

# Changes of toxic metals during biological stabilization and their potential ecological risk assessment

Hou-cheng Wang, Zheng-zhong Zeng, He-fei Zhang and Zhong-ren Nan

## ABSTRACT

With various disadvantages of pollution control technologies for toxic metal-contaminated soil, we mixed contaminated soil with sludge for *in situ* composting to stabilize toxic metals, so plants are enriched to take up the toxic metals. When simulating the above, we added toxic metal solution into sewage sludge, and then composed it with steel slag to determine inhibition of the availability of toxic metals. When toxic metals were added into sludge, the potential ecological index and geoaccumulation index of Cd became high while Zn was low. Steel slag had an inhibited availability of Cd, and when the adjunction of steel slag was 7%, the availability of Cd was lowest. Steel slag promoted the availability of Zn, and when the adjunction of steel slag was 27%, the availability of Zn was highest. Results showed that during composting, with increasing steel slag, Cd stabilizing time was reached sooner but Zn stabilizing time was slower, and the availability of all metals became lower. In the end, composting inhibited the potential ecological index of Cd, but it promoted the potential ecological index of Zn. Steel slag promoted the stability of Cd and Zn as Fe/Mn oxide-bound and residual species. Therefore, composting sludge and steel slag could be used as an effective inhibitor of Zn and Cd pollution.

**Key words** | Cd, sewage sludge, steel slag, Zn

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## INTRODUCTION

With the increasing contamination of the natural environment, the problem of toxic metal in soil becomes more and more significant, especially given that toxic metals present poor mobility in soil, long retention times, and non-biodegradability by microbes (Namasivayam & Ranganathan 1993). Soil remediation methods for the purpose of removing toxic metals from polluted soil have two fundamental technologies: *in situ* remediation and bioremediation. In bioremediation, contaminated soil is removed and then subjected to centralized processing. However, this method is not a permanent solution, high costs are generally involved, there is failure to process highly polluted soil, and it destroys ecosystems. As such, *in situ* remediation technologies, including chemical stabilization technology, bioremediation, vapor extraction, electrokinetic remediation, and electromagnetic wave heating, have been developed. Despite the advantages of these technologies, physical and chemical methods used to remove toxic metals also entail high costs; furthermore, equipment used to remove toxic metals is relatively complex. Although biological toxicities can be reduced by stabilization technology through adding

chemicals, the total amount of toxic metals remains unchanged and soil is potentially contaminated (Cao & Wang 1966; Zhang 1990). In addition, toxic metal pollutants can be removed from soil by bio-concentration at low costs, but this strategy requires a long treatment period (Pinheiro *et al.* 1994; Zhang *et al.* 2001). In this study, bioremediation was combined with stabilization technology to promote plant growth by composting sewage sludge with contaminated soil. Sludge and composting could promote the stabilization of toxic metals in soil. Plant growth subsequently led to the gradual release of toxic metals from sludge compost. The toxic metals were then absorbed by plants; thus, remediation was achieved. Therefore, sludge or composting sludge should be applied to the contaminated soil. Sludge stabilizes toxic metals in soil by *in situ* composting, regulates pH by the addition of steel slag, and promotes toxic metal stabilization.

This research demonstrated the changes in toxic metal speciation when these substances were added to sludge and compost. Our results provide a theoretical foundation for sludge and compost application to stabilize toxic

metals in contaminated soil. In addition, this study provided a theoretical basis for remediation of toxic metal-contaminated soil by combining *in situ* sludge composting and phytoremediation.

## MATERIALS AND METHODS

### Materials

Sewage sludge was obtained from Yan'er Wan Wastewater Treatment Plant in Lanzhou City, China. The water content was decreased to 40–50% from 70–75% through natural drying, and then placed in a dry and ventilated place. The sawdust was obtained from Lanzhou University with particle size ranging from 0.1 cm to 2 cm.

The steel slag was retrieved from Gansu Yuzhong Iron and Steel Plant and sifted through a 100 mesh sieve. Fe was removed by means of magnetism.

The concentrations of toxic metal solutions are listed in Table 1; the concentrations of toxic metals in the sludge are kept higher than the limited concentration in basic soil as stipulated in 'The Disposal of Sludge from Municipal Wastewater Treatment Plant – The Quality of Sludge Used in Gardens or Parks' (CJ248-2007).

The physicochemical properties of the above-mentioned materials are given in Table 1. The speciation and distributions of the toxic metals are shown in Tables 2 and 3, respectively.

Atomic absorption spectrometry (AAS)(Thermo M6) was used in the experiment.

### Composting

Composting is performed as follows. A sprinkling can was used to spray the prepared solution evenly on the surface of the sludge. The proportion of steel slag is given in Table 4. The composting experiment was performed in a compost bin (900 mm × 700 mm × 800 mm), and an air heater was used for forced ventilation. The experiment

lasted for 54 d. The ambient temperature ranged from 21 °C to 27 °C. From the 1st day to the 20th day, the compost was stirred once a day; it was stirred twice a day after the first 20 d. The temperature of the stack center was measured twice a day (at 9:30 AM and 4:30 PM, taking the average as the stack temperature for that day). Water was added to the compost to maintain its water content between 50% and 60%. From the 1st day to the 6th day, samples were taken once every 2 days. From the 6th day to the 30th day, samples were taken once every 4 days. After 30 d, samples were taken once every 8 days. The samples were dried, ground, sifted through a 100 mesh sieve, and saved for later use.

### Test methods

The test methods used in the experiment are listed in Table 5.

The chemical fractions of toxic metals were determined by the use of the sequential extraction procedure of Tessier *et al.* (1979), which is widely used in various studies of composting. The steps are listed below.

- (i) Exchangeable (EXCH). The sludge was extracted at room temperature for 1 h with 8 ml of magnesium chloride solution (1 M MgCl<sub>2</sub>, pH 7.0) with continuous agitation.
- (ii) Bound to carbonates (CAR). The residue from (i) was leached at room temperature with 8 mL of 1 M NaAc adjusted to pH 5.0 with acetic acid. Continuous agitation was maintained and the time necessary for complete extraction was evaluated.
- (iii) Bound to Fe-Mn oxides (FeMnOx). The residue from (ii) was extracted with 20 mL of 0.04 M NH<sub>2</sub>OH-HCl in 25% (v/v) HAc. The experiments were performed at 96 °C with occasional agitation and the time needed for complete dissolution of the free iron oxide was evaluated.
- (iv) Bound to organic matter (OMB). To the residue from (iii) were added 3 ml of 0.02 M HNO<sub>3</sub> and 5 ml of 30% H<sub>2</sub>O<sub>2</sub> adjusted to pH 2 with HNO<sub>3</sub>. The mixture

Table 1 | Physicochemical properties of the compost mixture

Materials	pH	Moisture content	Granulometric mm	Density g/cm <sup>3</sup>	Organic Matter mg/kg	C/N	Zn mg/kg	Cd mg/kg
Sludge	5.98	80%	–	1.26	66.14	9/1	480.85	1.01
Sawdust	–	7%	1–20	0.4	9.50	200/1	101.14	0.58
Steel slag	12.07	–	0.008–0.154	4.56	3.99	–	205.75	0.11
Concentration of the added toxic metals to the compost mixture							3,755.60	20.95

**Table 2** | Speciation of Cd in the compost mixture

	Exchangeable		Carbonate-bound		Fe/Mn oxide-bound		Organic matter-bound		Residual	
	Concentration mg/kg	Proportion %	Concentration mg/kg	Proportion %	Concentration mg/kg	Proportion %	Concentration mg/kg	Proportion %	Concentration mg/kg	Proportion %
Sludge	0.04	3.47	0	0	0.59	57.92	0.1	9.41	0.32	28.71
Sawdust	0	0	0	0	0.03	19.23	0.05	38.46	0.06	42.31
Steel slag	–	–	–	–	–	–	–	–	–	–

**Table 3** | Speciation of Zn in the compost mixture

	Exchangeable		Carbonate-bound		Fe/Mn oxide-bound		Organic matter-bound		Residual	
	Concentration mg/kg	Proportion %	Concentration mg/kg	Proportion %	Concentration mg/kg	Proportion %	Concentration mg/kg	Proportion %	Concentration mg/kg	Proportion %
Sludge	5.47	1	34.97	7	309.12	64	83.11	17	48.19	10
Sawdust	–	–	–	–	–	–	–	–	–	–
Steel slag	0.47	0	1.17	1	68.12	33	7.50	4	128.50	62.4

**Table 4** | Ratio of each component in the compost

Serial no.	Material	Ratio (dry weight)
GZ0	Sludge: Sawdust: Steel Slag	0 kg: 14 kg: 2 kg
GZ7	Sludge: Sawdust: Steel Slag	14 kg: 2 kg: 0.98 kg
GZ14	Sludge: Sawdust: Steel Slag	14 kg: 2 kg: 1.96 kg
GZ21	Sludge: Sawdust: Steel Slag	14 kg: 2 kg: 2.94 kg
GZ28	Sludge: Sawdust: Steel Slag	14 kg: 2 kg: 3.92 kg
GZ35	Sludge: Sawdust: Steel Slag	14 kg: 2 kg: 4.90 kg

**Table 5** | Test methods

Items	Test method
Organic matter	Potassium dichromate volumetric method
pH	pH meter
Moisture content	Gravimetric method
Temperature	Thermometer
Total nitrogen	Semi-micro Kjeldahl method
Total amount of toxic metals	Nitric acid-hydrofluoric acid-perchloric acid digestion
Toxic metals morphology	Tessier five-step sequential extraction method

was heated to  $85 \pm 2$  °C for 3 h with intermittent agitation. After cooling, 5 ml of 3.2 M  $\text{NH}_4\text{OAc}$  in 20% (v/v)  $\text{HNO}_3$  was added and the sample was diluted to 20 ml and stirred continuously for 30 min.

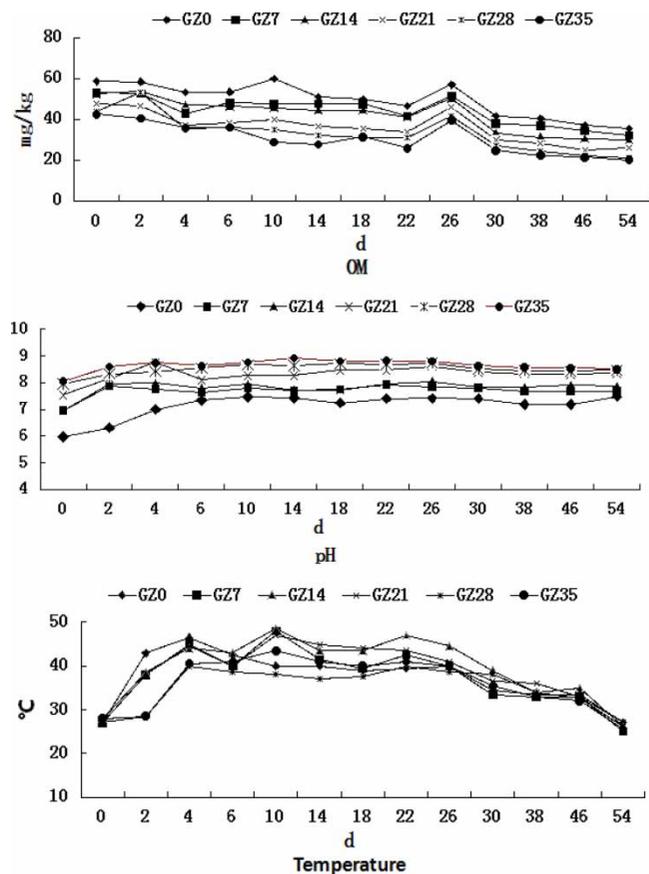
- (v) Residual (RES). The residue from (iv) was digested with  $\text{HCl} + \text{HNO}_3 + \text{HF} + \text{HClO}_4$  (1:4:1) at 180 °C and then determined using Thermo M6 AAS.

Between each extraction, the samples were centrifuged (5,000 rpm for 30 min) and filtered. The filtrate was digested with  $\text{HCl} + \text{HNO}_3 + \text{HF} + \text{HClO}_4$  (1:4:1) at 180 °C before being used for the determination of toxic metal concentration using Thermo M6 AAS.

## RESULTS AND ANALYSIS

### Evaluation of temperature, pH and organic matter

As shown in Figure 1, a slower rise in temperature was observed in composting sludge with steel slag compared to the control. The control entered the cooling phase at day 18, while sludge with a 7–21% steel slag amendment had a

**Figure 1** | Change of temperature, pH and organic matter (OM) during composting.

longer thermophilic phase of about 22 d, respectively, which reflected that the steel-amended sludge compost was able to maintain a sufficient microbial population for organic degradation. Addition of steel slag at 7–35% increased the initial pH of the composting mixture effectively to 6.96–8.05, respectively (Figure 1). The changes in pH of the steel-amended sludge compost showed a similar trend to the control. At the end of composting, the pH of all steel-amended sludge compost was significantly higher than the control, which was 7.68–8.50, respectively. Organic matter was lower in steel-amended sludge compost compared to the control (Figure 1). Steel slag as a bulking material has the ability to increase the porosity of the substrate and as a result, to improve the composting process and the biodegradability of the organic matter. In addition, steel slag could dilute the content of organic matter. Sludge compost with or without steel treatment in the present experiment reached maturation after 22 d of composting, which indicates that the addition of steel did not affect the length of maturation for sewage sludge compost.

### Changes in toxic metal speciation when they were added to sewage sludge

Table 6 shows that the added Cd (20.95 mg/kg) was mainly transformed into exchangeable (60.37%), Fe/Mn oxide-bound (21.87%), and carbonate-bound (11.92%) in the control compost. The results revealed that Cd did not immediately react with the chemicals in the sludge. Cd also exists in a hydrated ion state, which is fixed on the surfaces of particles; thus, the conversion of Cd to other forms is inhibited (Schuster 1999; Naidu *et al.* 1997; Kocman *et al.* 2004). In our study, as the steel slag proportion increased, the conversion of Cd to carbonate-bound (9.75–14.64%) and organic matter-bound (4.51–6.26%) forms increased; this conversion prevented the transformation of Cd to Fe/Mn oxide-bound (11.15–18.57%). This finding may be associated with pH. Steel slag had inhibited the availability of Cd. When the adjunction of steel slag was 7%, the availability of Cd was lowest.

As shown in Table 7, after Zn (3,755.60 mg/kg) was added to the sludge, it mainly converted to Fe/Mn oxide-bound (49.43%), exchangeable (17.79%), and carbonate-bound (13.52%) forms; Zn easily binds to small molecules (Hayes *et al.* 1989). Aringhieri *et al.* (1985) demonstrated that 80% of exogenous toxic metals are adsorbed in 10 min after these metals are added to sludge when organic matter (>14%) and clay content (>60%) are high. Likewise, after Zn was added to sludge, it reacted rapidly with the chemical components of sludge and inhibited the transformation of Zn to Fe/Mn oxide-bound and organic matter-bound (2.21% to 3.76%) forms because steel slag improved pH in sludge. The pH and carbonate content elicit considerable effects on sorption and the morphological characteristics of toxic metals (Xia *et al.* 1992). As steel slag increased, carbonate-bound forms gradually increased; by contrast, organic matter-bound and Fe/Mn oxide-bound forms gradually decreased. So, steel slag promoted the availability of Zn. When the adjunction of steel slag was 27%, the availability of Zn was highest.

### Speciation of toxic metals during control composting

As shown in Figure 2, before Cd forms had stabilized, the results showed that carbonate-bound, Fe/Mn oxide-bound, and organic matter-bound were converted from the exchangeable form. After composting for 22 d, considerable transformations occurred among various species. Exchangeable decreased from 31.75% to 11.60%, carbonate-bound forms decreased from 29.37% to 27.10%. By contrast, Fe/Mn oxide-bound and organic matter-bound forms increased from 32.10% to 50.90% and from 6.14% to 9.23%, respectively. Therefore, the main occurrence involved transformation from exchangeable state to Fe/Mn oxide-bound state because NH<sub>3</sub> nitrification occurs in this stage (Jia *et al.* 2008); NH<sub>3</sub> nitrification results in a decrease in local pH and in an increase in oxidation–reduction potential. In the entire process, organic matter-bound Cd gradually increased. These findings are consistent with those of Chanmugathas & Bollag (1998), in which microorganisms can promote the dissolution of Cd combined with low-molecular weight organic acids. After composting for 26 d, Cd forms remained unchanged to the end; this result showed that Cd forms reached stability during composting for 26 d. Final exchangeable, carbonate-bound, Fe/Mn oxide-bound, organic matter-bound, and residual form contents were found to be 9.69%, 14.52%, 60.51%, 14.55%, and 0.72%, respectively.

Changes in Zn species were simple during the entire composting process (Figure 3). Considerable transformation among species occurred at 4 d to 6 d. Exchangeable forms decreased from 21.55% to 6.03%, whereas carbonate-bound species increased from 16.56% to 28.98%. Fe/Mn oxide-bound, organic matter-bound, and residual forms remained unchanged. Therefore, the process likely involves transition from exchangeable form to carbonate. During the entire process, Fe/Mn oxide-bound species maintained a high level (51.20–61.58%). These results are consistent with those in a previous study (Cai *et al.* 2007), in which Zn is mainly

Table 6 | Changes in added Cd

	Exchangeable	Carbonate-bound	Fe/Mn oxide-bound	Organic matter-bound	Residual
Control	60.37%	11.92%	21.87%	2.10%	0
7%	50.16%	9.75%	23.70%	5.06%	0
14%	48.41%	19.27%	11.15%	6.23%	0
21%	50.70%	14.64%	11.15%	4.51%	0
28%	45.74%	9.73%	17.57%	4.59%	0
35%	36.96%	12.78%	18.57%	6.26%	0

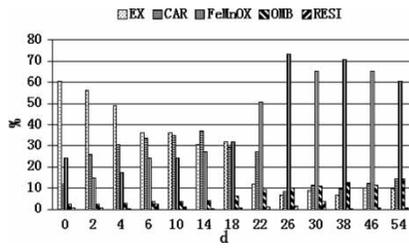


Figure 2 | Changes of Cd speciation during the control composting.

bound to Fe/Mn oxide-bound species; furthermore, the ability to combine with organic matter is weak (Cai et al. 2003). Zn forms remained unchanged until 6 d, which indicated that Zn had been stable after 6 d. Final exchangeable, carbonate-bound, Fe/Mn oxide-bound, organic matter-bound, and residual amounts were 5.01%, 26.00%, 56.21%, 11.40%, and 1.29%, respectively.

### Changes in Cd speciation during composting sludge with steel slag

In Figure 4, during composting sewage sludge with steel slag, changes in Cd speciation were similar to the control composting, but stabilizing time shifted to an earlier point in time. Stabilizing time periods were 10 d, 18 d, 14 d, 18 d, and 6 d when 7%, 14%, 21%, 28%, and 35% steel slag were added, respectively. Final exchangeable, carbonate-bound, Fe/Mn oxide-bound, organic matter-bound, and residual Zn amounts were 3.21% to 4.55%, 6.55% to 16.37%, 61.56% to 71.52%, 13.76% to 16.48%, and 0.9% to 6.03%, respectively. Compared with the control composting, the amount of exchangeable and carbonate-bound species had decreased by 3.21–4.55% and 3.38–7.97%. By contrast, Fe/Mn oxide-bound, organic matter-bound, and residual species increased by 1.05–11.01%, 0.15–1.93%, and 0.17–5.31%, respectively. Therefore, the addition of steel slag reduced available Cd in sludge. Changes in Fe/Mn oxide-bound and residual species were high. As steel slag content increased, carbonate content increased; this

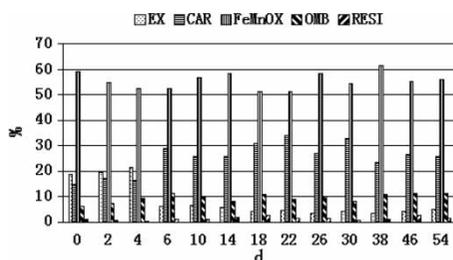


Figure 3 | Changes of Zn speciation during the control.

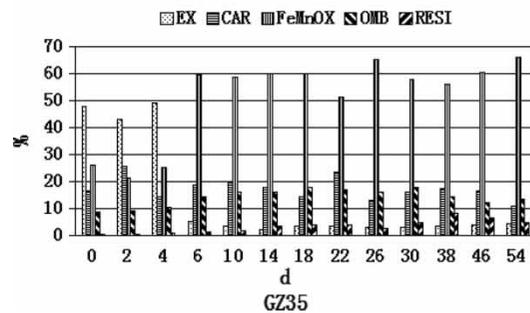
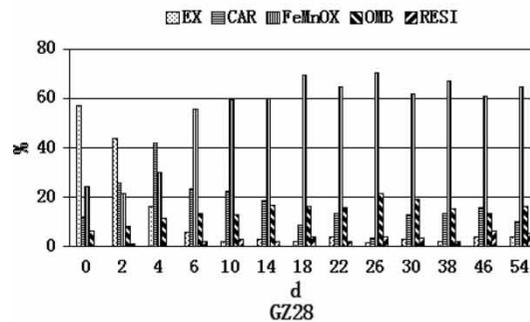
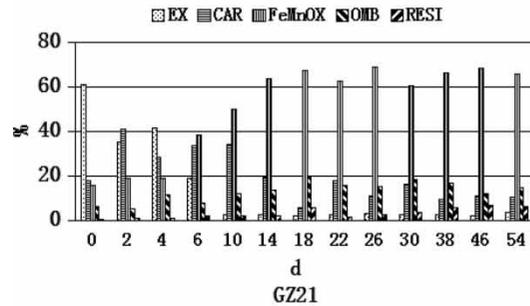
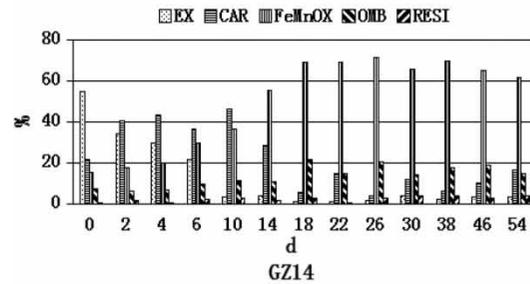
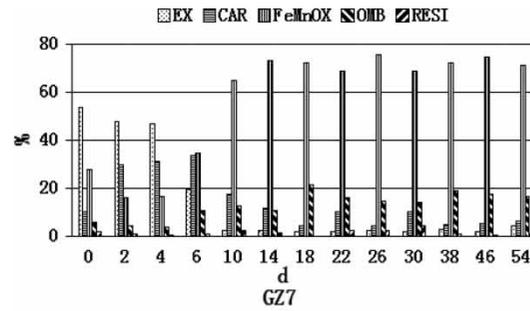


Figure 4 | Changes in Cd speciation during co-composting sludge with steel slag.

increase was associated with the increase in pH. Likewise, Fe/Mn oxide-bound content gradually increased as steel slag was added. Conversely, organic matter-bound species decreased as the amount of steel slag increased. The residual form increased as steel slag increased. With increasing content of steel slag, Cd stabilization was sooner and its availability was lower.

### Changes in Zn speciation during composting of sewage sludge with steel slag

In Figure 5, compared with the control compost, the stabilizing time was lengthened during composting sludge with steel slag. The stabilizing time of toxic metals in composting sewage sludge with 7, 14, 21, 28, and 35% steel slag were 18, 18, 18, 18, and 6 d, respectively. That was 12 d later than the control. During composting, the transformation between different speciations varied from control compost; for instance, the performance of these species (except 35%) for 6 d involved transformation of exchangeable species to carbonate-bound form and then from carbonate-bound form to Fe/Mn oxide-bound form; thus, stability was reached. In sludge compost with 35% added steel slag, exchangeable form was directly transformed to Fe/Mn oxide-bound species at 6 d; stability was reached. This result occurred possibly because Fe/Mn oxide-bound Zn had formed rapidly before composting was performed; however, addition of steel slag inhibited this formation. Increase of pH resulted in the conversion from exchangeable to carbonate in the thermophilic period. And then  $\text{NH}_3$  nitrification resulted in the decrease in pH and an increase in redox potential in the maturity stage. Carbonate-bound species were then converted to Fe/Mn oxide-bound form. Final exchangeable, carbonate-bound, Fe/Mn oxide-bound, organic matter-bound, and residual Zn form amounts were 1.28–2.33%, 23.22–27.31%, 59.99–63.31%, 6.76–8.25%, and 1.76–0.51%. Compared with the control compost, in the composting sludge with steel slag, the amount of exchangeable form decreased by 2.77–3.82%; likewise, the amount of carbonate-bound species reduced by 0.49–2.78%. Conversely, Zn bound to Fe/Mn oxides increased by 3.78–7.10% and organic matter-bound species reduced by 1.41–4.64%; residual form increased by 0.47–2.22%. The generation of Fe/Mn oxide-bound was mainly promoted by steel slag. This result is consistent with that of Sheng *et al.* (2007), who demonstrated that Fe/Mn oxide-bound form changes slightly as the steel amount varies. Organic matter-bound species decreased, whereas residual form increased; thus, the addition of slag possibly promoted the generation of

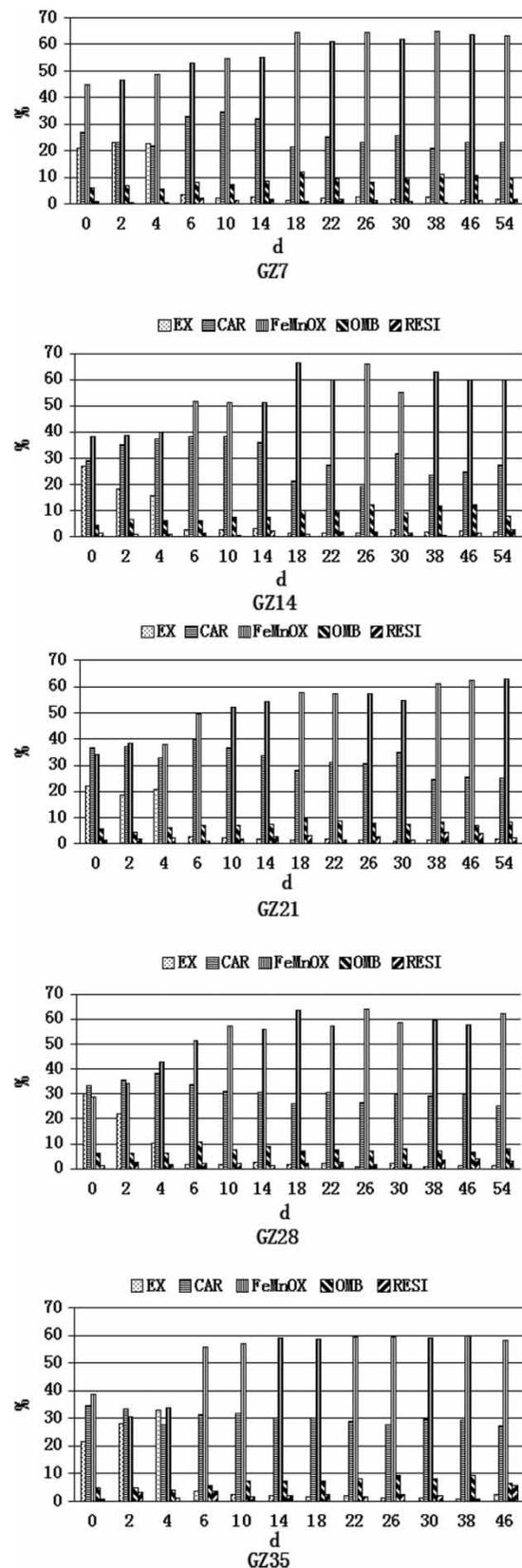


Figure 5 | Changes in Zn speciation during co-composting of sewage with steel slag.

**Table 7** | Changes in added Zn

	Exchangeable	Carbonate-bound	Fe/Mn oxide-bound	Organic matter-bound	Residual
Control	17.79%	13.52%	49.43%	4.01%	0
7%	19.35%	24.09%	34.59%	3.76%	0
14%	22.55%	23.94%	25.72%	2.21%	0
21%	18.04%	29.25%	21.70%	3.06%	0
28%	24.21%	26.08%	17.56%	3.46%	0
35%	17.64%	27.83%	26.51%	2.62%	0

residual Zn. With increasing content of steel slag, Zn stabilization was slower but its availability had become lower.

### Potential ecological risk assessment

Ecological risk assessment is to assess whether adverse ecological effects may occur or are in the process of happening due to one or more external factors. It is used to assess future ecological adverse effect or the possibility of ecological change due to certain factors in the past. In this paper, potential ecological index method and geoaccumulation index method were used to evaluate the pollution degree of toxic metals added into sludge and compost. Hakanson (1980) proposed the potential ecological index method, which is one of the most commonly used methods in evaluating toxic metal pollution. The formula is as follows:

$$E_r^i = T_r^i \times C_n / B_n$$

In the formula,  $C_n$  is the content of element  $n$  in the sediments (mg/kg). This paper used the sum amount of exchangeable and carbonate-bound species.  $B_n$  is the geochemical background value of elements in the sediment (mg/kg). This paper uses Cd and Zn exchangeable and carbonate-bound species combined in sludge from Lanzhou Wastewater Treatment Plant. Finally,  $T_r^i$  reflects the strength of toxic metal toxicity. In this paper, Cd = 30 and Zn = 1.

The index of geoaccumulation composed by Muller (1969), a German scholar, was proposed in 1969. This method is widely used as a quantitative indicator of the degree of toxic metal pollution in sediment research. Geoaccumulation is calculated as follows:

$$I_{geo} = \log_2 [C_n / (KB_n)]$$

In this equation,  $C_n$  is the content of element  $n$  in the sediment (mg/kg). This paper uses the sum of exchangeable and carbonate-bound species.  $B_n$  is the geochemical

background value of elements in the sediment (mg/kg). This paper uses Cd and Zn exchangeable and carbonate-bound combined in sludge from Lanzhou Wastewater Treatment Plant.  $K$  is the coefficient of variation of the background value, which is  $K = 1.5$ .

In Table 8, after toxic metals were obtained, the Cd potential ecological index was extremely high at >360 (the degree of ecological risk is serious). This result showed that the applied toxic metals considerably increased the ecological risk of Cd. However, the Cd ecological index in the mixture of steel slag and sludge was lower than that in the pure sludge, showing that slag slowed the ecological risk of toxic metals. After composting, although >360 (the degree of ecological risk is serious), the Cd ecological index in the mixture was considerably reduced, decreasing to 29% of the original in composting pure sewage; this finding showed that compost sludge weakened the ecological risk degree of Cd. Compared with compost pure sewage sludge, the ecological index of Cd was lower in composting sewage sludge with steel slag, which was at 12–17% of the original. Therefore, steel greatly weakened the ecological

**Table 8** | Potential ecological index and geoaccumulation of toxic metals

Orders		Potential ecological risk index		Index of geoaccumulation	
		After adding	After composting	After adding	After composting
Cd	GZ0	13,050.00	3,757.50	8.18	6.38
	GZ7	13,140.00	1,627.50	8.19	5.18
	GZ14	11,883.75	2,625.00	8.05	5.86
	GZ21	11,115.00	1,826.25	7.95	5.45
	GZ28	12,116.25	1,691.25	8.07	5.24
	GZ35	11,163.75	1,863.75	7.96	5.38
Zn	GZ0	28.99	30.33	4.27	4.34
	GZ7	29.07	22.26	4.28	3.89
	GZ14	24.77	23.83	4.05	3.99
	GZ21	24.43	20.63	4.03	3.78
	GZ28	26.95	19.24	4.17	3.68
	GZ35	24.76	19.19	4.05	3.68

risk degree of Cd. After adding Zn, the toxic metal potential ecological index was low at less than <40 (degree of ecological risk is low). This result showed that pollution from additional toxic metal Zn on sludge was low. Zn ecological index in the mixture of steel slag and sludge was lower than that in the pure sludge, thus showing that slag slowed the ecological risk of toxic metals. Although <40 (degree of ecological risk is low) after composting, the Zn ecological index of each mixture increased in pure sludge compost, which showed that sludge compost enhanced the degree of ecological risk for Zn. The Zn ecosystem index was smaller in composting sludge with steel slag. Therefore, steel slag weakened the ecological risk degree of Zn in composting sludge.

After toxic metals were obtained, Cd geoaccumulation was >5 (the degree of pollution is extremely strong), which showed that the presence of toxic metals lead to serious pollution of Cd in sewage sludge. The influence of steel slag on the geoaccumulation of Cd was small. Although higher than 5 after composting, geoaccumulation of Cd showed a decrease by 1.8 in pure sewage and 2.19 to 3.01 in the mixture of sewage sludge and steel slag. The difference between various amounts of steel slag was insignificant, which showed that steel slag promoted a weakening effect on the pollution level of Cd in the composting process. After Zn was added, Zn geoaccumulation was 4.03 to 4.27. The pollution level was 5, and the degree of pollution was strong-to-strong. This result indicated that toxic metals represent a certain amount of Zn pollution on sludge. After composting, Zn geoaccumulation was 4.34 in pure sewage sludge, which indicated an increase, and a mild boost to Zn pollution was observed. However, Zn geoaccumulation had decreased by 0.25 to 0.49 in composting sewage sludge with steel slag. The final result was 3.68 to 3.99, the pollution level was 4, and the degree of pollution was strong. Steel slag presented a depressing effect on the pollution of Zn. Therefore, steel slag presented an inhibitory effect on the Zn and Cd potential ecological index and on geoaccumulation in sludge and during composting.

## CONCLUSION

When toxic metals were added into sludge, Zn converted to Fe/Mn oxide-bound (49.43%) immediately, but Cd showed little change. So, the potential ecological index and geoaccumulation index of Cd became high while Zn was low. Steel slag had inhibited availability of Cd, when the adjunction of steel slag was 7%, availability of Cd was lowest. Steel slag

promoted availability of Zn, when the adjunction of steel slag was 27%, availability of Zn was highest. Results showed that during composting, with increasing steel slag, Cd stabilization time was sooner but Zn stabilization time was slower, their availability all become lower. In the end, composting inhibited the potential ecological index of Cd, but it promoted the potential ecological index of Zn. Steel slag promoted stability of Cd as Fe/Mn oxide-bound (61.56–71.52%) and residual species (0.9–6.03%), and it promoted Zn transformation to Fe/Mn oxide-bound (59.99–63.31%) and residual fractions (1.76–3.51%) during composting. Therefore, composting sludge and steel slag could be used as an effective inhibitor of Zn and Cd pollution.

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## REFERENCES

- Arignhieri, R., Carrai, P. & Petruzzelli, G. 1985 Kinetics of Cu<sup>2+</sup> and Cd<sup>+</sup> adsorption by an Italian soil. *Soil Science* **139** (3), 197–204.
- Cai, Q.-y., Zeng, Q.-y., Mo, C.-h. & Yang, G. 2003 Distribution of forms for copper and zinc in composting of municipal sludge with rice straw. *Journal of Agro-Environment Science* **22** (4), 458–462.
- Cai, Q. Y., Mo, C. H., Wu, Q. T. & Huang, C. H. 2007 Concentration and speciation of heavy metals in six different sewage sludge composts. *Journal of Hazardous Materials* **147** (3), 1063–1072.
- Cao, L. & Wang, H. 1996 Study on cadmium-pollution of soil-crop system and its control. *Environmental Pollution & Control* **18** (5), 8–11.
- Chanmugathas, P. & Bollag, J.-M. 1998 Microbial role in immobilization and subsequent mobilization of cadmium in soil. *Arch. Environ. Contamin. Toxicol.* **17** (22), 9–235.
- Hakanson, L. 1980 An ecology risk index for aquatic pollution control A sedimentological approach. *Water Research* **14** (8), 975–1001.
- Hayes, M. H. B., MacCarthy, P., Malcolm, R. L. & Lo, S. L. 1989 Humic substances. In: *Search of Structure*, Wiley-Interscience, Chichester, UK.
- Jia, C., Zhang, Z.-q. & Zhang, Y. 2008 Transformation of nitrogen forms during co-composting of sewage sludge and wheat straw. *Acta Scientiae Circumstrantiae* **28** (11), 2269–2276.
- Kocman, D., Horvat, M. & Kotnik, J. 2004 Mercury fractionation in contaminated soils from the Idrija mercury mine region. *Journal of Environmental Monitoring* **6** (8), 696–703.

- Lundin, M., Olofsson, M., Pettersson, G. J. & Zetterlund, H. 2004 [Environmental and economic assessment of sewage sludge handling options](#). *Resour. Conserv. Recycl.* **41**, 255–278.
- Muller, G. 1969 Index of geoaccumulation in sediments of the Rhine River. *Geojournal* **2** (3), 108–118.
- Naidu, R., Kookana, R. S., Summer, M. E., Harter, R. D. & Tiller, K. G. 1997 [Cadmium sorption and transport in variable charge soils: a review](#). *Journal of Environmental Quality* **26** (3), 602–617.
- Namasivayam, C. & Ranganthan, K. 1993 [Waste Fe\(III\)/Cr\(III\) hydroxide as adsorbent for the removal of Cr\(VI\) from aqueous solution and chromium plating industry wastewater](#). *Environmental Pollution* **82**, 255–261.
- Pinheiro, J. P., Mota, A. M. & Goncalves, M. L. S. 1994 [Complexation study of humic acids with cadmium \(I\) and lead \(I\)](#). *Analytica Chimica Acta* **284** (3), 525–537.
- Schuster, E. 1991 [The behavior of mercury in the soil with special emphasis on complexation and adsorption processes – a review of the literature](#). *Water, Air, and Soil Pollution* **56** (1), 667–680.
- Sheng, J., Lu, W.-j. & Wang, H.-t. 2007 Effects of fly ash on the exchangeable toxic metals (Cu, Zn, Pb) during sewage sludge composting and land utilization. *Environmental Science* **28** (6), 1367–1371.
- Tessier, A., Campbell, P. G. C. & Bisson, M. 1979 [Sequential extraction procedure for the speciation of particulate trace metals](#). *Anal. Chem.* **51**, 844–858.
- Xia, Z.-l. 1992 *Soil environmental capacity of China*. Seismological Press, Beijing, China, pp. 1–245.
- Zhang, D.-y. 1990 The detoxification of soil organic matter on six valence chromium. *Agro-Environmental Protection* **4**, 29–31.
- Zhang, Y.-l., Shen, Q.-r. & Jiang, Y. 2001 Effects of organic manure on the amelioration of Cd-polluted soil. *Acta Pedologica Sinica* **38** (2), 212–218.

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