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Species distribution and concentration pollution of soil heavy metals in coal mine reclamation areas

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In order to understand the distribution characteristics of heavy metal elements in the soil of the coal mine reclamation area and its impact on the surrounding environment and provide technical support for the selection of a reasonable method for the coal mine land reclamation, taking the soil of the Shanxi coal mine reclamation area as the research object, the distribution characteristics of four heavy metal elements in the soil of two different reclamation methods in deep and shallow coal mines were studied by the continuous extraction method. The research results show that the content of heavy metals in the deep reclamation area is significantly higher than that in the unreclaimed area, and the content of Zn and Cr is 6.23 times and 1.57 times that of the unreclaimed area, respectively. The content of heavy metal Zn is nine times more than the national standard value. Soils in deep reclamation areas have been contaminated with Zn and Cr. The heavy metal content in the shallow reclamation area is higher than that in the unreclaimed area but lower than the national standard value. Pb in the coal mine reclamation area has a high pollution impact on the surrounding soil. Although the content of Zn in the soil is relatively large, due to the stable nature of the residue, it has little impact on the environment. Heavy metals Ni and Cr are dangerous to the surrounding soil under certain conditions; the RSP value of the heavy metal Pb in the soil of the deep and shallow reclamation areas is the largest, which has the greatest impact on the environment, and the other three heavy metals have no pollution. Pb in coal mines has a serious impact on the environment.

KEYWORDS

mining engineering, environmental pollution, reclamation area, morphological distribution, heavy metal

Introduction

Coal resources are the foundation of human development and the food for industrial development. Since the 21st century, China's economic construction has achieved remarkable development by leaps and bounds. At the same time, the consumption of coal resources is also very huge (Chen et al., 2021). Coal is the most important one-time energy in China, accounting for two-thirds of the consumption of one-time energy, and has become an indispensable and important resource for economic development. So far, more than 50 billion tons of coal resources have been mined (Zhang and Wang 2020). The 13th Five-Year Development Plan for Energy Development clearly states that by the end of the 13th Five-Year Plan, China's coal consumption will be controlled below 4.2 billion tons, accounting for about 58% of the energy. For a long time in the future, China's energy will still be dominated by coal (Teng et al., 2020; Wang 2020).

In the process of coal mining in China, underground mining and open-pit mining are mainly used. About 96% of the coal resources are mined by underground mining. Underground mining requires a large number of roadways (Chen 2020). When the coal seam is mined, the roof is damaged, causing surface subsidence; according to statistics, the amount of land damage caused by well mining in China has reached hundreds of thousands of square kilometers, and it is increasing at a rate of tens of thousands of square hectares every year (Bi et al., 2020; Jia and Hu 2020), resulting in a huge waste of land (Wang et al., 2020; Zhao and Fu 2020). The promulgation of the "Land Reclamation Regulations" fundamentally guarantees the effective use of land, marking that China's coal mine reclamation has entered a new stage. Due to the large amount of coal gangue and dust produced in the process of coal mining, the soil in the reclamation area is damaged. In particular, the pollution of heavy metals has a significant impact on the human body (Xia et al., 2020; Xiang et al., 2020), and at the same time, it is also an important factor affecting the quality of the land. Therefore (Pan et al., 2017; Fan 2020), it is of great significance to carry out research on the characteristics of heavy metal pollution in coal mine reclamation areas for mining reclamation methods and land use (Wang et al., 2019).

For the study of heavy metal pollution in the coal mine reclamation area, many scholars at home and abroad have carried out a lot of research. Jiang used the Tessier continuous extraction method to analyze the occurrence and morphological characteristics of Zn, Ni, Cr, Mn, and Pb in the soil of two reclamation areas of the Huainan mining area: coal gangue filling and deep excavation and shallow padding (Jiang et al., 2013). The Zn content of the soil in the reclamation area filled with coal gangue was 24.14 and 4.38 times that of the background value of the Huainan soil and that of the unreclaimed control soil, respectively, showing an obvious accumulation phenomenon. Ni, Cr, Mn, and Pb did not exceed the national secondary soil environmental quality standard. However, the content of heavy metals in the soil in the reclamation area with deep and shallow pads was lower than that in the reclaimed soil filled with gangue. Except for Zn in the reclaimed soil filled with coal gangue, the contents of other heavy metals were low in the two reclamation areas in Huainan. Jiang et al. (2019) took the reclamation area of the Antaibao open-pit coal mine in Pingshuo, Shanxi, as the study area, and collected soil samples from eight plots for application. The acid digestion method was used to determine the total content of eight heavy metals, namely, Cr, Ni, Cu, Zn, Pb, As, Hg, and Cd, and conduct pollution assessment and ecological risk assessment. The soil heavy metals in each plot did not exceed the standard value. The Nemerow comprehensive pollution index was 0.318–0.389, the soil was clean, and the potential ecological risk index was 9.93–12.65, which was a slight ecological risk. The content of the reclamation matrix itself and coal gangue stacking and leaching are important factors affecting the soil environmental quality. Yuan et al. (2019) took six coal mining areas in Chongqing as the research object, collected 17 soil samples from different areas such as industrial square, waste slag area, and affected area, and determined the contents of heavy metals Cr, Ni, Cu, Zn, Cd, Pb, As, and Hg. The soil pollution degree was evaluated by the single-factor pollution index method, the Nemerow comprehensive pollution index method, and the potential ecological hazard index method. The soil samples all met the relevant national soil environmental quality standards, the comprehensive pollution degree was clean, and the potential ecological risk was mild or moderate. Huang et al. (2012) analyzed the content of seven heavy metals, Cd, Cr, Ni, Pb, Cu, Zn, and Hg at different depths in the study area and summarized their vertical distribution characteristics. These seven heavy metals have different degrees of pollution, and the soil is mostly polluted by Cd. Seriously, there is no definite distribution law of heavy metals in the soil in the vertical direction, and the potential ecological risk of heavy metals in the soil is a strong ecological hazard.

The Lvliang mining area is located in the western part of Shanxi province, and its total coal reserves account for 33% of the coal reserves in North China. Due to coal mining, a large number of subsidence areas have been formed in the city. According to statistics, the maximum subsidence of the surface in the subsidence area is 21 m. If the reclaimed soil is polluted by heavy metals, it will enter the human body through the food chain and endanger human health. It is of great scientific and practical significance to study the heavy metal content, chemical forms, and ecological risks of different land use patterns in the coal mine reclamation area of Lvliang City.

Due to the long-term mining of coal mines and inadequate reclamation measures, the problem of heavy metal pollution in reclaimed soil is very serious. Heavy metals can be absorbed by plant roots, posing a threat to the ecosystem and human health. Focusing on the content and spatial distribution of heavy metals, the morphological distribution of heavy metals is less involved, and the toxicity and environmental behavior of heavy metals are not only reflected by the total amount but also largely depend on the chemical forms in the soil influenced by the physical and chemical properties of the soil. This study will take the reclaimed soil of the coal mine in the Lvliang mining area as the research object and analyze the content and morphological distribution characteristics of heavy metals in the soil of the coal mine reclamation area under different land use methods. The

FIGURE 1
Location of the sampling points.

content distribution characteristics of heavy metals under different land use methods and the difference in the soil's heavy metal content under different reclamation methods. The selection of mines provides a reference and useful reference, which can effectively improve the soil fertility and the yield and quality of crops in the reclamation area, and has important guiding significance for the reclamation of the mining area.

Experimental methods

Research area

The coal mine is located in the central part of Shanxi province and has a temperate continental monsoon climate. The reclamation area of the coal mine is mainly used for arable land, construction, and other projects. In this reclamation area, the reclaimed and unreclaimed soils were selected for comparative analysis. The main methods of reclamation are filling with coal gangue during underground mining and shallow digging. Among them, the land reclaimed by coal gangue has been carried out since 2005. The bottom of the land is filled with coal gangue from the underground mining process of the coal mine, and a certain thickness of the soil is laid on the upper part of the coal gangue as the surface soil, and related crops are planted on it., For the shallow digging pit, it is mainly through a large amount of cultivated soil generated during the construction of the pond, and this part of the excess pond soil is used to lay on the top of the coal gangue.

Sample collection and processing

The collection of samples is mainly selected by the grid point method, and sampling is carried out on the land in the reclamation area. The samples are mainly collected from the shallow digging pads and the soil filled with coal gangue during the underground mining process of coal mines. A total of 15 samples were collected from each area (Figure 1), and a total of 30 samples were collected from the two soils. In the process of collection, first, select a center point, select two points at a certain distance from the center point as sample collection points, mix the origin and the maps collected from two collection points at different positions, and the mixed soil is used as the center. The sampling map of the point and the sampling depth is kept at about 0.1 m, and about 1,000 g of soil is collected at each point. After collecting and mixing, air drying is carried out in a natural state, impurities such as stones and roots in the soil are selected and sieved, and finally, a qualified sample is formed.

Heavy metal extraction

A five-step extraction method was used for the extraction of heavy metals in soil (Huang et al., 2012; Li and Zhu 2021; Zhou, 2022). The method divides heavy metals in soil into five forms: the metal exchangeable state, carbonate-bound state, iron and manganese-hydrated oxide-bound state, organic matter and sulfide-bound state, and residual state. The metal exchangeable state refers to the exchange of clay minerals and other components adsorbed on sediments, which are very sensitive to environmental changes, easy to migrate and transform, and can be absorbed by plants. Since the metal concentration in the water-soluble state is often lower than the detection limit of the instrument, the water-soluble state and the exchangeable state are generally calculated together, which is also called the water-soluble state and the exchangeable state. Exchangeable heavy metals reflect the impact of recent human pollution and their toxic effects on organisms. The carbonate-bound state refers to some heavy metals bound by carbonate precipitation. It is most sensitive to soil environmental conditions, especially pH value. When the pH value drops, it is easily released into the environment; on the contrary, the increase in the pH value is conducive to the formation of carbonate. The iron-manganese hydrated oxide is in the combined state. This form of heavy gold generally exists in the outer capsule of minerals and finely dispersed particles. The active iron-manganese oxide has a large specific surface area and is formed by adsorbing or co-precipitating anions. The changes in pH and redox conditions in soil have important effects on the binding state of iron and manganese oxides. Higher pH and redox potential are favorable for the formation of iron and manganese oxides (Jiang et al., 2013; Cui et al., 2022). The binding state of iron and manganese oxides reflects the pollution of human activities to the environment. The organic matter and sulfide combined state, that is, the organic matter combined state, means that the heavy metals in the particulate matter enter or wrap on the organic matter particles in different forms to chelate with the organic matter, etc., or generate sulfides. Organically bound heavy metals reflect the results of aquatic biological activities and human discharge of organic-rich sewage. Residual states, generally found in soil lattices such as silicates, and primary and secondary minerals, are the result of natural geological weathering processes (Jiang et al., 2019; Li 2020; Liu 2021). It is not easy to be released under normal conditions in nature, can be stable in the sediment for a long time, and is not easy to be absorbed by plants. The residual heavy metals are mainly affected by mineral composition, rock weathering, and soil erosion.

For the extraction method of five states:

Metal exchangeable state: add 8 ml 1.0 M $MgCl_2$ solution (pH = 7.0) to the sample, continuously shake at 25 ± 1°C for 1 h, centrifuge at 4,000 r/min for 10 min, filter out the supernatant, add 5 ml of deionized water to wash the residue, then centrifuge at 4,000 r/min for 10 min, filter out the supernatant, dilute all the supernatant in a 50-ml colorimetric tube, and determine the concentration of heavy metals by ICP-OES.

Carbonate-binding state: add 8 ml of 1.0 M NaAc solution (adjusted to pH = 5.0 with HAc) to the residue in the previous step, shake continuously for 5 h at 25 ± 1°C, centrifuge at 4,000 r/min for 10 min, filter out the supernatant, add 5 ml of deionized water to wash the residue, then centrifuge at 4,000 r/min for 10 min, and filter the supernatant.

Combined state of iron and manganese hydrated oxide: add 20 ml of 25% HAc solution of 0.04 M NH_2OH HCl to the residue in the previous step, shake at 96 ± 3°C for 6 h, centrifuge at 4,000 r/min for 10 min, filter out the supernatant, add 5 ml of deionized water to wash the residue, and then centrifuge at 4,000 r/min for 10 min to filter out the supernatant. All the supernatant is fixed in a 50 ml colorimetric tube, and the concentration of heavy metals is determined by ICP-OES.

Combined state of organic matter and sulfide: add 3 ml 0.02 M HNO_3 solution and 5 ml 30% H_2O_2 solution to the residue in the previous step, adjust to pH = 2, shake intermittently at 85 ± 2°C for 2 h, add 3 ml 30% H_2O_2 solution at 85 ± 2°C, shake intermittently for 3 h at 2°C, cool to 25 ± 1°C, add 5 ml of 20% HNO_3 solution of 3.2 M NH_4OAc, dilute to 20 ml, and shake continuously for 30 min. Centrifuge at 4,000 r/min for 10 min, filter out the supernatant, add 5 ml of deionized water to wash the residue, then centrifuge at 4,000 r/min for 10 min, filter out the supernatant, and put all the supernatant in a 50-ml colorimetric tube. The concentration of heavy metals was determined by ICP-OES.

Residual state: aqua regia digestion should be carried out, following ISO specifications. The clarified solution should be fixed in a 50-ml colorimetric tube, and the concentration of heavy metals should be determined by ICP-OES.

Analytical method

The secondary phase and primary phase distribution ratio method is generally used to distinguish the natural and anthropogenic sources of heavy metals, reflecting the chemical activity and bioavailability of heavy metals and evaluating the degree of environmental pollution caused by heavy metals. The greater the possibility of pollutants being released into the environment, the greater is the potential harm to the environment. Its calculation formula is as follows:

$$RSP = M_c \Big/ M_y. \tag{1}$$

TABLE 1 Characteristics of the heavy metal content in deep and shallow reclaimed areas and unreclaimed areas.

Heavy metal characteristic		Pb	Zn	Ni	Cr
Deep reclamation area	Average value (mg/kg)	32.45	2,250.48	43.96	74.13
	Coefficient of variation (%)	18.04	77.99	27.18	41.32
	No reclamation content (mg/kg)	30.29	361.23	39.58	47.15
Shallow reclamation area	Average value (mg/kg)	25.13	56.95	40.85	73.92
	Coefficient of variation (%)	12.15	20.22	16.49	25.15
	No reclamation content (mg/kg)	14.15	18.69	28.59	39.62
GB15618-2009 (mg/kg)	600	250	80	200	

In the formula, *RSP* is the ratio of the secondary phase to the primary phase indicating the degree of pollution, M_c is the secondary phase except for the residue state, M_y is the primary phase of the residue state, no pollution when *RSP* <1, mild pollution when 1< *RSP* ≤2, moderate pollution when 2< *RSP* ≤3, and heavy pollution when *RSP* >3.

Results and discussion

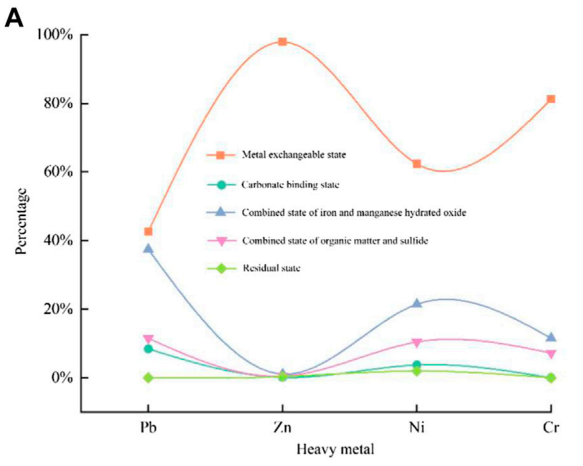
Characteristics of the heavy metal content

The soil in the reclamation area filled with coal gangue during the underground mining process of this coal mine contains a variety of heavy metals, and the values are shown in Table 1.

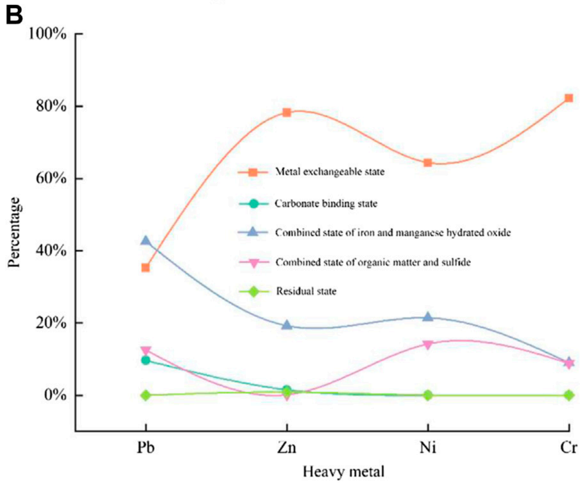
It can be seen from Table 1 that there are mainly five kinds of heavy metals in the soil of the deep reclamation area. The heavy metals are Pb, Zn, Ni, and Cr, and the contents are 32.45 mg/kg, 2,250.48 mg/kg, 43.96 mg/kg, and 74.13 mg/kg, respectively.,. The content of heavy metals in the soil of the reclaimed area filled with coal gangue during the underground mining of coal mines is significantly higher than that in the unreclaimed soil, especially the content of Zn is 6.23 times. The contents of heavy metals Pb and Ni are basically the same as those in the unreclaimed area, with a small difference, while the content of heavy metals Cr is higher than that in the unreclaimed area, which is 1.57 times the content. It can be seen that the mining activities of coal mines and the production of coal gangue filling and reclamation areas can increase the content of heavy metals in the soil and cause heavy metal pollution in the soil. Among them, Zn is the most serious, followed by Cr. Heavy metal contamination of Pb and Ni is not obvious. According to the national soil environmental quality standard (GB15618-2009), the content of heavy metal Zn is significantly higher than the standard value, and its content is nine times more than the standard value, while the content of the other three heavy metals is significantly lower than the standard value. It can be seen that the soil filled with coal gangue in the process of underground coal mining has been polluted by heavy metals, among which Zn is particularly serious, followed by Cr.

It can be seen from Table 1 that there are mainly five heavy metals in the soil of the shallow reclmnation area with deep excavation and deep pads. 25.13 mg/kg, 56.95 mg/kg, 40.85 mg/kg, and 73.92 mg/kg. The heavy metal content in the soil in the shallow unreclaimed area was significantly higher than that in the unreclaimed area. Compared with the national soil environmental quality standard (GB15618-2009), its heavy metal content is significantly lower than its standard value, not exceeding the minimum limits specified in the standard.

Combining the heavy metals in the soil filled with coal gangue during the underground mining process of the deep coal mine and the soil in the shallow reclamation area, it can be seen that there are great differences in the degree of heavy metal pollution for different forms of reclamation. The content of heavy metals in the soil filled with coal gangue during the underground mining process of coal mines is significantly higher than that in the soil of the shallow reclamation area, especially the content of heavy metal Zn. The deep soil is the shallow soil. 39.51 times. The content of heavy metal Zn in the deep soil is obviously too high. After analysis, the coal mining uses underground mining, which is closed and located below the reclamation area. During the mining and transportation process, the heavy metal content in the deep soil is too high. On the other hand, the heavy metals in the coal gangue enter the soil by means of transport, resulting in the increase of the heavy metal content of Zn in the soil. The variation of heavy metals in soil can intuitively reflect the distribution of heavy metals in the region and the difference in pollution degree. According to the characteristics of the heavy metal content in the soil of deep and shallow reclaimed areas and unreclaimed areas in Table 1, it can be seen that the coefficient of variation of Zn content in the soil filled with coal gangue in the underground mining process of deep coal mines is the largest, reaching 77.99%, indicating that Zn. The interference from the outside world is relatively large, and there is a big difference in the spatial distribution. It is followed by the heavy metal Cr, which is 41.32%, indicating that the degree of external interference is general, and there are certain differences in the spatial distribution. Then, it is followed by the heavy metal Ni, which is 27.18%, and the smallest heavy metal Pb, which is 18.04%. The last two heavy metals are disturbed by the outside world,to a lesser



Deep reclamation area



Shallow reclamation area

FIGURE 2
Distribution characteristics of soil heavy metal forms in the coal mine reclamation area. **(A)** Deep reclamation area. **(B)** Shallow reclamation area.

extent. However, the coefficient of variation of the heavy metal content in the soil in the shallow reclamation area with deep excavation pads is generally small. It can be seen that the spatial distribution of heavy metals in the soil in the shallow reclamation area with deep excavation pads is relatively uniform, with less external influence.

Morphological characteristics of heavy metals

Figure 2 shows the distribution characteristics of heavy metals in the soil in the coal mine reclamation area.

According to the distribution characteristics of heavy metals in the deep reclamation area in Figure 1A, the heavy metal Pb is mainly in the residual state and the combined state of iron and manganese hydrated oxides, accounting for 42.58% and 37.48%, respectively. For the heavy metal Pb, the proportion of iron and manganese hydrated oxide-binding state is relatively high. After analysis, it is due to the existence of the metal exchangeable state and carbonate-binding state, and the exchange transformation of heavy metal Pb occurs with the environment. It forms a stable complex with iron and manganese oxidation, and it is easy to release, therefore, resulting in a relatively high proportion of iron and manganese hydrated oxides. Pb in this area has a high impact on the environment; for heavy metals, Zn is mainly in the residual state, accounting for 97.89%, the smallest metal exchangeable state. The residual state is very stable. In the case of planting crops, the availability of the heavy metal Zn is very small, and its contribution to the soil is not large. Due to its good stability, it is generally not harmful to the soil. It is mainly in the residual state and the combined state of iron and manganese hydrated oxides, accounting for 62.35% and 21.45%, respectively. Since the oxidized heavy metals of iron and manganese can be easily activated under acidic conditions, the biological effects of heavy metal Ni in the soil is low, but it will cause potential harm to the surrounding soil under acidic conditions; heavy metal Cr is mainly in the residual state, and the combined state of iron and manganese hydrate oxides is the main state, accounting for 81.21% and 11.58%, respectively. Since the heavy metal Cr can be easily activated under acidic conditions, the biological effectiveness of the heavy metal Cr in the soil is low, but the heavy metal Cr will have potential harm to the surrounding soil under the action of acidic conditions.

According to the distribution characteristics of heavy metals in the shallow reclamation area in Figure 1B, the heavy metal Pb is mainly in the bound state and residual state of iron and manganese hydrated oxides, accounting for 42.57% and 35.26%, respectively. For the heavy metal Pb, the proportion of iron and manganese hydrated oxide binding state is relatively high. After analysis, it is due to the existence of the metal exchangeable state and carbonate-binding state, and the exchange transformation of heavy metal Pb occurs with the environment. It forms a stable complex with iron and manganese oxidation, and it is easy to release. Therefore, the proportion of the combined state of iron and manganese hydrate oxide is relatively high, and Pb in this region has a high impact on the environment; for heavy metal Zn, its state is mainly residual. Zn is the main state, and its proportion reaches 78.25%. The smallest is the organic state and the sulfide combined state. The residual state is very stable. In the case of planting crops, the available heavy metal Zn is very small, and its contribution to soil is very small. Because of its good stability, it is generally not harmful to soil; for heavy metal Ni, it is mainly in the residual state and the combined state of iron and manganese hydrated oxides, accounting for 64.35% and 20.85%, respectively. Since the heavy metals in the bound state of iron and manganese hydrate oxides can be easily activated under acidic conditions, the biological effectiveness of the heavy metals Ni in the soil is low, but it will cause potential harm to the surrounding soil under acidic conditions; the heavy metals Cr are mainly The residual state and the combined state of iron and manganese hydrated oxides are the main ones, accounting for 82.19% and 9.01%, respectively. Since the heavy metal Cr can be easily activated under acidic conditions, the biological effectiveness of the heavy metal Cr in the soil is low, but the heavy metal Cr will have potential harm to the surrounding soil under the action of acidic conditions.

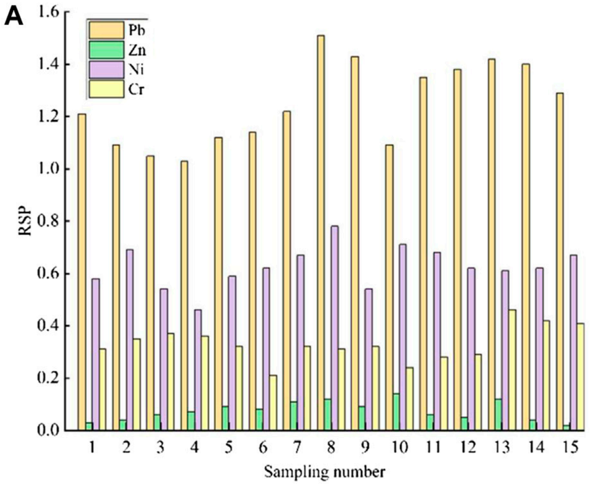
Heavy metal content and morphological characteristics

The correlation analysis results of the heavy metal content and the content of various forms in the reclaimed soil of the mining area show that the content of heavy metal Cr in different chemical forms of the soil is largely affected by the total amount. In the coal gangue filling and reclamation area, there is a close relationship between the total amount and the form of each element except that there are certain differences among different elements. The total amount of each element has a very significant correlation with the residual state content, and it increases with the increase in the total amount. In the reclamation area with deep pads and shallow pads, except for the total organic content of Ni, which is extremely significantly correlated, the correlations of other heavy metals are not obvious. However, the total amount of each element has a very significant correlation with the residual state content, and it increases with the increase in the total amount. This may be related to the fact that the residual state is the main form of heavy metals in the soil of the reclamation area in the study area and is relatively stable.

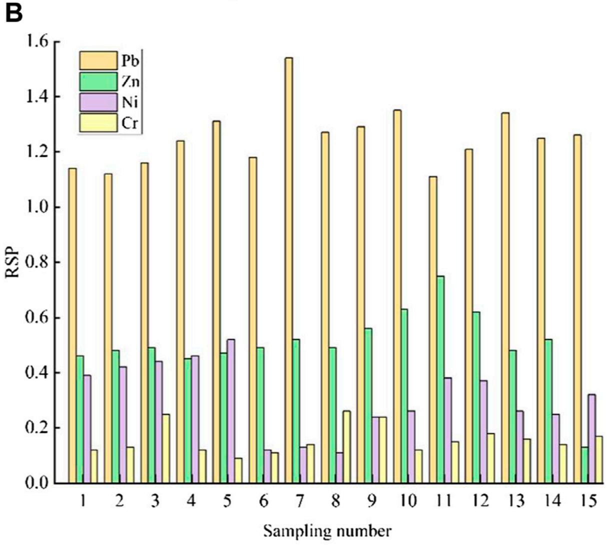
From the morphological evaluation results, Pb pollution in the coal mine reclamation area in the study area is more serious. From the perspective of reclamation methods, the enrichment effect of coal gangue filling and reclamation is more obvious, and the enrichment effect of deep excavation and shallow reclamation is more obvious. Therefore, the choice of reclamation method should be adapted to local conditions, and the appropriate reclamation method should be selected according to the content of heavy metals in the local soil.

Characteristics of heavy metal pollution

In order to better analyze the pollution characteristics of heavy metals in soil to soil. The distribution ratio method of the secondary phase and primary phase was used to analyze the characteristics of pollution impact, and the data graph obtained is shown in Figure 3.



Deep reclamation area



Shallow reclamation area

FIGURE 3
Distribution map of the RSP value of heavy metals in soil in deep and shallow reclamation areas. **(A)** Deep reclamation area. **(B)** Shallow reclamation area.

Figure 3A shows the distribution of heavy metal RSP values in the soil in the deep reclamation area. The heavy metal Pb has the largest RSP value, and its average value can reach 1.24, and its value is between 1 and 2, indicating that heavy metals can pollute the soil, but the degree of pollution is relatively low, which belongs to mild pollution, and has been affected to a certain extent, which will cause certain harm to the environment; followed by heavy metal Ni, with an average value of 0.65, and the smallest heavy metal Zn, with a value of 0.07, and the latter three heavy metals have a value of 0.07. The values are all less than 1, which means that the heavy metals cannot pollute the soil, that is, a pollution-free state.

Figure 3B shows the distribution of heavy metal RSP values in the soil in the shallow reclamation area. The same RSP value is the largest heavy metal Pb, and its average value is 1.25, and its value is between 1 and 2, which means that heavy metals can pollute the soil. However, the degree of pollution is low, and it belongs to mild pollution. It has been affected to a certain extent and caused certain harm to the environment. The second is heavy metal Zn, whose RSP average is 0.50, the smallest is heavy metal Cr, whose RSP average is 0.16, and for the latter, the values of the three heavy metals are all less than 1, indicating that the heavy metals cannot pollute the soil, that is, a non-polluting state.

To sum up, the impact of Pb in the coal mine on the environment is relatively serious. For the selection of the reclamation method, the coal gangue in the underground mining process of the deep coal mine is very obvious for the enrichment of the heavy metal Zn. Therefore, in the operation of coal mine reclamation, appropriate measures should be selected according to local conditions.

Conclusion

The content of heavy metals in the soil of the reclaimed area filled with coal gangue is significantly higher than that of the unreclaimed soil. Compared with the national soil environmental quality standard, the content of Zn is higher than the standard value, and the other three are lower than the standard value. The content of heavy metals in the soil in the reclaimed area with deep pads and shallow pads was also higher than that in the unreclaimed area but lower than the standard value. Ni and Cr are potentially dangerous under acidic conditions; the RSP value of heavy metal Pb in the soil of deep and shallow reclamation areas is the largest, which has the greatest impact on the environment, and the other three heavy metals are not polluted.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

JX, LG, and LH contributed to the conception and design of the study. JX conducted the sampling and laboratory analysis. LG summarized the test data. LH analyzed and summarized the test data. JX wrote the first draft of the manuscript. LG and LH wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

Conflict of interest

Author LH is employed by the Chemical Geological Prospecting Institute of Liaoning Province Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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