1. Introduction

Sludge is an unavoidable product of wastewater treatment plants and contains persistent organic pollutants, heavy metals, endocrine disruptors, pathogens and other microbiological pollutants [1,2]. More than 25 million tons of municipal sewage sludge (moisture content of approximately 80%) was produced every year in China until 2013 [3]. With the economic development and increasing attention paid to environmental protection by the government in China, sludge production will continue to increase rapidly [4,5], and addressing large quantities of sludge in a scientific and economical manner is crucial for the protection of the ecological environment. Because sludge is rich in nutrients that are beneficial to plant growth, the agricultural utilization of sludge has become an important disposal practice as a result of economic and environmental pressures and resource considerations [6,7]. The prevailing final sludge disposal technology in EU-15 is recycling through agriculture application (44%) [8]. However, sludge contains numerous toxic and harmful substances, especially heavy metals, which restricts its agricultural utilization when directly applied to soils [9]. The long-term application of sludge can lead to the accumulation in soils of heavy metals, which can enter the food chain through direct or indirect pathways, thus endangering human health. How to reduce the environmental risk of heavy metal elements in sludge so that the sludge can re-enter the material and energy cycles of the natural environment has become a key problem in sludge treatment and disposal [10–12].

Attapulgite is a hydrated octahedral layered magnesium aluminium silicate mineral with a specific nanocrystalline structure, special fibre structure similar to a porthole, large surface area, surface with extra positive and negative charges and special surface charge distribution, resulting in strong adsorption, catalytic and ion exchange properties [13]. Specifically, attapulgite has a large adsorption capacity for heavy metal ions [14]. In recent years, many researchers have reported the use of attapulgite for heavy metal adsorption and soil heavy metal solidification with good results [15,16]. Zhang et al. [17] used attapulgite to remediate copper in soil and found that the maximum Cu$^{2+}$ adsorbed by attapulgite was 1501 mg/kg in an aqueous sorption experiment and that the acid-exchangeable Cu in soil decreased with increasing amounts of attapulgite, with the best remediation achieved at a content of 8%. Rong et al. [18] reported that the leaching concentrations of Cd in soil decreased by 45% with the addition of 20% attapulgite. Chen et al. [19] reported that the heavy metal immobilization mechanism of attapulgite included the following: (1) ion exchange adsorption, (2) surface complexation, (3) octahedral crystal lattice replacement, and (4) hydrolysis-precipitation. Therefore, attapulgite holds promise as a potential inexpensive and environmentally friendly stabilizing agent for the remediation of soil contaminated with heavy metals.
At present, research on the use of attapulgite as a stabilization agent for sewage sludge to reduce heavy metal availability has rarely been reported. After attapulgite is applied to sludge, it is expected to change the physicochemical properties of the sludge and decrease the migration of heavy metals through fixation and inactivation via its own adsorption, ion exchange, complexation and electrostatic action. Heavy metals exist in many forms in the soil, and these different forms have different mobility and plant availability. Studying the chemical speciation changes of heavy metals in soil amended with sewage sludge is important for understanding the bioavailability and mobility of heavy metals in soils [20]. Sequential extraction can be used to determine the distribution of heavy metals among the acid-extractable, reducible, oxidizable and residual fractions in soil or sediment, providing more accurate information about environmental risk [21].

The distribution of loess in China is the largest in the world, with a total area of approximately 642,000 km² that is mostly distributed over arid and semi-arid seasonally frozen cold regions. Cold and arid areas are very fragile ecological environments with a loose soil structure, large porosity, high permeability, poor reunion ability, and relatively low organic matter content, as well as a soil quality and stability that are vulnerable to environmental and human activities [22]. The application of sludge in the ecologically fragile loess area has great theoretical and practical value for improving the loess soil structure and properties, enhancing the soil fertility and increasing the crop yield. However, controlling the mobility and bioavailability of heavy metals in the sludge is critical to this type of application.

The main aims of this research were to (1) investigate the forms of the heavy metals in attapulgite-amended sludge using sequential extraction to better understand the heavy metal transformation mechanisms, (2) assess the effects of loess soil applied with attapulgite-stabilized sludge on the growth of corn, (3) identify the mechanism by which heavy metal accumulation and translocation occur in corn, and (4) evaluate the influence of the addition of attapulgite-amended sludge on the phytoavailability of heavy metals in loess soil.

2. Materials and methods

2.1. Attapulgite-stabilized sewage sludge

Sewage sludge samples were taken from the An-ning Wastewater Treatment Plant in Lanzhou, China, and natural attapulgite was collected from Jinyuan County in Gansu Province. Four metals (Cu, Ni, Cr and Zn) were selected for analysis because they represent the heavy metals of interest in sewage sludge. Selected physicochemical properties and the heavy metal contents of the attapulgite and sewage sludge are listed in Table 1. Attapulgite-stabilized sewage sludge was prepared in the following manner. Attapulgite was added to dewatered sludge in a series of proportions of 0%, 5%, 10%, 15%, 20%, 25% and 30% (dry weight basis), marked as SS, SA1, SA2, SA3, SA4, SA5 and SA6, respectively. The mixtures were thoroughly mixed using a mechanical blender. The attapulgite-sludge mixtures were air-dried, and samples from each mixture were taken for chemical analysis.

2.2. Greenhouse experiment

Loess soil from cultivated land in a Lanzhou suburb was collected for the corn growth experiment in a greenhouse. Selected physicochemical properties and the heavy metal contents of the loess soil are listed in Table 1. The attapulgite-sludge mixtures prepared above were added to the loess soil at a dry weight ratio of 1:4. The specific experimental design was as follows: CK: Loess control soil, LS: Loess soil +SS, LS +SA1, LS +SA2, LS +SA3, LS +SA4, LS +SA5, LS +SA6. Eight treatments with three replicates were set up to assess the efficiency of heavy metal extraction by corn. The treated soil was packed into pots that were 21 cm in diameter and 18 cm in height. The pot culture

| Table 1. Physicochemical properties of the attapulgite, sewage sludge and loess. |
|-----------------------------------------------|
| Parameters                          | Attapulgite | Sewage sludge | Loess |
| pH soil/water = 1:5                  | 8.27 (0.28)* | 6.23 (0.20)   | 8.06 (0.07) |
| Electrical conductivity (EC, Ds m⁻¹) (soil/water = 1:5) | 1.060 (0.130) | 3.020 (0.120) | 0.190 (0.020) |
| Organic carbon (%)                   | ND          | 47.3 (0.29)   | 0.76 (0.05)  |
| Moisture content (%)                 | 8.52 (3.25) | 80.6 (0.36)   | 9.23 (1.61)  |
| Total N (%)                          | 0.0820 (0.0030) | 3.950 (0.170) | 0.0650 (0.0080) |
| Total P (%)                          | 0.57 (0.02)  | 2.13 (0.11)   | 0.073 (0.012) |
| Total K (%)                          | 1.65 (0.09)  | 0.96 (0.03)   | 1.06 (0.17)  |
| Total Cr (mg kg⁻¹)                   | 112 (9)      | 116(9)        | 48(5)        |
| Total Zn (mg kg⁻¹)                   | 63(3)        | 368 (28)      | 92(15)       |
| Total Cu (mg kg⁻¹)                   | 38.6 (1.8)   | 78.3 (3.9)    | 65.8(11.3)   |
| Total Ni (mg kg⁻¹)                   | 23.4 (1.0)   | 56.0 (3.2)    | 31.9(5.6)    |

* Values in brackets are the standard deviation of the mean of triplicate measurements. ND: not determined.
experiment was conducted for a period of 60 days in a greenhouse. All plants were grown under controlled environmental conditions with a 25/16°C day/night temperature regime and 60% relative humidity. All the pots were watered every day to maintain the soil moisture at 70%. After the incubation time, the plants and their roots were carefully removed from the pots, washed with tap water to remove any attached particles, and then rinsed twice with deionized water. The aboveground parts and roots were separated by cutting and then oven-dried at 80°C for 24 h. The dry mass of the aboveground parts and roots was recorded. The oven-dried aboveground and root tissues were then ground using a stainless-steel mill to pass through a 1-mm sieve for chemical analysis.

2.3. Chemical analysis

The plant-available metal fractions were determined after 10 h of horizontal reciprocating shaking at 25°C of a sample diluted at a ratio of 1:10 (w/v) with a 0.05 mol/L diethylenetriaminepentaacetic acid (DTPA) solution. The extract was separated from the solid residue by centrifugation at 4500 rpm for 30 min. The supernatant was filtered through a GF/C glass filter and stored in a cool room.

The sequential extraction procedure for sediment analysis from the Community Bureau of Reference (BCR) of the European Commission was followed, which divided the heavy metals into acid-extractable (F1), reducible (F2), oxidizable (F3) and residual (F4) fraction [23]. The metal concentrations in all of the solutions were subsequently determined by AAS (Varian 220FS, USA). Each experiment was conducted in triplicate.

2.4. Calculation of the bioaccumulation and translocation factors

The metal bioaccumulation factor (BF) is defined as the ratio between the metal content in shoots and the total content in soil. The metal translocation factor (TF) is defined as the ratio between the metal content in shoots and that in roots [24].

2.5. Statistical analysis

The data were analysed using IBM SPSS Statistics V21.0. The significance of the treatment effects was analysed using one-way ANOVA with least significant difference (LSD, F-test, p < 0.05). The differences between individual means were tested using the LSD (p < 0.05). The Pearson correlation coefficients were calculated to determine the correlation coefficients between the amounts of the heavy metal fractions in the rhizosphere soil and in the aboveground and root tissues of corn. A level of p < 0.05 was considered significant.

3. Results and discussion

3.1. Physicochemical properties of attapulgite-stabilized sludge

The physicochemical properties of the attapulgite-stabilized sewage sludge, including the pH, EC and DTPA-extractable metal content, are summarized in Table 2. The organic acids produced by the decomposition of organic matter in the sludge made the pH of the original sludge weakly acidic. With the addition of increasing amounts of alkaline attapulgite (pH = 8.27), the pH of the attapulgite-stabilized sludge significantly increased, reaching a maximum at SA6 that was 29.2% higher than the pH of SS. In contrast, the EC decreased with the increase in the attapulgite content, which may have been due to the precipitation of soluble cations in the mixture that resulted from the increasing pH of the sludge with the addition of alkaline attapulgite. DTPA-extractable metals are considered to be the most available form for plant uptake [25]. As shown in Table 2, attapulgite amendment influenced the contents of DTPA-extractable heavy metals, significantly reducing the plant-available Cr, Ni and Zn concentrations. The plant-available concentrations of Cr, Ni and Zn in the treatments with the highest attapulgite content decreased by 34.89, 34.53, and 22.38% compared to SS, respectively. Different from the other metals, the content of DTPA-extractable Cu after attapulgite amendment was significantly higher than that in SS potentially because attapulgite addition converted more of the oxide-bound Cu into its soluble and exchangeable forms.

| Treatment | pH   | EC (Dm·m⁻¹) | DTPA-Cr mg·kg⁻¹ | DTPA-Ni | DTPA-Zn | DTPA-Cu |
|-----------|------|-------------|-----------------|---------|---------|---------|
| SS        | 6.23 | 3.020       | 6.65 (0.38) a   | 3.62 (0.17) a | 51.2(3.2) a | 3.21 (0.15) c |
| SA1       | 6.72 | 2.460       | 5.69 (0.33) b   | 2.35 (0.13) a | 35.1 (4.4) a | 3.59 (0.13) c |
| SA2       | 6.95 | 2.100       | 6.17 (0.35) ab  | 2.96 (0.21) b | 46.7 (3.2) b | 3.92 (0.17) b |
| SA3       | 7.18 | 1.870       | 5.04 (0.29) bc  | 3.02 (0.16) b | 49.8 (2.4) ab | 4.62 (0.25) bc |
| SA4       | 7.56 | 1.720       | 3.64 (0.24) d   | 2.94 (0.18) b | 47.8 (3.6) b | 4.37 (0.13) a |
| SA5       | 7.82 | 1.130       | 4.35 (0.33) c   | 2.90 (0.12) b | 43.3 (2.0) c | 3.64 (0.22) c |
| SA6       | 8.05 | 1.160       | 4.33 (0.26) cd  | 2.37 (0.20) c | 39.8 (2.8) d | 3.29 (0.22) c |
| LSD       | 8.42 | 0.090       | 0.71            | 0.28     | 0.29     | 2.99     |

*Values followed by the same letter within the same column do not differ significantly at the 5% level according to the LSD test; values in brackets are the standard deviation of the mean of triplicate measurements.
3.2. Chemical speciation of Cr, Ni, Zn and Cu in attapulgite-stabilized sludge

Sequential extraction is often used to assess the heavy metal distribution among soil or sediment fractions, which provides an indication of the mobility and bioavailability of metals [26]. Generally, heavy metal speciation includes an acid-soluble (exchangeable and carbonate-bound metals), reducible (Fe–Mn oxide-bound metals), oxidizable (organic-bound metals) and residual fractions [27,28]. The acid-soluble fraction is considered to have the greatest translocation ability. The reducible and oxidizable fractions of metals are potentially toxic and can be transformed into more readily available forms when the redox potential of the external environment changes. The acid-soluble, reducible and oxidizable fractions are the bioavailable forms of metals, while the residual fraction is the most stable form and less bioavailable. As a result, we expect a reduction in the bioavailability of metals in the sludge. As the attapulgite amendment increased from 0% to 30%, the contents of Ni, Zn and Cu decreased from 56.1, 367.56, and 87.29 mg/kg to 53.98, 278.19, and 72.56 mg/kg, while the Cr concentration remained essentially flat, with more or less the same amount in both the sludge and attapulgite.

The percentages of Cr in the acid-soluble, reducible and oxidizable fractions with increasing attapulgite amendment decreased from 2.98%, 18.61% and 34.27% to 1.20%, 12.12% and 29.16%, respectively (Figure 1). However, the residual Cr significantly increased from 51.71% to 64.17%. The percentage distribution of Ni among its various chemical species differed from that of Cr. The acid-soluble Ni in the raw sludge accounted for 22.86%, which was the highest content among the three metals and indicates high bioavailability. With the increase in the attapulgite content, the content of acid-soluble Ni was greatly reduced to 13.62%; the reducible and oxidizable fractions did not significantly change; and the percentage of Ni in the residual fraction significantly increased, similar to Cr. Zn in the acid-soluble, reducible and oxidizable fractions in the raw sludge accounted for 12.36%, 36.70% and 31.31%, respectively. The sum of the Zn percentages in the three fractions was highest compared with those of the other elements investigated in this study, indicating that Zn had high mobility and bioavailability. As observed for Cr, the Zn percentages in the acid-soluble, reducible and oxidizable fractions noticeably decreased with the increase in attapulgite content, while that in the residual fraction significantly increased. After attapulgite application, the Zn in the oxidizable fraction decreased the most compared to the other fractions and decreased by 63.2% at SA6 compared to SS. Similar to the findings of other researchers [29,30], Cu was mainly distributed in the oxidizable fraction in the raw sludge and accounted for 56.10%. As a result of 30% attapulgite application (SA6), the Cu content was reduced by 42.1%, 43.8% and 68.5% in the acid-soluble, reducible and oxidizable fractions, respectively, compared to the SS. Mean

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Figure 1. Distribution of metals in attapulgite-stabilized sludge as a function of different treatments.
while, the proportion of Cu present in the residual fraction sharply increased by 153.3% in SAA6. These results indicate a significant decrease in the ecotoxicity of Cu in the amended sludge.

These results indicated the portions of the metals in the acid-soluble, reducible, and oxidizable fractions were transferred into the residual fraction. Ni was the most mobile metal, followed by Zn, whereas Cr and Cu were the least mobile, as observed from the percentages of the metal fractions in raw sludge. The reduction of the heavy metal contents in the oxidizable fraction of the attapulgite-stabilized sludge was the largest, which may have been due to the slow mineralization of organic matter in the sludge under oxidizing conditions and easy transfer to the acid-soluble and reducible fractions [27]. The soluble metallic fractions have the highest mobility and bioavailability, followed by the reducible fraction; are thermodynamically unstable; and can remain available under anoxic conditions. After attapulgite amendment, the released metals from the mineralization of organic matter or reduction reaction can form metal sulfides via sulfate reduction or become strongly connected to the attapulgite mineral structure [31]. Metals confined in the residual fractions are the most stable, and increasing the amount of this form through attapulgite application can effectively lower the environmental risk of sludge disposal.

3.3. Effects of attapulgite-stabilized sludge on plant growth

The dry weight yields of corn grown in loess soil receiving attapulgite-stabilized sludge are listed in Table 3. When attapulgite-stabilized sludge was applied to the loess soils in the present study, the dry biomass of the aboveground and root of corn significantly increased. In the LSA3 treatment, the aboveground biomass of corn was significantly higher than in the other treatments, 60.65% higher than CK and 41.07% higher than LS. With the increase in the attapulgite content in the sludge, the aboveground biomass of corn first increased and then slightly decreased. When the amount of attapulgite in the sludge was less than 15%, the increase in biomass may have been due to the reduction by attapulgite of the influence of harmful substances in the sludge. However, increasing the attapulgite amendment level above 15% in the attapulgite-sludge mixture decrease the nutrients required for corn growth. The root of corn continued to increase with the increasing attapulgite content in the sludge because of the addition of attapulgite, which reduced the toxicity of pollutants in the sludge and improved the soil microbial environment.

3.4. Heavy metal accumulation and translocation in corn

The heavy metal concentration in aboveground and root tissues, as well as the BF and TF of corn, are presented in Table 3. With an increasing attapulgite content in the sludge, the concentrations of Cr, Ni, Zn and Cu in the aboveground tissues and shoots of corn decreased significantly. When the maximum applied amount of attapulgite was used, compared with the raw sludge, the contents of Cr, Ni, Zn and Cu in the aboveground tissues were reduced by 51.29%, 69.72%, 36.43% and 47.80%, respectively. This indicates that the application of attapulgite effectively reduced the phytoavailability of metals in the sludge. The contents of four heavy metals in the aboveground tissues of corn were significantly lower than those in the roots.

The BF of corn for Cr, Zn, and Cu ranged from 0.04 to 0.06, 0.17 to 0.21, 0.40 to 0.83, respectively, but were all lower than 1. These results indicate that only small amounts of the metals were maintained in the corn roots, despite the relatively high concentrations of these metals in the soil. In contrast, the BF of Ni ranged from 0.64 to 1.20, which was higher than the other three heavy metals. The BF in SS and LSA1 exceeded 1, indicating that the Ni content in corn was higher than that in the soil. At the same time, the BF of the four heavy metals in corn decreased with the increase in attapulgite content. The BF of Cu at the maximum sludge application decreased by more than half, which was the greatest decrease compared to the SS treatment. Cr is not an essential element for plants, and its BF values are expected to be much lower than the BF values of the other three essential elements. The application of attapulgite significantly reduced the accumulation of heavy metals in corn, which was directly related to a reduction in the plant-available heavy metal forms in the sludge with the addition of attapulgite.

The TF values of all four heavy metals in corn were less than 1, indicating that corn has a lower transport capacity for the metals and that the metals ions are mainly retained in the roots. Although Ni had the highest BF in
corn, its TF ranged from 0.05 to 0.07, indicating that the Ni content in the aboveground tissues was very low. However, the Ni concentration in the roots was high because corn hinders the entrance of heavy metals by binding the metals to exuded organic acids or to the anionic groups of cell walls.

3.5. Phytoavailability of the chemical fractions of Cu, Cr, Ni and Zn

The chemical forms of heavy metals in soil have a significant impact on the corresponding amounts of metals in the plants. No significant correlation was observed between the amounts of residual metals in the rhizosphere soils and the Ni concentrations in the rhizosphere of corn. The concentrations of Cu and Zn in the aboveground and root tissues positively correlated with the amounts of acid-extractable metals in the rhizosphere soils. Similar to the correlation between the amounts of acid-extractable metals in the rhizosphere soils and the Cu and Zn concentrations in the aboveground and root tissues, the amounts of reducible metals in the rhizosphere soils and the Cu and Zn concentrations in the aboveground and root tissues were significantly positively correlated. However, the Ni concentration in the root tissues was very low, because corn hinders the entrance of heavy metals by binding the metals to cell walls.

### Table 3. Heavy metal concentration in aboveground and root tissues of corn grown in soil receiving attapulgite-stabilized sludge; BF and TF of heavy metals in corn.

| Treatment | Aboveground Cr | Root Cr | BF Cr | TF Cr | Aboveground Ni | Root Ni | BF Ni | TF Ni | Aboveground Zn | Root Zn | BF Zn | TF Zn | Aboveground Cu | Root Cu | BF Cu | TF Cu |
|-----------|----------------|--------|-------|-------|----------------|--------|-------|-------|----------------|--------|-------|-------|----------------|--------|-------|-------|
| SS        | 3.41(0.49)a*   | 7.40(0.50)a | 0.06  | 0.46  | 3.98(0.34)a    | 67.3(4.4)a | 1.20  | 0.06  | 63.1(4.0)a     | 74.2(5.9)a | 0.20  | 0.85  | 36.7(3.8)a    | 72.3(3.3)a | 0.83  | 0.51  |
| LSA1      | 3.26(0.59)ab   | 6.35(0.85)ab | 0.05  | 0.51  | 3.10(0.60)ab   | 65.2(2.4)ab | 1.19  | 0.05  | 47.8(3.6)bc    | 67.2(6.2)ab | 0.19  | 0.71  | 29.6(2.1)b    | 65.0(1.6)b | 0.75  | 0.46  |
| LSA2      | 2.78(0.22)bc   | 5.61(0.26)bc | 0.05  | 0.50  | 3.35(0.49)bc   | 59.2(2.7)bc | 1.08  | 0.05  | 49.5(3.8)bc    | 63.7(4.7)bc | 0.18  | 0.78  | 24.6(1.4)c    | 58.6(3.1)c | 0.70  | 0.42  |
| LSA3      | 2.36(0.31)cd   | 5.75(0.46)bc | 0.05  | 0.41  | 3.77(0.38)cd   | 51.4(3.4)cd | 0.98  | 0.06  | 42.0(5.2)c     | 59.6(3.0)bc | 0.18  | 0.70  | 20.7(1.3)d    | 55.0(4.1)c | 0.66  | 0.38  |
| LSA4      | 1.64(0.16)e    | 5.38(0.11)bc | 0.05  | 0.40  | 3.05(0.30)bc   | 53.2(1.1)bc | 0.98  | 0.06  | 26.9(4.4)d     | 60.9(7.0)bc | 0.19  | 0.44  | 22.8(2.5)cd   | 54.0(3.9)c | 0.66  | 0.42  |
| LSA5      | 2.15(0.18)d    | 5.32(0.22)c | 0.05  | 0.40  | 2.64(0.47)bc   | 49.7(3.6)cd | 0.92  | 0.05  | 28.5(2.5)d     | 52.7(2.2)cd | 0.17  | 0.54  | 19.5(2.5)de   | 40.3(4.3)d | 0.51  | 0.48  |
| LSA6      | 1.78(0.24)d    | 4.27(0.97)d | 0.04  | 0.42  | 2.53(0.21)c    | 34.5(2.5)e  | 0.64  | 0.07  | 19.1(1.1)e     | 58.1(5.9)cd | 0.21  | 0.33  | 17.9(2.0)e    | 29.1(2.5)e | 0.40  | 0.61  |
| LSD       | 0.51           | 0.82    | 0.61  | 6.46  | 5.35           | 6.40      |      |      | 3.46           | 5.35      |      |      |

* Values followed by the same letter within the same column do not differ significantly at the 5% level.
soluble, reducible and oxidizable fractions) was converted into the residue-bound fraction as a result of the adsorption and complexation of the metals by attapulgite. The effect of stabilization in attapulgite amendment was shown by the transformation of metals from the directly toxic forms to the stable fractions. The application of attapulgite significantly reduced the accumulation of heavy metals in corn, which was directly related to a reduction of the plant-available heavy metal forms in the soil with the addition of attapulgite. The BF values of corn for Cr, Zn, and Cu were all less than 1. These results indicate that only small amounts of the metals were maintained in the corn roots. The TF values of all four heavy metals in corn were less than 1, indicating that corn had a lower transport capacity for the metals and that the metals ions were mainly retained in the roots. The application of attapulgite-stabilized sludge to loess significantly increased the aboveground and root biomass of corn. The amounts of the acid-soluble, reducible and oxidizable fractions in the rhizosphere soils were significantly positively correlated with the heavy metal contents in corn. Nevertheless, a significant negative correlation was observed between the amounts of residual metals in the rhizosphere soils and the metals contained in the corn tissue. Finally, the present stabilization method not only influenced the metal distribution and lowered their bioavailability but also improved the corn growth. However, the time span of these experiments was relatively short, and long-term investigations should be carried out to examine the repair effect in loess amended with attapulgite-stabilized sludge.

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**Table 4. Correlation coefficients between the amounts of the heavy metal fractions in rhizosphere soil receiving attapulgite-stabilized sludge and in aboveground and root tissues of corn.**

| Content   | Element | Total content | Acid-extractable | Reducible | Oxidizable | Residual |
|-----------|---------|---------------|------------------|-----------|------------|----------|
| Aboveground | Cr      | −0.48         | 0.83**           | 0.97**    | 0.81*      | −0.95**  |
|           | Ni      | 0.51          | 0.86*            | 0.82*     | 0.44       | −0.82*   |
|           | Zn      | 0.95**        | 0.89**           | 0.95**    | 0.96**     | −0.99**  |
|           | Cu      | 0.81*         | 0.99**           | 0.92**    | 0.97**     | −0.96**  |
| Root      | Cr      | −0.32         | 0.97**           | 0.93**    | 0.84*      | −0.90**  |
|           | Ni      | 0.66          | 0.95**           | 0.86*     | 0.58       | −0.86*   |
|           | Zn      | 0.94*         | 0.86*            | 0.73      | 0.88**     | −0.83*   |
|           | Cu      | 0.97**        | 0.89**           | 0.82*     | 0.94**     | −0.82*   |

*Correlation is significant at the 0.05 level. **Correlation is significant at the 0.01 level.

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