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Spatial distribution characteristics and risk assessment of soil heavy metal pollution around typical coal gangue hill located in Fengfeng Mining area

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Abstract The pollution of heavy metals in soil caused by exposed coal gangue and its prevention and control has become a hot issue restricting the green mining of coal in China. Nemerow integrated pollution index (*NIPI*), potential ecological risk index (*RI*) and human health risk assessment model were used to evaluate the pollution and risk of heavy metals (Cu, Cr, As, Pb) in the soil around the typical coal gangue hill in Fengfeng mining area of China. The results show that: firstly, the accumulation of coal gangue leads to the enrichment of four heavy metals in the surrounding shallow soil, and *NIPI* and *RI* were 1.0–4.4 and 21.63–91.28, respectively. The comprehensive pollution level of heavy metals in soil reached the warning line and above, and the potential ecological risk level reached slightly and above. When the horizontal distance exceeded 300 m, 300 m and 200 m, respectively, the influence of coal gangue hill on the heavy metal content in shallow soil, the comprehensive pollution level of heavy metals and the potential ecological risk level basically disappeared. In addition, based on the potential ecological risk assessment results and main risk factors, the ecological risk configuration of the study area was divided into five categories: "strong ecological risk + As," "intermediate ecological risk + As + Cu," "intermediate ecological risk + As + Cu or Pb," "minor ecological risk + As + Cu" and "minor ecological risk + As + Cu or Pb." The hazard index (*HI*) and total carcinogenic risk (*TCR*) of shallow soil polluted by heavy metals in the study area were 0.24–1.07 and 0.41×10^{-4}–1.78×10^{-4}, respectively, which posed non-carcinogenic and carcinogenic risks to children, but the risks were controllable. This study will help to take strategic measures to accurately control and repair the heavy metal pollution in the soil around the coal gangue hill and provide a scientific basis for solving the safe use of agricultural land and realizing the construction of ecological civilization.

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Introduction

It is estimated that about 1 trillion tons of coal can be used globally at present (Gopinathan et al., 2022b;

Santosh et al., 2023). In the process of coal mining, it will not only cause damage to the environment, but also produce coal-based solid waste that will affect human health and global ecology (Gopinathan et al., 2022a, c). Coal gangue is a solid waste generated in the process of coal mining. The amount of gangue discharged in China's coal mines accounts for about 8~20% of the coal mining amount (Wei et al., 2016). Coal gangue is usually piled up near mines in the form of cones close to residential areas. At present, the accumulated stacking amount of coal gangue in China has exceeded 6 billion tons, forming 1500–1700 coal gangue hills, occupying 1.3×10^4 hm^2 of the land, and the annual discharge rate is increasing by 500–800 million tons(Zhou et al., 2020). The stockpiling of coal gangue not only occupies a large amount of land resources, but also easily causes spontaneous combustion, dust, debris flow and other phenomena in the stockpiling process, polluting the surrounding environment (Hou et al., 2020). More importantly, coal gangue contains As, Pb, Hg, Cd, Cu, Cr and other heavy metal elements. Under the action of weathering, leaching and sedimentation, it is very easy to migrate to the surrounding soil environment and cause heavy metal pollution, which not only affects the safe use of land and causes land degradation (Verma et al., 2021b), but also generates ecological risks, posing a threat to human health (Chen et al., 2021b; Okedeyi et al., 2014).

The production and stockpiling of coal gangue have brought a series of heavy metal pollution problems. Six metal elements (Ni, Pb, Cu, Cd, Fe and Zn) in the coal gangue of a coal mining enterprise in Southern Zambia have the risk of polluting the environment (Chilikwazi et al., 2022). The average concentration of heavy metals Ti, Mn, Zn, Pb, As, Fe, Rb, Sr, Nb and Zr in the farmland soil of coal mining area in northern Bangladesh exceeded the world normal level (Bhuiyan et al., 2010). Heavy metal pollution and its ecological risk and human health risk in the soil of coal gangue accumulation area have attracted great attention in China. The rhizosphere soil associated with 13 native plants around Taoyuan coal gangue hill in China was strongly polluted by Cd, moderately polluted by Cu, slightly polluted by Cr and not polluted by Pb (Han et al., 2020). Pollution of eight heavy metals (As, Cd, Cr, Cu, Ni, Pb, V, Zn) in soil samples around the coal gangue storage area in Shanxi Province, China, may pose health risks

to children and affect their early neural development (Yang et al., 2021). But some scholars measured the content of Cd, Cr, Cu, Ni, Pb and Zn heavy metals in the soil around the coal gangue hill in Huainan mining area of China and found that the linear characteristics of the content change curve of six elements with distance were not obvious (Wei et al., 2017). Previous studies showed that the total potential ecological risk of heavy metals in the topsoil around the gangue hill of Haizhou Mine in Fuxin, China, was slight (Cong et al., 2017a). The accumulation of coal gangue in Fengfeng mining area is large, and it takes a long time, which causes heavy metal pollution to surrounding soil. The existing research found that there was certain Cr and Pb pollution and a low level of ecological risk in the soil around the coal gangue hills of Fengfeng No. 5 Mine, Yangquhe Mine and Jiulong Mine (Fan et al., 2011). The stockpiling of coal gangue in Fengfeng mining area has the effect of increasing the effective state mass fraction of Cu, Cr, As, Pb in the surrounding soil and reducing the residual state mass fraction, and the MF of heavy metal Cu reaches a medium risk level at a horizontal distance of 200 m in the SE direction (Sun et al., 2022). Long-term exposure to metal pollution is the main source of human diseases (Kumar et al., 2022a, 2022b). Heavy metals released in the environment are absorbed by crops and ingested by humans body through the food chain, causing pathological problems related to kidneys, liver and bones, posing great risks to human beings (Kawatra & Bakhetia, 2008). The incident of osteopathy in Japan in the nineteenth century was caused by poisoning caused by residents eating cadmium-containing rice and drinking water. To sum up, the spatial change rule of heavy metals in the soil of the coal gangue accumulation area, the understanding of heavy metal risk assessment and human health risk assessment vary from place to place, and the impact of heavy metals in different areas is different, which needs further study (Fig. 1).

In view of this, this paper took the farmland soil near a typical coal gangue accumulation area in Fengfeng mining area in Hebei Province as the research object and used inductively coupled plasma spectrometer (ICP-OES, Optima 8000), pH meter (PSC-25) and total organic carbon analyzer (Vario TOC) to determine the content of four heavy metals(Cu, Cr, As and Pb), soil pH value and organic matter content, in the soil around the coal gangue hill (within 400 m

Fig. 1 Geographic location of coal gangue hill
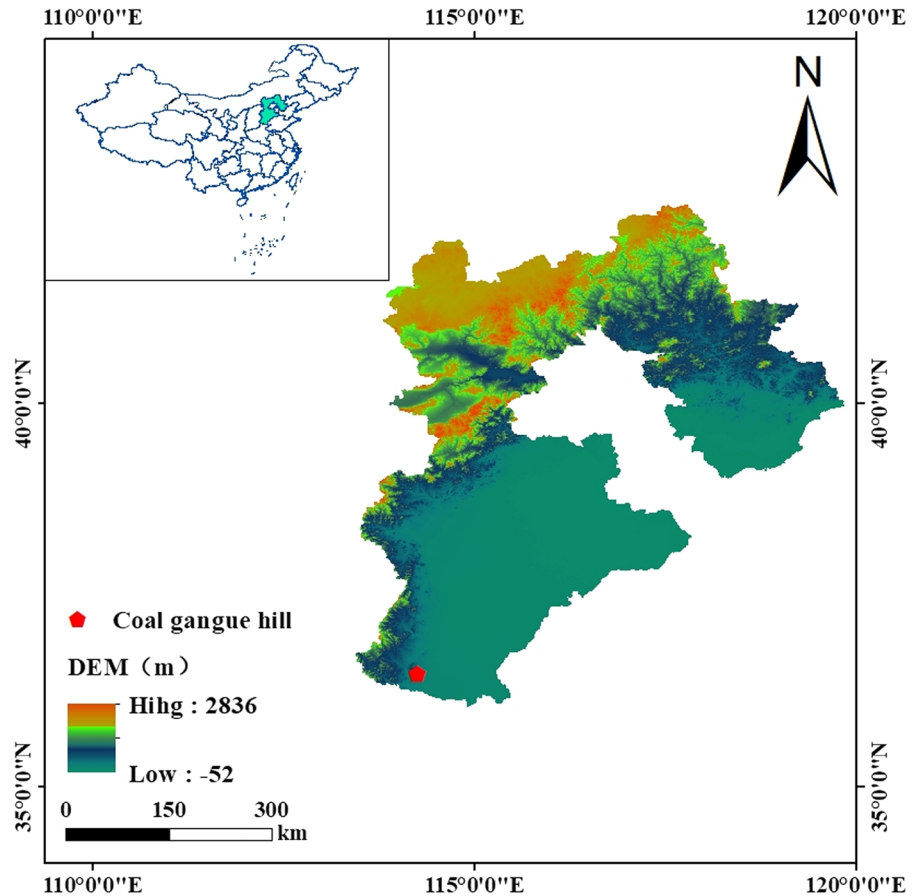
horizontal distance and 40 cm in vertical depth). We detailed analysis of its spatial distribution characteristics, and evaluation of its pollution degree, ecological risk and human health risk, in order to enrich and expand related research, and provide scientific basis for precise treatment of heavy metal pollution in soil of coal gangue accumulation area in Fengfeng mining area.

Study area

Fengfeng mining area is located in the southwest of Handan City, Hebei Province, with geographic coordinates of E114° 3′ -114° 16′ and N36° 20′ -36° 34′. The terrain is flat, and the highest elevation is 891 m. It is one of the four mining areas in Hebei Province. The mining area belongs to the warm temperate semi humid continental monsoon climate, with the annual average temperature of 14.1 °C and the annual average precipitation of 627 mm. The dominant wind direction in winter and spring is northwest wind, while there is no dominant wind direction in summer and autumn, with the maximum wind speed of 21.7 m/s (Sun et al., 2022). The inland water system of the mining area belongs to the Haihe River basin, and the main surface water systems are Fuyang River and Mangniu River (Li et al., 2021). The soil type in the mining area is mainly loess light loamy calcareous cinnamon soil, and the land use type is mostly farmland. The vegetation types are mainly artificial agricultural vegetation and semi-artificial woodland–shrub land and shrub grassland, and corn, wheat and other crops are most widely distributed. Due to the long mining history and large scale, the problem of surface discharge and stockpiling of coal gangue in Fengfeng mining area is very prominent. According to statistics, there were 20 coal gangue hills in this mining area, with a total storage capacity of over 55.891 million tons, covering an area of over 179.37

hm^2, and the storage time was as long as 23–72 years (Liu, 2021). A typical coal gangue accumulation area in Fengfeng mining area is taken as the study area, and its central coordinates are E114° 16′ 6.59″ and N36° 29′ 18.92″.

Materials and methods

Soil sample collection and pretreatment

Because the west side of coal gangue hill was a residential area, and the soil was disturbed by human activities, the flat agricultural land on the east side was the main choice for sample collection. Considering the terrain and wind direction around the coal gangue hill, the sampling points were laid out. The specific sampling scheme was as follows: Firstly, three sampling lines were determined in the downwind direction and vertical wind direction of coal gangue hill: One sampling line was arranged in the upwind area of northwest (NW), one sampling line was arranged in the downwind area of southeast (SE), and one sampling line was arranged in the vertical wind direction of northeast (NE). At the same time, considering the deviation of wind direction, two sampling lines, namely due east direction (E) and due south direction (S), were arranged at an angle of 45 to both sides with the southeast sampling line as the symmetry axis. Ten sampling points were set at 0 m, 20 m, 40 m, 60 m, 80 m, 100 m, 150 m, 200 m, 300 m and 400 m of each sampling line. Soil samples with depths of 0–20 cm and 20–40 cm were collected at each sampling point, and three parallel samples were collected at each depth. A sampling pattern has been formed with the gangue dump as the center, from near to far and from dense to sparse (Fig. 2). We randomly selected three background points in the wasteland far away from coal gangue hill, residential areas and roads to collect blank samples as background values. A total of 303 soil samples were collected. Multi-point mixed sampling was adopted to collect soil samples, and the soil samples (about 0.5 kg in weight) from each sampling point were put into sealed bags and took them back to the laboratory. The collected soil was removed impurities, naturally air-dried at room temperature (18–25 °C) and ground through a 200-mesh sieve for later use, which was used to determine the content of heavy metals in the soil (Fig. 3).

Fig. 2 Schematic diagram of soil sampling points around coal gangue hill

Measuring method

According to the results of our previous survey of the total amount of nine heavy metals (Cu, Cr, As, Pb, Hg, Mn, Cd, Ni and Zn) in the soil around the target coal gangue hill, we found that only Cu, Cr, As and Pb have high content and significantly exceed the background value of the study area, while the content of other heavy metals was not significantly different from the background value of the study area, so we chose that Cu, Cr As and Pb were the representative research objects in the study area.

In the preliminary research work, we used pH meter (PCS-25) to measure soil pH, and the result was 8.09–10.2. The soil organic TOC was determined by inductively coupled plasma spectrometer (ICP-OES, Optima 8000), and the results were 0.465–5.73%. The conductivity of soil was measured by conductivity meter (DDS-307), and the result was 214.5–244.15 μs cm^{-1}. The total potassium in soil was determined by automatic Kjeldahl nitrogen analyzer (Haineng K1100), and the results were 8.12–8.98 g kg^{-1}. The total phosphorus and total nitrogen in soil were determined by ICP-MS (Agilent 7900), and the results were 14.14–14.77 mg kg^{-1} and 0.03–0.04%, respectively. The mass fraction of soil mechanical composition was measured by laser particle size analyzer

Fig. 3 Collection and treatment of soil samples around coal gangue hill. **a** Air-drying of soil samples, **b** Grinding and sieving of soil samples

(a) Air drying of soil samples

(b) Grinding and sieving of soil samples

(MS2000), and the results of sand, silt and clay were 65.40–67.86%, 31.42–33.76% and 0.73–0.82%, respectively. Except pH and TOC, the other indexes are obviously homogenized within 300 m of the study area. Considering that soil pH and TOC are the key factors that affect and control the content, speciation, migration and transformation of heavy metals in soil (Chen et al., 2014; Vega et al., 2006; Zeng et al., 2011), this paper will focus on analyzing and discussing the effects of soil pH and TOC on the spatial variation characteristics of Cu, Cr, As and Pb.

Table 1 lists the main instruments used. Microsoft Excel 2010 software was used to process the data, and ArcGis 10.2, Origin 2021, Sufer 15.0 were used to draw the map.

Evaluation methods and standards

Assessment of heavy metal pollution in soil

NIPI was used to evaluate the pollution degree of heavy metals in the soil of the study area (Wang et al., 2011, 2019). The calculation formula is:

$$P_i = C_i/C_0 \tag{1}$$

$$NIPI = \sqrt{\frac{P_{ave}^2 + P_{max}^2}{2}} \tag{2}$$

where C_i is the average content of heavy metal i in soil (mg kg^{-1}), C_0 is the background value of soil heavy metal i (mg kg^{-1}), P_i is the single pollution index of soil heavy metal i, P_{ave} is the average index of single pollution of heavy metal i in soil, P_{max} is the largest single pollution index of heavy metal i

in soil, and *NIPI* is Nemerow integrated pollution index of soil heavy metal i. The results are classified into 5 grades: $NIPI \leq 0.7$, clean; $0.7 < NIPI \leq 1.0$, still clean (alert); $1.0 < NIPI \leq 2.0$, slight contamination; $2.0 < NIPI \leq 3.0$, moderate contamination; and $NIPI > 3$, severe contamination.

Potential ecological risk assessment

The ecological risk level of soil heavy metal pollution in the study area was evaluated by using the *RI* proposed by Håkanso (Hakanson, 1980), and the *RI* is defined as follows:

$$Er^i = Tr^i \times PI \tag{3}$$

$$RI = \sum_{i=1}^{n} Er^i \tag{4}$$

where *PI* is the single pollution index of heavy metal i; E_r^i is the potential ecological risk coefficient of heavy metal i; T_r^i is the toxicity response coefficient of heavy metal i, and the toxicity response coefficients of Cu, Cr, As and Pb are 5, 2, 10 and 5, respectively (Huang et al., 2018). *RI* is the potential ecological risk index. The evaluation criteria are set as shown in Table 2.

Human health risk assessment

This study used the health risk assessment model developed by the USEPA to assess the human health risk level of heavy metal pollution in the soil of the study area (Song et al., 2017). Due to differences in physiology and behavior, residents are divided into children and adults.
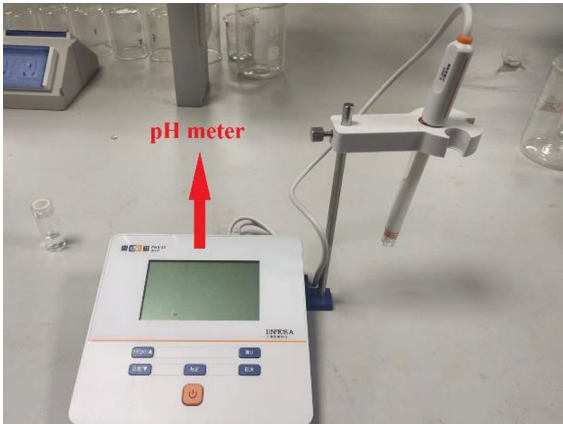
Table 1 Models and photographs of main instruments

Instrument	Manufacturer	Photo
Inductively coupled plasma spectrometer (ICP-OES, Optima 8000)	PerkinElmer	
pH meter (PSC-25)	Rex Electric Chemical	
Total organic carbon analyzer (Vario TOC)	Elementar	

Table 2 Grading standards for potential ecological risks (Ma et al., 2020)

E_r^i Category	Risk level	RI Category	Risk level
$E_r^i < 10$	Slight	$RI < 30$	Slight
$10 \leq E_r^i < 20$	Intermediate	$30 \leq RI < 60$	Intermediate
$20 \leq E_r^i < 40$	Strong	$60 \leq RI < 120$	Strong
$40 \leq E_r^i < 80$	Very strong	$120 \leq RI$	Extremely strong
$80 \leq E_r^i$	Extremely strong		

The average daily intake is calculated as follows (Liu et al., 2022; Mehmood et al., 2019; Zerizghi et al., 2022):

$$ADI_{\text{ing}} = \frac{C_i \times IngR \times EF \times ED \times CF}{BW \times AT} \quad (5)$$

$$ADI_{\text{inh}} = \frac{C_i \times InhR \times EF \times ED}{PEF \times BW \times AT} \quad (6)$$

$$ADI_{\text{der}} = \frac{C_i \times SA \times ABS \times AF \times EF \times ED \times CF}{BW \times AT} \quad (7)$$

In the formula, ADI_{ing}, ADI_{inh} and ADI_{der} are the daily average intake of heavy metals by mouth, respiration and skin, respectively (mg kg^{-1} d^{-1}); C_i is the content of heavy metal i in soil(mg kg^{-1}). $IngR$ is the ingestion soil rate (mg d^{-1}); $InhR$ is the inhalation rate of soil(m^3 d^{-1}); EF is the exposure frequency(d a^{-1}); ED is the exposure duration(a); BW is the average weight(kg); AT is the average exposure time of heavy

metals(d); PEF is the particle emission factor(m^3 kg^{-1}); SA is the skin exposure area(cm^2); AF is skin adhesion factor(mg cm^{-2} d); and ABS is the dermal absorption factor (dimensionless). See Table 3 for the values of relevant parameters of human health risk assessment.

The non-carcinogenic and carcinogenic health risks of soil heavy metals were characterized as:

$$HQ_i = \sum \frac{ADI_{ij}}{RfD_{ij}} \quad (8)$$

$$HI = \sum HQ_i \quad (9)$$

where HQ_i is the non-carcinogenic risk hazard quotient of heavy metal i; ADI_{ij} is the average daily intake of the jth exposure route of non-carcinogenic heavy metal i(mg kg^{-1} d^{-1}); RfD_{ij} is the reference dose of the average daily intake of the jth exposure route of non-carcinogenic heavy metal i(mg kg^{-1} d^{-1}); and HI is hazard index. The evaluation criteria of non-carcinogenic risk HQ_i and HI are set as follows: HQ_i or $HI < 1$, the level of non-carcinogenic risk is not obvious; HQ_i or $HI \geq 1$, the level of non-carcinogenic risk is obvious.

$$CR_i = ADI_{ij} \times SF_{ij} \quad (10)$$

$$TCR = \sum CR_i \quad (11)$$

where CR_i is the single carcinogenic risk of carcinogenic heavy metal i; SF_{ij} is the carcinogenic slope

Table 3 Values of relevant parameters(Liu et al., 2022; Mehmood et al., 2019; Song et al., 2017; Zerizghi et al., 2022; Zhang et al., 2021)

Symbol	Unit	Children	Adults
$IngR$	mg d^{-1}	200	100
$InhR$	m^3 d^{-1}	10	20
EF	d a^{-1}	350	350
ED	a	8.48	16
BW	kg	22.22	65.1
$AT_{\text{non-carcinogenic}}$	d	$365 \times ED$	$365 \times ED$
$AT_{\text{carcinogenic}}$	d	365×70	365×70
PEF	m^3·kg^{-1}	1.36×10^{-9}	1.36×10^{-9}
SA	cm^2	2800	5700
AF	mg cm^{-2} d^{-1}	0.2	0.07
ABS	dimensionless	0.001(As is 0.03)	0.001(As is 0.03)
CF	mg kg^{-1}	1×10^{-6}	1×10^{-6}

d:day; a:year

factor of the jth exposure route of carcinogenic heavy metal i(mg kg^{-1} d^{-1}); and *TCR* is total carcinogenic risk. The evaluation criteria of *CR$_i$* and *TCR* of carcinogenic risk are set as follows: $1.00 \times 10^{-6} \leq CR_i$ (or *TCR*) $< 1.00 \times 10^{-4}$, the level of carcinogenic risk is not obvious; *CR$_i$* (or *TCR*) $\geq 1.00 \times 10^{-4}$, the level of cancer risk is obvious. Table 4 lists the toxicity index reference values of heavy metals.

Quality control

In order to ensure the quality of test data, all the chemicals and reagents used in this study are excellent grade pure. And all containers were treated with dilute nitric acid for 24 h and washed with ultra-pure water before use. The analysis of each batch of samples was set to 3 replicates, and the reagent blank was used to eliminate the analysis deviation and increase the accuracy of the data. All the heavy metal elements in the soil have a good recovery rate, ranging from 90.4 to 106.4%.

Results and discussion

Spatial distribution characteristics of heavy metals in shallow soil

Total quantity characteristics

Within 400 m around the target gangue hill, the total amount of heavy metal elements Cu, Cr, As and Pb in 0–20 cm soil were 14.06–64.13 mg/kg, 18.18–77.88 mg/kg, 4.13–20.25 mg/kg and 15.05–38.38 mg/kg in turn. The average content was 26.99 mg/kg, 37.16 mg/kg, 8.42 mg/kg and

20.97 mg/kg, which were 1.88 times, 2.06 times, 1.99 times and 1.36 times of the background value. The total amount of Cu, Cr, As and Pb in 20–40 cm soil was 14.14–62.77 mg/kg, 17.99–74.56 mg/kg, 4.12–18.47 mg/kg and 15.06–36.96 mg/kg, respectively. The average content was 24.47 mg/kg, 34.36 mg/kg, 7.27 mg/kg and 19.52 mg/kg, which were 1.70 times, 1.91 times, 1.72 times and 1.27 times of the background value, respectively. It can be seen that the exposed stockpiling of coal gangue caused the enrichment of four kinds of heavy metal elements, Cu, Cr, As and Pb, in the 0–40 cm shallow soil within 400 m around, and the 0–20 cm surface soil was more prominent.

Variation characteristics under different horizontal distances

In the NW direction, when the horizontal distance was 0 m, the contents of heavy metal elements Cu, Cr, As and Pb in 0–20 cm soil were 33.69 mg/kg, 57.38 mg/kg, 11.36 mg/kg and 22.39 mg/kg, respectively, which were 134.28%, 218.22%, 168.63% and 45.48% higher than the background value, respectively, and were 2.40 times, 3.13 times, 2.67 times and 1.47 times higher than the horizontal distance of 400 m. When the horizontal distance was 150 m, the contents of heavy metal elements Cu, Cr, As and Pb in the soil were 14.84 mg/kg, 18.27 mg/kg, 4.36 mg/kg and 15.50 mg/kg, respectively, which were 1.03 times, 1.01 times, 1.03 times and 1.01 times of their background values, and all basically return to the background values. The results show that in the NW direction, the influence of coal gangue hill on the contents of heavy metal elements Cu, Cr, As and Pb

Table 4 Reference value of toxicity index of heavy metals (Liu et al., 2022; Zerizghi et al., 2022)

Heavy metals	Reference dose(mg kg^{-1} d^{-1})			Slope factor(mg kg^{-1} d^{-1})		
	RfD$_{ing}$	*RfD$_{inh}$*	*RfD$_{der}$*	*SF$_{ing}$*	*SF$_{inh}$*	*SF$_{dermal}$*
Cu	4.00×10^{-2}	4.02×10^{-2}	1.20×10^{-2}			
Cr	3.00×10^{-3}	2.86×10^{-5}	6.00×10^{-5}	0.5	42	20
As	3.00×10^{-4}	3.00×10^{-4}	1.23×10^{-4}	1.5	15.1	3.66
Pb	3.50×10^{-3}	3.52×10^{-3}	5.25×10^{-4}			

RfD$_{ing}$, *RfD$_{inh}$* and *RfD$_{der}$* are the reference dose of heavy metals for oral intake, respiratory intake and skin intake, respectively, and *SF$_{ing}$*, *SF$_{inh}$* and *SF$_{dermal}$* are the carcinogenic slope factors of heavy metals for oral intake, respiratory intake and skin intake, respectively

in surface soil basically disappeared beyond the horizontal distance of 150 m.

In the NE direction, when the horizontal distance was 0 m, the contents of heavy metal elements Cu, Cr, As and Pb in 0–20 cm soil were 42.63 mg/kg, 67.83 mg/kg, 15.38 mg/kg and 28.88 mg/kg, respectively, which were increased by 196.42%, 276.22%, 263.48% and 87.62%, respectively, compared with the background value, and were 2.99 times, 3.72 times, 3.55 times and 1.87 times, respectively, at the horizontal distance of 400 m. When the horizontal distance was 200 m, the contents of heavy metal elements Cu, Cr, As and Pb in the soil were 14.64 mg/kg, 18.36 mg/kg, 4.38 mg/kg and 15.66 mg/kg, respectively, which are 1.02 times, 1.02 times, 1.04 times and 1.02 times of their background values, and all basically return to the background values. The results show that in the NE direction, the influence of coal gangue hill on the contents of heavy metal elements Cu, Cr, As and Pb in surface soil basically disappeared beyond the horizontal distance of 200 m.

In the E direction, when the horizontal distance was 0 m, the contents of heavy metal elements Cu, Cr, As and Pb in 0–20 cm soil were 52.13 mg/kg, 73.53 mg/kg, 18.89 mg/kg and 32.69 mg/kg, respectively, which were 262.48%, 307.81%, 346.50% and 112.39% higher than the background value, respectively, and were 3.62 times, 4.05 times, 4.58 times and 2.11 times higher than the horizontal distance of 400 m. When the horizontal distance was 300 m, the contents of heavy metal elements Cu, Cr, As and Pb in the soil were 14.39 mg/kg, 18.57 mg/kg, 4.30 mg/kg and 15.42 mg/kg, respectively, which were 1.00 times, 1.03 times, 1.02 times and 1.00 times of their background values, and all basically return to the background values. The results show that the influence of coal gangue hill on the contents of heavy metal elements Cu, Cr, As and Pb in surface soil basically disappeared beyond the horizontal distance of 300 m in E direction.

In the SE direction, when the horizontal distance was 0 m, the contents of heavy metal elements Cu, Cr, As and Pb in 0–20 cm soil were 64.13 mg/kg, 77.88 mg/kg, 20.25 mg/kg and 38.38 mg/kg, respectively, which were 332.02%, 331.92%, 378.72% and 149.40% higher than the background value, respectively, and were 4.54 times, 4.24 times, 4.76 times and 2.48 times higher than the horizontal distance of 400 m. When the horizontal distance was 300 m, the

contents of heavy metal elements Cu, Cr, As and Pb in the soil were 14.88 mg/kg, 18.63 mg/kg, 4.50 mg/kg and 15.50 mg/kg, respectively, which were 1.03 times, 1.03 times, 1.06 times and 1.01 times of their background values, and all basically return to the background values. The results show that the influence of coal gangue hill on the contents of heavy metal elements Cu, Cr, As and Pb in surface soil basically disappeared beyond the horizontal distance of 300 m in SE direction.

In the direction of S, when the horizontal distance was 0 m, the contents of heavy metal elements Cu, Cr, As and Pb in 0–20 cm soil were 37.13 mg/kg, 63.26 mg/kg, 13.36 mg/kg and 24.13 mg/kg, respectively, which were 158.17%, 250.86%, 215.86% and 56.76% higher than the background value, respectively, and were 2.59 times, 3.44 times, 3.04 times and 1.57 times higher than the horizontal distance of 400 m. When the horizontal distance was 200 m, the contents of heavy metal elements Cu, Cr, As and Pb in the soil were 14.54 mg/kg, 18.44 mg/kg, 4.38 mg/kg and 15.33 mg/kg, respectively, which were 1.01 times, 1.02 times, 1.03 times and 1.00 times of their background values, and all basically return to the background values. The results show that in the S direction, the influence of coal gangue hill on the contents of heavy metal elements Cu, Cr, As and Pb in surface soil basically disappeared beyond the horizontal distance of 200 m..

With the increase in the horizontal distance from the coal gangue hill, the contents of heavy metals Cu, Cr, As and Pb in the shallow soil in any direction show a significant decline. The contents of heavy metals Cu, Cr, As and Pb in shallow soil at the horizontal distance of 0 m were 2.40–4.54 times, 3.13–4.24 times, 2.67–4.76 times, and 1.47–2.48 times, respectively, in the horizontal distance of 400 m. The target coal gangue hill can lead to the enrichment of heavy metal elements Cu, Cr, As and Pb in the 0–20 cm topsoil around, which was mainly concentrated within the horizontal distance of 300 m. However, the scope of the effect varies in different directions. In the NW, NE, S, E, SE directions, the coal gangue hill caused the surrounding 0–20 cm shallow soil to enrich four heavy metals within 150 m, 200 m, 200 m, 300 m and 300 m, respectively. The spatial variation characteristics of the contents of heavy metals Cu, Cr, As and Pb in 20–40 cm shallow soil at different horizontal distances were basically the same as those in 0–20 cm

soil, but the coal gangue hill lead to the reduction of the scope of action of soil enrichment of four heavy metals to 200 m on the whole.

Variation characteristics in different directions

The spatial content changes of four heavy metals, Cu, Cr, As and Pb, in shallow soil in different directions and horizontal distances around coal gangue hill are shown in Fig. 4.

At any horizontal distance, the contents of four heavy metals in soil vary greatly in different directions. The average content of Cu in 0–20 cm soil in NW, NE, E, SE and S directions was 1.45, 1.68, 2.10, 2.56 and 1.58 times of the background value. The average content of Cr was 1.58, 1.99, 2.33, 2.45 and 1.96 times of the background value. The average content of As was 1.49, 1.92, 2.38, 2.43 and 1.74 times of the background value. The average content of Pb was 1.14, 1.33, 1.50, 1.64 and 1.21 times of the background value. The order of the average contents of four heavy metals in different directions was SE > E > NE > S > NW. The spatial variation characteristics of heavy metal elements Cu, Cr, As and Pb in 20–40 cm shallow soil in different directions were basically the same as those in 0–20 cm shallow soil. The results show that the effect of the target coal gangue hill on the enrichment of heavy metal elements Cu, Cr, As and Pb in the surrounding shallow soil was mainly concentrated in the downwind area, which was closely related to the dominant wind direction in the study area.

Cause analysis

The correlation coefficients between the contents of Cu, Cr, As and Pb in the shallow soil in different directions and horizontal distances around the coal gangue hill and the soil pH value and TOC content are shown in Table 5.

Coal gangue stored in the open air is easily weathered and broken into solid particles with different particle sizes under the action of exposure, rain and wind erosion. Under the influence of the dominant wind direction in the study area, a large number of coal gangue migrated to the surrounding shallow soil, especially in the downwind area (Masto, 2011; Zhang et al., 2008), and the heavy metal elements carried by it also enter the soil (Wang et al., 2008). Studies have

shown that the particles produced by natural weathering of coal gangue are mainly coarse particles (particle size greater than 0.15 mm) (Li & Huang, 2015). Under the action of wind transport, they fall on the shallow soil near the coal gangue hill in the form of creep and saltation (Li & Shen, 2006), while the fine particles (particle size less than 0.1 mm) migrate in the form of suspension and continuously disperse and settle on the shallow soil in the atmosphere. Therefore, the closer to the coal gangue hill, the more coal gangue particles will migrate to the shallow soil, the more heavy metals they will bring into the soil, and the higher the content of heavy metals in the soil (Li, 2004; Li et al., 2004). Under the influence of the dominant monsoon in the study area (Ding et al., 2017), all kinds of particles formed by the weathering of the target coal gangue hill and heavy metal elements such As Cu, Cr, As and Pb carried by them migrate to the shallow soil in the downwind area (Cong et al., 2017a, b), and the SE direction is the most obvious (Zhang et al., 2011).

In the NW, NE, E, SE and S directions, the correlation coefficients of Cu content and TOC mass fraction in 0–20 cm soil around the target coal gangue hill were 0.834, 0.940, 0.956, 0.919 and 0.863, respectively. The correlation coefficients between Cr content and soil TOC content were 0.761, 0.944, 0.945, 0.920 and 0.967, respectively. The correlation coefficients between heavy metal As and soil TOC content were 0.775, 0.943, 0.967, 0.899 and 0.843, respectively. The correlation coefficient between heavy metal Pb and soil TOC mass fraction was` 0.822, 0.964, 0.952, 0.915 and 0.883, respectively. Except that the correlation between heavy metal Cr content and soil TOC mass fraction in NW direction was significantly positive ($p < 0.05$), the others reached a very significant positive correlation level ($p < 0.01$). The correlation between the contents of four heavy metals in 20–40 cm soil and TOC mass fraction was basically the same as that in 0–20 cm soil. It can be seen that the content of heavy metal elements Cu, Cr, As, Pb in the shallow soil around the target coal gangue hill was significantly positive correlated with the soil TOC mass fraction. The reason is that the soil around the coal gangue hill is agricultural land, and frequent agricultural activities such as fertilization result in rich organic matter content in the shallow soil, especially high dissolved organic matter content (Xu et al., 2018). Dissolved organic matter entering the soil is

Fig. 4 Spatial variation characteristics of four heavy metals in shallow soil. **a** Variation of Cu content in 0–20 cm soil, **b** Variation of Cu content in 20–40 cm soil, **c** Variation of Cr content in 0–20 cm soil, **d** Variation of Cr content in 20–40 cm soil, **e** Variation of As content in 0–20 cm soil, **f** Variation of As content in 20–40 cm soil, **g** Variation of Pb content in 0–20 cm soil, **h** Variation of Pb content in 20–40 cm soil
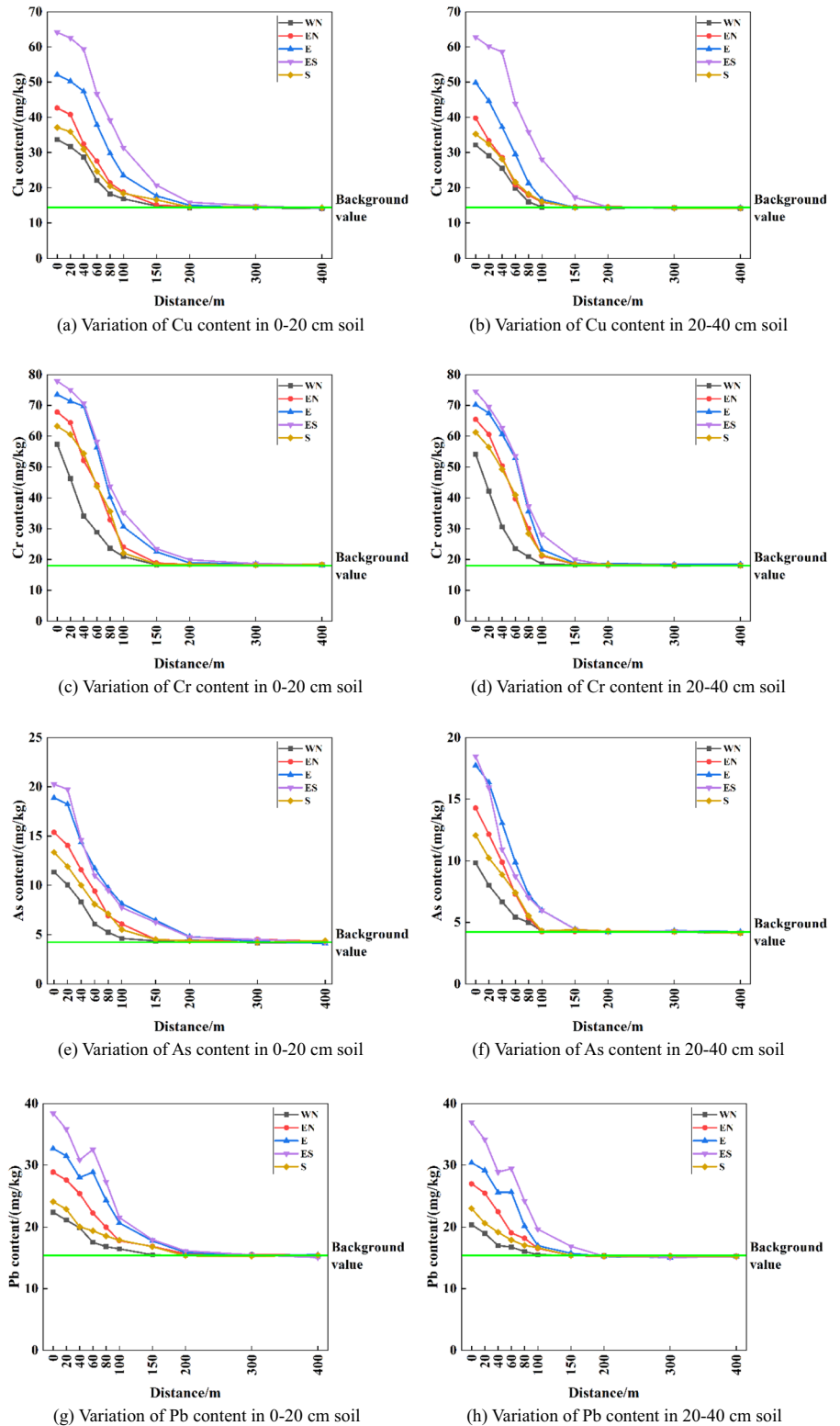
(a) Variation of Cu content in 0-20 cm soil

(b) Variation of Cu content in 20-40 cm soil

(c) Variation of Cr content in 0-20 cm soil

(d) Variation of Cr content in 20-40 cm soil

(e) Variation of As content in 0-20 cm soil

(f) Variation of As content in 20-40 cm soil

(g) Variation of Pb content in 0-20 cm soil

(h) Variation of Pb content in 20-40 cm soil

Table 5 Correlation coefficient between content of four heavy metal elements and pH and TOC in shallow soil

Physical and chemical indexes of soil	Soil depth	Sampling direction	Heavy metals			
			Cu	Cr	As	Pb
pH	0–20 cm	NW	−0.515	−0.352	−0.425	−0.432
		NE	−0.225	−0.195	−0.232	−0.183
		E	0.124	0.124	0.138	0.152
		SE	−0.227	−0.208	−0.11	−0.161
		S	0.297	0.375	0.275	0.160
	20–40 cm	NW	−0.336	−0.346	−0.335	−0.413
		NE	−0.829**	−0.755*	−0.820**	−0.793**
		E	−0.165	−0.021	−0.152	−0.006
		SE	−0.415	−0.36	−0.176	−0.388
		S	0.638*	0.648*	0.656*	0.636*
TOC	0–20 cm	NW	0.834**	0.761*	0.775**	0.822**
		NE	0.940**	0.944**	0.943**	0.964**
		E	0.956**	0.945**	0.967**	0.952**
		SE	0.919**	0.920**	0.899**	0.915**
		S	0.863**	0.867**	0.843**	0.883**
	20–40 cm	NW	0.942**	0.939**	0.958**	0.960**
		NE	0.851**	0.891**	0.846**	0.879**
		E	0.646*	0.668*	0.669*	0.690*
		SE	0.857**	0.852**	0.851**	0.864**
		S	0.770**	0.782**	0.788**	0.802**

**Means extremely significant correlation at 0.01 level, and *means significant correlation at 0.05 level

preferentially adsorbed on the surface of soil particles and serves as a complexing bridge between soil particles and heavy metal ions, enhancing the affinity of soil particle surface, thus increasing the adsorption capacity of heavy metal ions (Li et al., 2012b). At the same time, dissolved organic matter contains carboxyl, hydroxyl, carbonyl, methoxy and other active functional groups (Guo et al., 2012), which can complex and chelate with heavy metals Cu, Cr, As, Pb attached to the fine particles of coal gangue to form a ligand into the soil solution, thus increasing the content of heavy metals in the soil. The high positive correlation between heavy metal content in soil and TOC mass fraction in soil obtained in this study is basically consistent with previous studies (Pandey et al., 2015; Zhang, 2018).

In any direction, there was no significant correlation between the contents of four heavy metal elements in 0–20 cm soil around the target coal gangue hill and soil pH. In the direction of NE, the correlation coefficients of heavy metal elements Cu, As, Pb in 20–40 cm soil with soil pH were −0.829, -0.820 and -0.793, which all reach extremely significant negative correlation level ($p < 0.01$), and the correlation coefficient of Cr content

with soil pH was −0.755, which reaches significant negative correlation level ($p < 0.01$). The correlation coefficients between the contents of heavy metal elements Cu, Cr, As and Pb in the soil of 20–40 cm in S direction and soil pH were 0.638, 0.648, 0.656 and 0.636, respectively, all reaching significant positive correlation levels ($p < 0.05$). It can be seen that the correlation between the content of heavy metal elements Cu, Cr, As, Pb and soil pH in the shallow soil around the target gangue hill was complex and changeable. This may be due to the differences in planting mode, tillage frequency, fertilizer type and irrigation intensity in different regions due to different crops (Li et al., 2012a, 2012b; Liu et al., 2020).

Heavy metal pollution level of shallow soil

The *NIPI* of soil heavy metal pollution was calculated based on the content of 4 kinds of heavy metals in the soil around the gangue hill.

Within 400 m around the target gangue hill, the *NIPI* range of 0–20 cm and 20–40 cm soil heavy metal pollution was 1.0–4.4 and 1.0–4.1, respectively (Fig. 5). It is shown that the comprehensive heavy

Fig. 5 Spatial variation characteristics of *NIPI* of heavy metal pollution in shallow soil. **a** 0–20 cm, **b** 20–40 cm
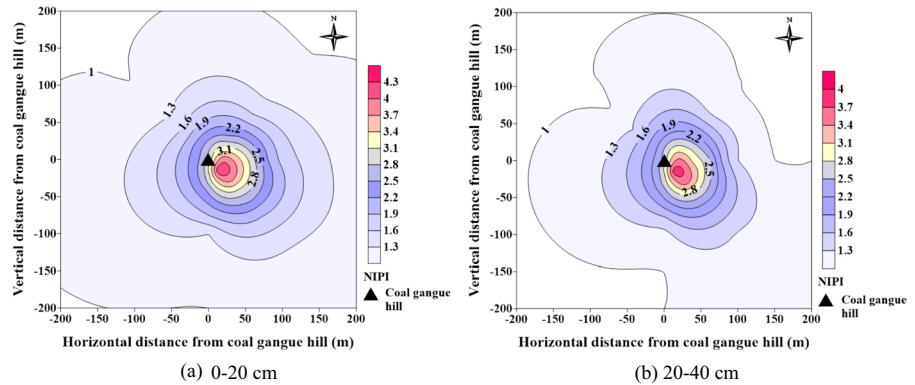
(a) 0-20 cm

(b) 20-40 cm

metal pollution level of shallow soil around the target gangue hill reached the warning line or above, and the pollution level of 0–20 cm soil was higher than that of 20–40 cm soil.

With the increase in the horizontal distance from the coal gangue hill, the comprehensive pollution degree of heavy metals in the soil in any direction shows a significant decline. When the horizontal distances from NE, E, SE and S direction to the coal gangue hill were [0 m, 20 m], [0 m, 40 m], [0 m, 40 m] and [0 m, 20 m] in turn, 0–20 cm soil $NIPI > 3$, reaching the level of severe pollution. When the horizontal distance from NW, NE, E, SE and S direction to the coal gangue hill was [0 m, 20 m], [40 m, 60 m], [60 m, 80 m], [60 m, 80 m] and [20 m, 60 m], 0–20 cm soil $2 < NIPI \leq 3$, reaching the moderate pollution level. When the horizontal distance between NW, NE, E, SE and S direction and the coal gangue hill was [40 m, 100 m], [80 m, 150 m], [100 m, 200 m], [100 m, 300 m] and [80 m, 150 m], 0–20 cm soil $1 < NIPI \leq 2$, reaching the level of mild pollution. When the horizontal distance between NW, NE, E, SE and S direction and the coal gangue hill was [150 m, 400 m], [200 m, 400 m], [300 m, 400 m], [300 m, 400 m] and [200 m, 400 m], 0–20 cm soil $0.7 < NIPI \leq 1$ was at a still clean (alert) level. It is shown that the heavy metal pollution of the surface soil caused by the target coal gangue hill basically disappeared beyond the 300 m radius. In addition, in the NW, NE, E, SE and S direction, the heavy metal pollution effect of coal gangue hill on the surface soil basically disappears beyond the horizontal distance of 150 m, 200 m, 300 m, 400 m and 200 m. And the heavy metal pollution of 20–40 cm soil by the target coal gangue hill basically disappeared beyond 200 m around. In the NW, NE, E, SE and S direction, the heavy metal pollution of 20–40 cm soil caused by coal

gangue hill basically disappears beyond the horizontal distance of 100 m, 150 m, 150 m, 200 m and 150 m.

At any horizontal distance, the comprehensive pollution level of heavy metals in 0–20 cm soil in different directions was quite different. The average values of heavy metal *NIPI* in 0–20 cm soil in NW, NE, E, SE and S directions were 1.5, 1.8, 2.3, 2.5 and 1.8, respectively. The difference characteristics of the comprehensive pollution level of heavy metals in 20–40 cm soil in all directions were basically consistent with those in 0–20 cm soil. It can be seen that the comprehensive pollution degree of soil heavy metals in the downwind area of the target coal gangue hill was higher than that in the upwind area.

Potential ecological risk of heavy metal pollution in shallow soil

The *RI* of soil heavy metal comprehensive pollution was calculated based on the content of four heavy metals in the soil around the gangue hill. Its spatial variation characteristics are shown in Fig. 6, and the potential ecological risk composition types are shown in Fig. 7.

Within 400 m around the target coal gangue hill, the *RI* of heavy metal pollution in 0–20 cm and 20–40 cm soil was 21.81–91.28 and 21.63–85.77, respectively. It is shown that the potential ecological risk level of comprehensive pollution of heavy metals in the shallow soil around the target coal gangue hill was slight or above, and the potential ecological risk of 0–20 cm soil was greater than 20–40 cm soil.

With the increase in the horizontal distance from the coal gangue hill, the potential ecological risk level of soil heavy metal pollution in any direction shows a significant decline. When the horizontal distance

from NE, E and SE direction to the coal gangue hill was [0 m, 20 m], [0 m, 40 m] and [0 m, 40 m], the soil $60 \leq RI < 120$ in 0–20 cm soil layer, reaching a strong ecological risk level; when the horizontal distance between NW, NE, E, SE and S direction and the coal gangue hill was [0 m, 60 m], [40 m, 80 m], [60 m, 100 m], [60 m, 150 m] and [0 m, 80 m], the soil $30 \leq RI < 60$ in 0–20 cm soil layer, reaching the intermediate ecological risk level; and when the horizontal distance between NW, NE, E, SE and S direction and the coal gangue hill was [80 m, 400 m], [100 m, 400 m], [150 m, 400 m], [200 m, 400 m] and [100 m, 400 m], RI of 0–20 cm soil was less than 30, reaching the level of slight ecological risk. It is shown that the potential ecological risk of heavy metal comprehensive pollution of surface soil around the target coal gangue hill was reduced to a low level beyond 200 m. In addition, when the horizontal distance from the coal gangue hill in NW, NE, E, SE and S direction was greater than 80 m, 100 m, 150 m, 200 m and 200 m, respectively, the potential ecological risk of heavy metal comprehensive pollution in the surface soil can be reduced to a lower level. The potential ecological risk of the target coal gangue hill to heavy metals in 20–40 cm soil drops to a low level beyond 150 m around. And when the horizontal distance from the coal gangue hill in NW, NE, E, SE and S direction was greater than 60 m, 80 m, 100 m, 150 m and 80 m in turn, the potential ecological risk of comprehensive pollution of heavy metals in 20–40 cm soil can be reduced to a low level.

At any horizontal distance, the potential ecological risk levels of 0–20 cm soil comprehensive pollution by heavy metals in different directions were quite different. The average potential ecological risk index of heavy metal comprehensive pollution of 0–20 cm soil in NW, NE, E, SE and S direction was 31.01, 38.26, 46.50, 50.13 and 35.25, respectively. The difference characteristics of potential ecological risk level of heavy metals in 20–40 cm soil in all directions were basically consistent with 0–20 cm soil. It can be seen that the potential ecological risk level of soil heavy metal comprehensive pollution in the downwind area of the target coal gangue hill was higher than that in the upwind area. From the composition of potential ecological risk of soil heavy metal comprehensive pollution, As was the largest contributor to the potential ecological risk of soil heavy metal comprehensive pollution in the study area.

The average contribution rate of As in 0–20 cm and 20–40 cm soil were 48.41% and 47.00%, respectively. Combined with the results of potential ecological risk assessment and main risk factors (risk contribution rate >65%), the potential ecological risk components of soil heavy metal comprehensive pollution in the study area can be divided into five types: "strong risk+As","intermediate risk+As+Cu"," intermediate risk+As+Cu or Pb","minor risk+As+Cu", and "minor risk+As+Cu or Pb".

Risk of heavy metal pollution to human health in shallow soil

Based on the contents of four heavy metals in the soil around coal gangue hill, the HI and TCR of soil heavy metal comprehensive pollution were calculated. It can be seen from the calculation results that within 400 m around the target coal gangue hill, the range of HI of 0–20 cm and 20–40 cm soil heavy metal pollution for adults was 0.04–0.19 and 0.04–0.18, respectively, and the range of TCR for adults was $0.13 \times 10^{-4} - 0.57 \times 10^{-4}$ and $0.13 \times 10^{-4} - 0.55 \times 10^{-4}$, respectively. The comprehensive pollution of heavy metals in the shallow soil around the target coal gangue hill did not pose a carcinogenic or non-carcinogenic risk to adults. Therefore, only carcinogenic and non-carcinogenic risks of children were carefully analyzed, and their spatial variation characteristics are shown in Fig. 8.

Total non-carcinogenic risk assessment of children

Within 400 m around the target coal gangue hill, the HI of 0–20 cm and 20–40 cm soil heavy metal pollution to children was 0.25–1.07 and 0.24–0.99, respectively. The comprehensive pollution of heavy metals in 0–20 cm soil around the target coal gangue hill posed non-carcinogenic risk to children within 20 m of SE direction, but the risk was slight. With the increase in the horizontal distance from the coal gangue hill, the total non-carcinogenic risk index of comprehensive soil heavy metal pollution on children in any direction showed a significant decline, and the total non-carcinogenic risk index of comprehensive soil heavy metal pollution in the downwind area of the target coal gangue hill was higher than that in the upwind area.

Fig. 6 Spatial variation characteristics of *RI* of heavy metal comprehensive pollution in shallow soil. **a** NW direction 0–20 cm, **b** NW direction 20–40 cm, **c** NE direction 0–20 cm, **d** NE direction 20–40 cm, **e** E direction 0–20 cm, **f** E direction 20–40 cm, **g** SE direction 0–20 cm, **h** SE direction 20–40 cm, **i** S direction 0–20 cm, **j** S direction 20–40 cm
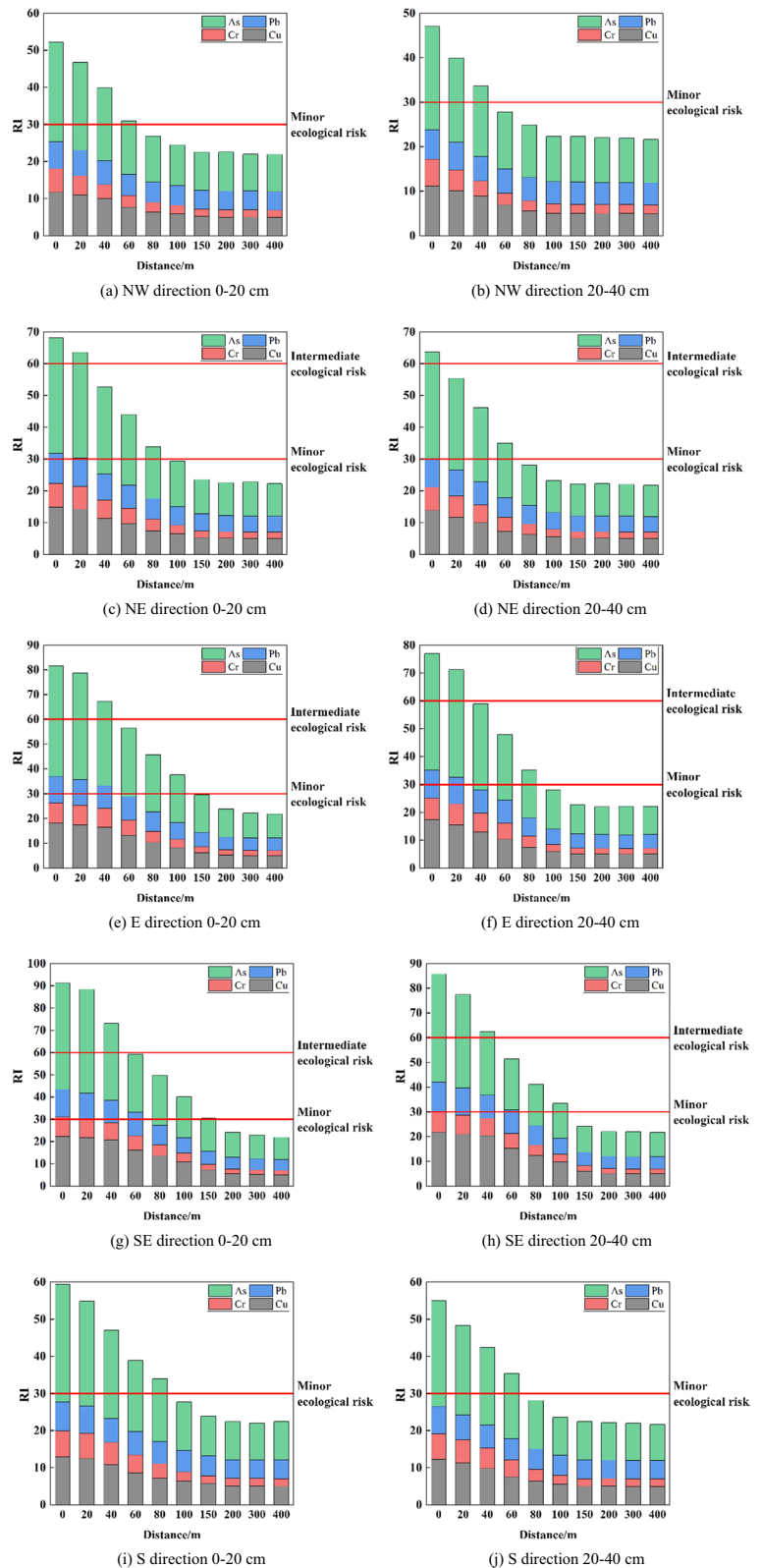

(a) NW direction 0-20 cm

(b) NW direction 20-40 cm

(c) NE direction 0-20 cm

(d) NE direction 20-40 cm

(e) E direction 0-20 cm

(f) E direction 20-40 cm

(g) SE direction 0-20 cm

(h) SE direction 20-40 cm

(i) S direction 0-20 cm

(j) S direction 20-40 cm

Fig. 7 Distribution of comprehensive potential ecological risk types of heavy metal pollution in shallow soil

(a)0-20 cm   (b)20-40 cm

▲CGH ■SERA+As ■IERA+As+Cu ■IERA+As+Cu/Pb ■MERA+As+Cu ■MERA+As+Cu/Pb
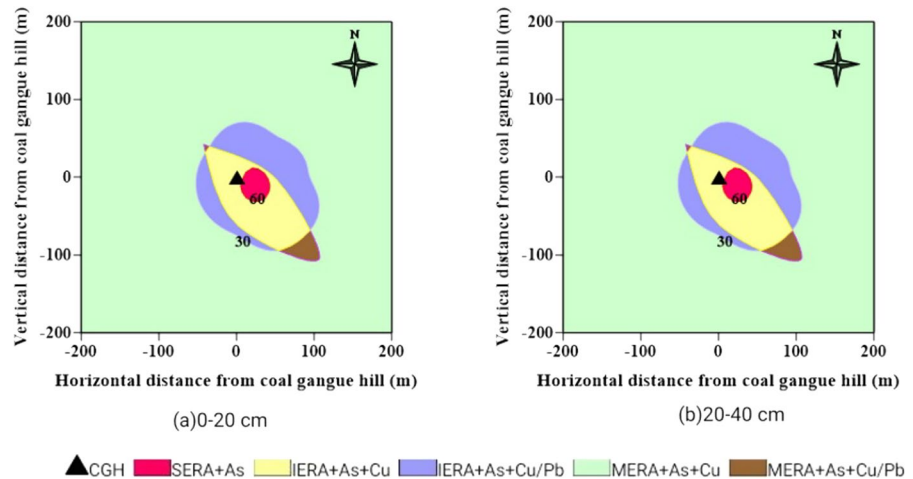
Total carcinogenic risk assessment of children

In view of previous research results (Chen et al., 2018, 2021a, 2021b; Liu et al., 2022), Cu and Pb did not have cancer risk, this paper only calculated and evaluated the carcinogenic risk of heavy metals Cr and As.

Within 400 m around the target coal gangue hill, the *TCR* of heavy metal pollution in 0–20 cm and 20-40 cm soil to children was 0.41×10^{-4}–1.78×10^{-4} and 0.41×10^{-4}–1.70×10^{-4}. It is shown that the comprehensive pollution of heavy metals in the shallow soil around the target coal gangue hill within 60 m in E and SE directions, 40 m in NE and S directions and 20 m in NW directions posed carcinogenic risk to children, but the risk was controllable and the soil heavy metal Cr was the key carcinogenic risk factor. With the increase in the horizontal distance from the coal gangue hill, the total carcinogenic risk index of comprehensive soil heavy metal pollution on children in any direction showed a significant decline, and the total carcinogenic risk index of comprehensive soil heavy metal pollution in the downwind area of the target coal gangue hill was higher than that in the upwind area.

Heavy metals are non-degradable, which will pose a threat to ecosystem and human health after entering the environment (Verma et al., 2021a). Previous studies have shown that some heavy metals are toxic and can directly cause toxicity to human organs, thus threatening human health (Antoniadis et al., 2019). In addition, they can accumulate in human tissues, thus affecting the digestive system, reproductive

system and central nervous system (Kumar et al., 2022a, 2022b). Children's nervous system is still in the development stage, and it is more sensitive to the neurotoxicity of heavy metals. Long-term exposure to lead and cadmium pollution may affect children's neurocognitive function and lead to decreased memory ability (Wang et al., 2020; Zhou & Zhou, 2018).Within 400 m around the target coal gangue hill, the *HI* of comprehensive soil heavy metal pollution for children was 5.55 times that of adults on average, and *TCR* for children was 3.11 times that of adults on average. The combined pollution of heavy metals in soil of the same degree posed a significantly higher non-carcinogenic and carcinogenic risk to children than adults, which was the same as the research results of some scholars (Kumar et al., 2022a; Zhang et al., 2022; Zhang et al., 2022). The reason is that children's weight is lighter than that of adults, and their ability to metabolize and excrete toxins is lower. Under the same heavy metal concentration, children are more sensitive to the impact of heavy metals in soil than adults and are more vulnerable to environmental hazards (Lian et al., 2019). In addition, children's higher respiratory rate per unit weight and frequent ingestion by hands and mouth makes them more likely to be exposed to contaminated heavy metal particles, so they are exposed to higher risk values (Qu et al., 2012). Due to the concealment and long-term accumulation of heavy metals (Kumar et al., 2022b), although the carcinogenic and non-carcinogenic risks of children in the study area are controllable at present, it will also lead to serious consequences in the long run. The problem of

Fig. 8 Spatial variation characteristics of children's health risk index of heavy metals in shallow soil. **a** NW direction *HI*, **b** NW direction *TCR,* **c** NE direction *HI*, **d** NE direction *TCR*, **e** E direction *HI*, **f** E direction *TCR*, **g** SE direction *HI*, **h** SE direction *TCR*, **i** S direction *HI*, **j** S direction *TCR*

(a) NW direction *HI*

(b) NW direction *TCR*

(c) NE direction *HI*

(d) NE direction *TCR*

(e) E direction *HI*

(f) E direction *TCR*

(g) SE direction *HI*

(h) SE direction *TCR*

(i) S direction *HI*

(j) S direction *TCR*
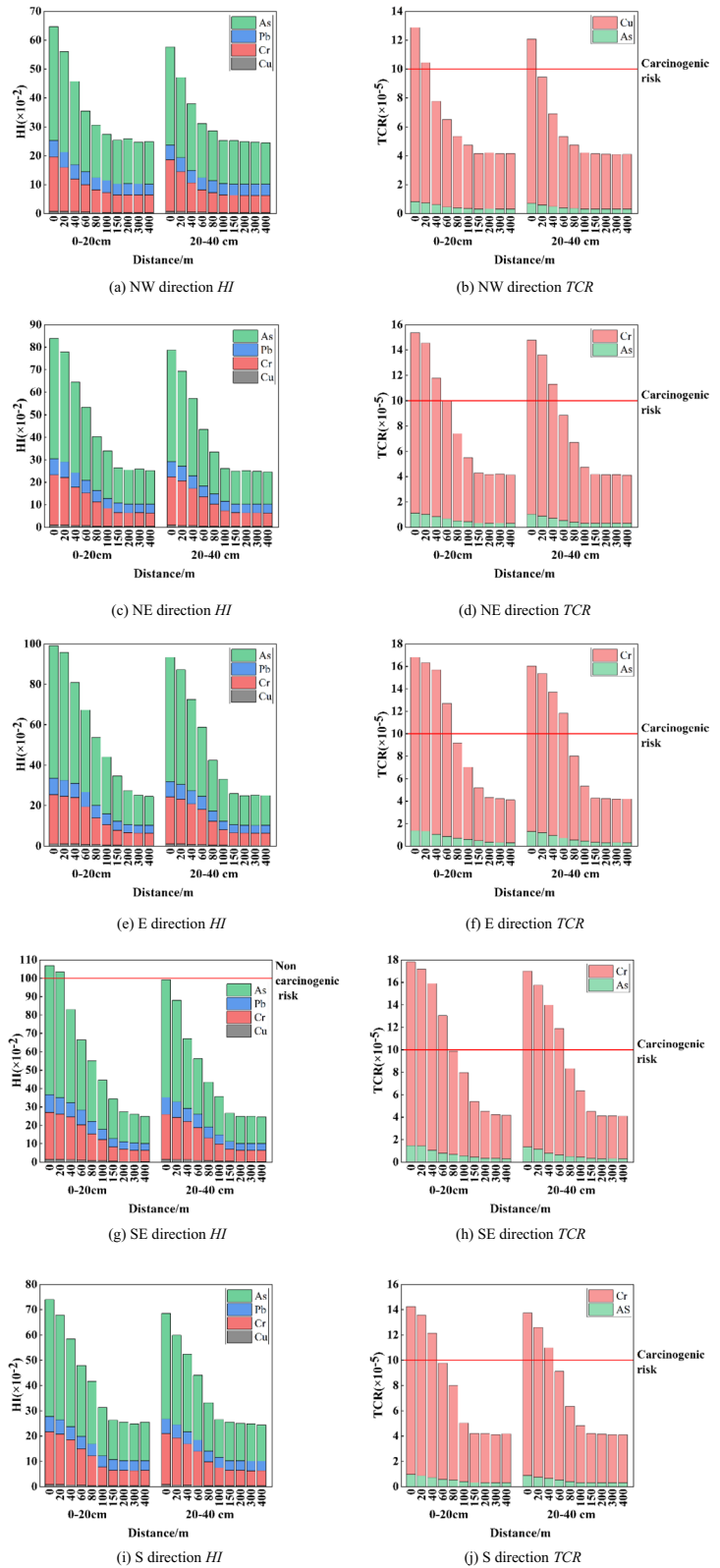
heavy metal pollution should be discovered as soon as possible, prevented in advance and ensured the physical and mental health of children.

Conclusion

The bare storage of coal gangue leads to the enrichment of Cu, Cr, As and Pb in the shallow soil around 0–40 cm. The contents of Cu, Cr, As and Pb in 0–20 cm soil were 14.06–64.13 mg/kg, 18.18–77.88 mg/kg, 4.13–20.25 mg/kg and 15.05–38.38 mg/kg, respectively, with the average contents of 26.99 mg/kg, 37.16 mg/kg, 8.42 mg/kg and 20.97 mg/kg, respectively, which were 1.88 times, 2.06 times, 1.99 times and 1.36 times of the background value. This enrichment phenomenon was more prominent in the 0–20 cm surface soil and was most obvious in the downwind area. With the increase in the horizontal distance from the coal gangue hill, the enrichment effect of four heavy metals in the shallow soil in any direction was obviously weakened. When the horizontal distance from the coal gangue hill exceeded 300 m, the effect basically disappears. The spatial variation characteristics of heavy metal content in the soil around the coal gangue hill were mainly controlled by the regional dominant wind direction and the content of organic matter in the surrounding soil. Accurately identify the spatial distribution characteristics and main controlling factors of regional soil heavy metal content, and implement effective measures to provide support for building a long-term mechanism for the full utilization of contaminated farmland.

The P_N of heavy metal pollution in shallow soil within 400 m around the typical coal gangue hill in Fengfeng mining area was 1.0–4.4, which indicates that the comprehensive heavy metal pollution level of soil in this area has reached the warning line and above, and mainly concentrated in the downwind area, and decreased with the increase in horizontal distance from the coal gangue hill. When the horizontal distance from the coal gangue hill exceeded 300 m, the influence of the coal gangue hill on the comprehensive pollution level of heavy metals in the surrounding shallow soil basically disappeared. Distinguish the heavy metal pollution in soil, and lay a scientific foundation for the subsequent accurate prevention and control of heavy metal pollution in soil.

The RI of heavy metal pollution in shallow soil within 400 m around the typical coal gangue hill in Fengfeng mining area was 21.63–91.28, which indicated that the potential ecological risk level of soil heavy metal comprehensive pollution in this area has reached slight or above, and was mainly concentrated in the downwind area, and decreased with the increase in the horizontal distance from the coal gangue hill. When the horizontal distance from the coal gangue hill was more than 200 m, the impact of the coal gangue hill on the potential ecological risk level of the comprehensive pollution of heavy metals in the surrounding shallow soil will basically disappear. As is the largest contributor (more than 47%) to the potential ecological risk of soil heavy metal pollution in the study area. Based on the assessment results of potential ecological risk level and main risk factors, the potential ecological risk configuration of soil heavy metal comprehensive pollution in the study area can be divided, which will provide an important reference for the classification and control of soil ecological risk in the coal gangue accumulation area. Heavy metal pollution of shallow soil within 400 m around the typical coal gangue hill in Fengfeng mining area will not pose a non-carcinogenic and carcinogenic risk to adults. The HI of heavy metal pollution in 0–20 cm and 20–40 cm soil for children was 0.25–1.07 and 0.24–0.99, respectively, and the TCR of children was 0.41×10^{-4}–1.78×10^{-4} and 0.41×10^{-4}–1.70×10^{-4}, posed a non-carcinogenic and carcinogenic risk to children, but compared with the evaluation standard, the risk was small and controllable. Among them, the children's non-carcinogenic risk area was located within 20 m in the SE direction of the gangue hill, and the children's carcinogenic risk area was located within 60 m in the E and SE directions, 40 m in the NE and S directions and 20 m in the NW direction. The soil heavy metal Cr was the key carcinogenic risk factor. The research results can avoid long-term heavy metal exposure of residents near the study area, thus reducing health risks.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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