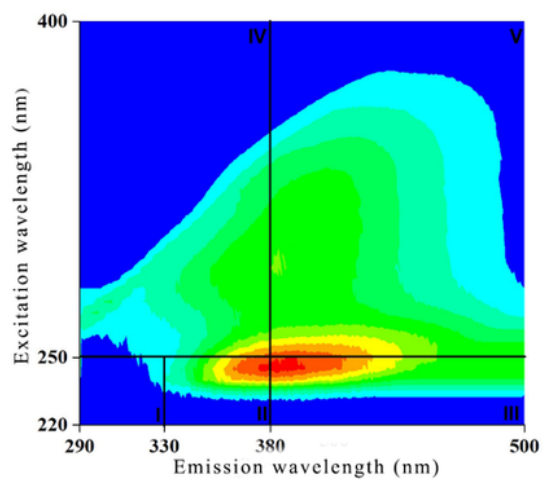
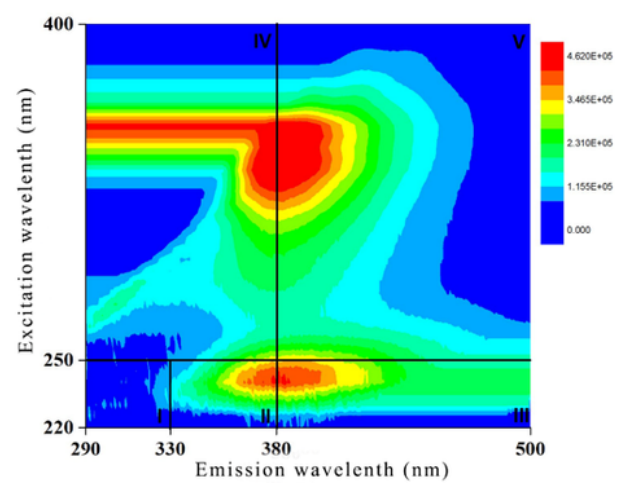


Figure 2

Three-dimensional fluorescence spectrum of soil dissolved organic matter

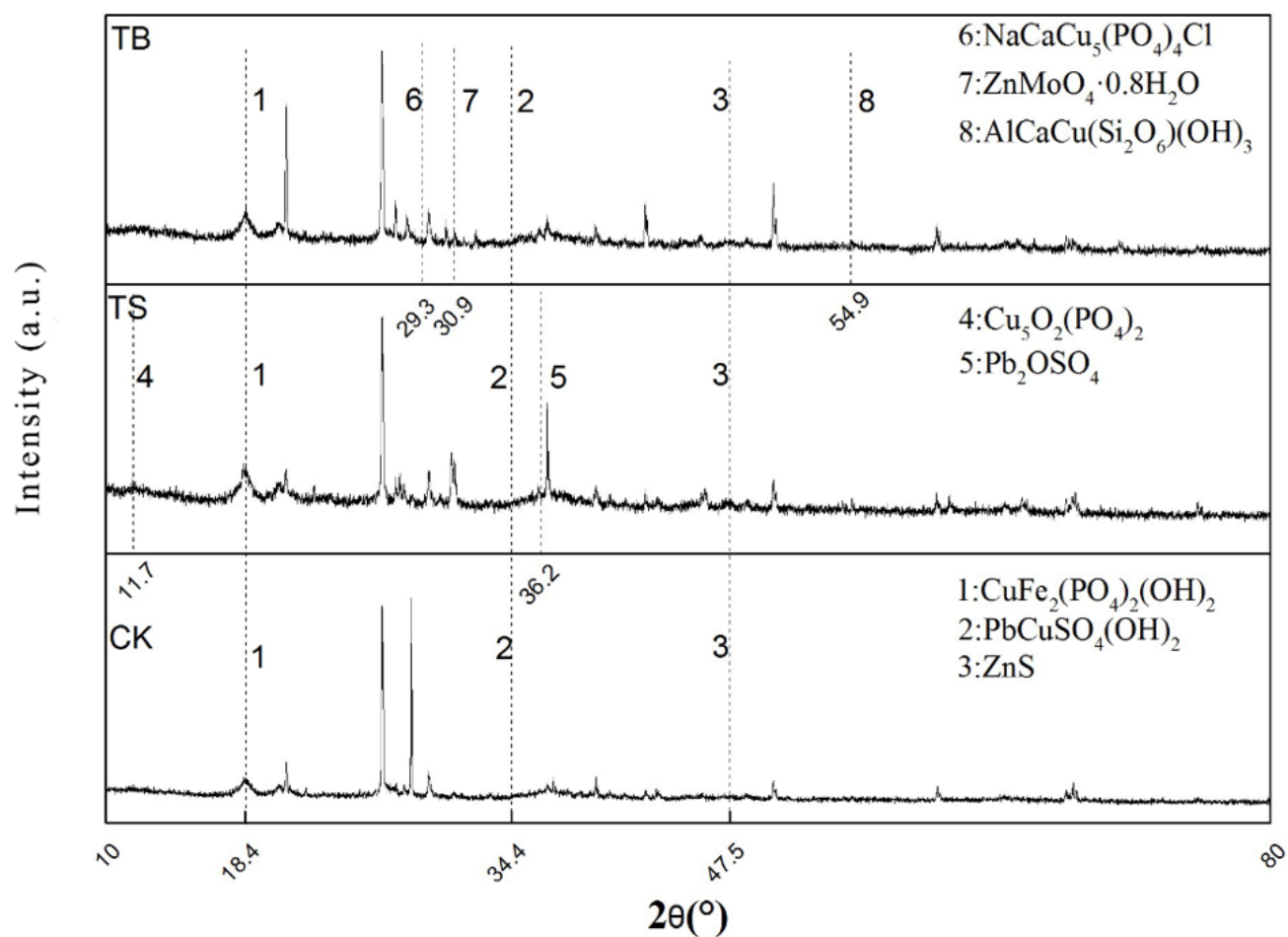


Figure 3

Effect of thermally treated sludge residue on soil heavy metal minerals (CK indicates control, TS indicates the application of sludge fermentation slag, and TB indicates the application of sludge pyrolysis slag)

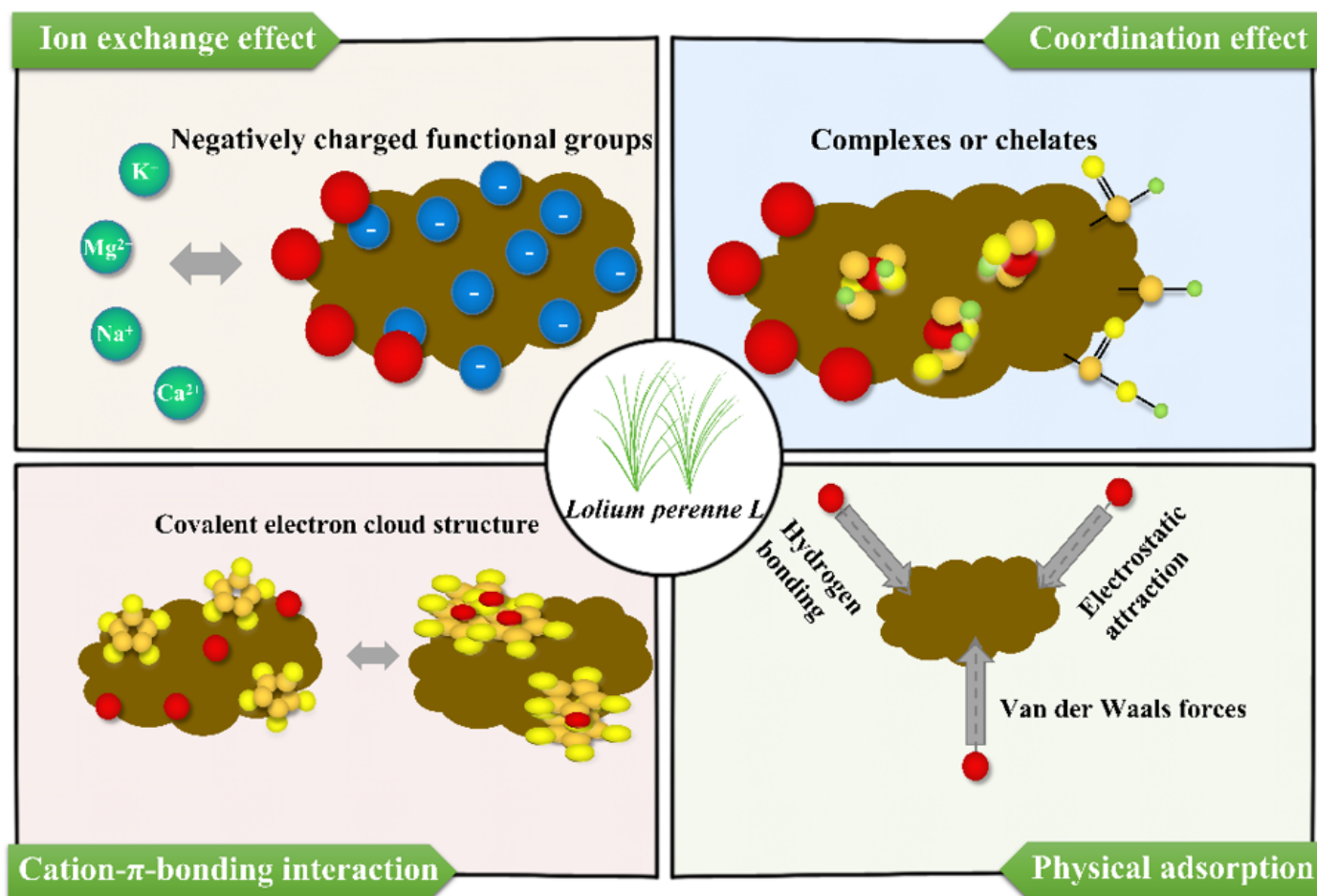


Figure 4

Mechanisms of synergistic stabilization of heavy metals remediation by thermally treated sludge residue in *Lolium perenne L.*

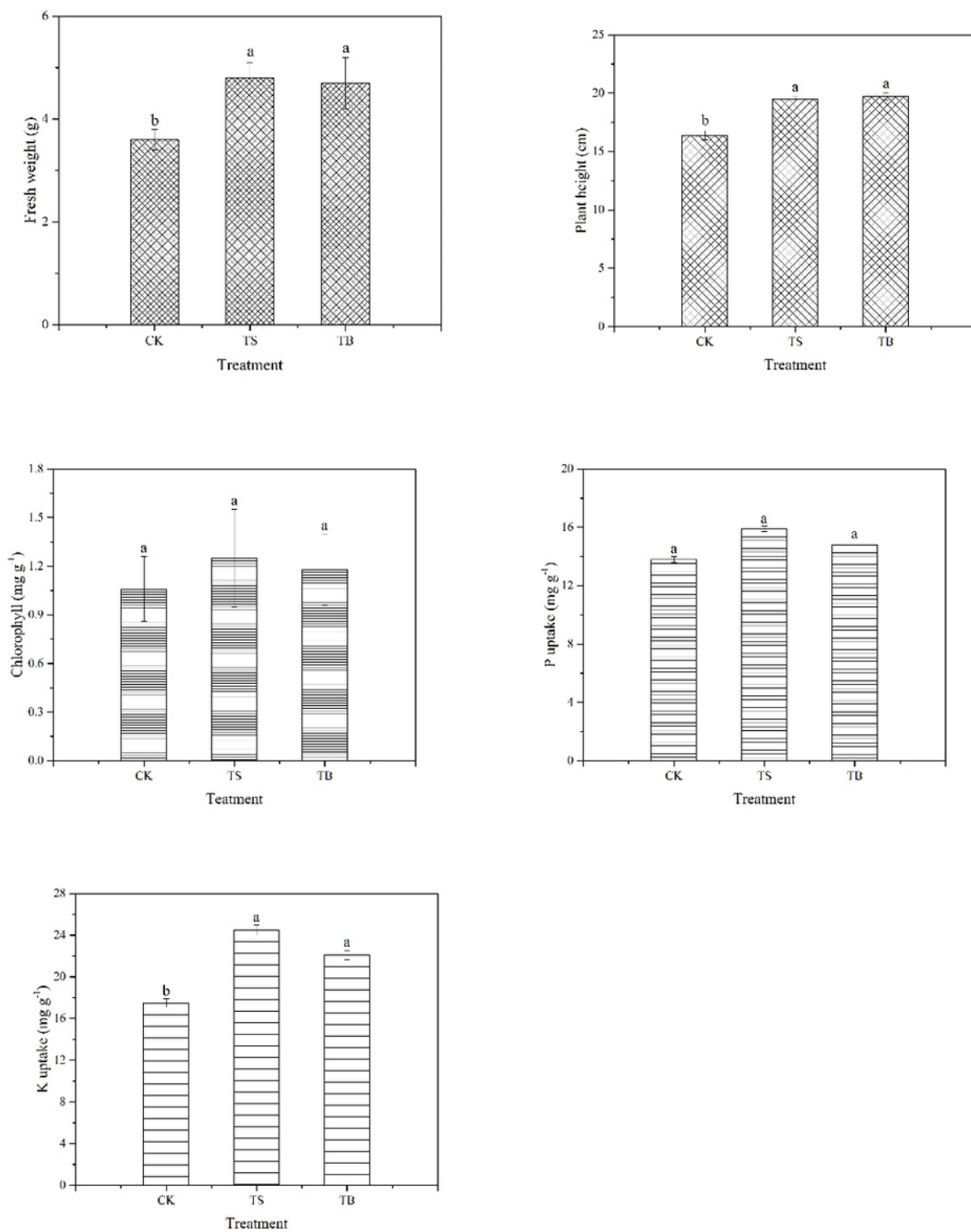


Figure 5

Effect of thermally treated sludge residue on *Lolium perenne* L. growth (Note: CK = control; TS = application of fermentation residue; and TB = application of pyrolysis residue. Different lowercase letters indicate significant differences between treatment groups (P<0.05))