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ECOLOGICAL AND HEALTH RISK ASSESSMENT OF SOIL HEAVY METAL CONTAMINATION ALONG NATIONAL HIGHWAY 107 IN CHINA

Abstract: This study investigates soil heavy metal contamination behind the green belts along National Highway 107 in China. Soil samples were collected from both sides of the highway to determine the concentrations of heavy metals such as copper, cadmium, chromium, lead, and zinc. The distribution patterns, ecological risks, and health hazards associated with these heavy metals were analysed. In order to provide more sample examples and data support for soil heavy metal pollution control. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) was employed to detect the concentrations and speciation of these five heavy metals in the soil samples. The Geo-Accumulation Index method, the Nemerow pollution index method, and a health risk assessment model were used to evaluate the ecological and health risks of heavy metal pollution adjacent to the highway. Results indicated that: (1) The concentrations of Cu, Cd, Cr, Pb, and Zn in the soil decreased with the increasing number of protective forest layers, highlighting the significant role of protective belts in impeding the migration of heavy metals from the highway. (2) In terms of pollution assessment, the Geo-accumulation index method revealed prominent Cd contamination, the Geo-accumulation index of Cd peaked at 1.95 indicating a moderate to mild pollution level overall. Conversely, the Nemerow index method suggested a medium to extremely high risk of soil heavy metal Cd contamination. Specifically, the peak value of Cd single-factor pollution index in the study area reached 5.78, and the mean value of its Nemerow index (*P*) was 4.67. (3) In health risk assessment, it was found that children are more susceptible to heavy metal threats. The non-carcinogenic risk indices of all five heavy metals were less than 1, implying minimal risk. However, the total carcinogenic risk index for Cr ranged between 10^{-6} and 10^{-4}, posing a certain level of carcinogenic risk to humans.

Keywords: highway, soil heavy metals, distribution patterns, ecological risk, health risk

Introduction

As technological advancements and societal development progress, the expansion of industrialisation and urbanisation has significantly accelerated transportation growth. However, this advancement comes with a caveat: heavy metals from transportation sources increasingly contaminate soils, impacting human lives, then monitoring and restoration of soil quality in areas adjacent to roads affected by transportation activities is essential for the ecological environment and human well-being [1]. The pollution of land resources occurs as a consequence of the soil heavy metal surpassing the self-purification capacity of the soil environmental system, which is attributed to rapid socio-economic growth and continued disturbance of land resources by human activities such as overgrazing and transportation [2]. Also some foreign scholars have confirmed that agricultural activities and sewage

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discharges cause heavy metal contamination of soils in agricultural areas as well as enrichment of water sources with organic salts and microorganisms by testing and analysing soil and water samples from agricultural areas [3]. Research by Li and Yan [4] has highlighted the potential of melatonin in reducing plant toxicity and soil heavy metal accumulation, thereby mitigating their human health impacts through dietary intake. However, the current stage of this research does not permit its widespread application. Consequently, investigating methods to reduce heavy metal accumulation in soils near highways is crucial for both preventing and remediating heavy metal pollution.

Numerous domestic and international studies have been conducted on soil heavy metal pollution alongside highways. Maksimtsev et al. [5] have demonstrated the significant role of roadside forest belts with different species compositions in accumulating heavy metals (Cd, Cu, Pb, and Zn) in the soil and forest litter under the conditions of Western Polissya in Ukraine. It has been found that the order of metal contamination in soil and plant leaves in different seasons is summer > fall > spring > winter. In addition, the metal accumulation potential of Acorus calamus was higher than that of other green belt species [6]. The metal content of the soil varies greatly under the conditions of different land use types, and the longer the age of the road, the greater the enrichment factor of the heavy metal in the soil. Zhang et al. [7] discovered that heavy metal concentrations in plant leaves can effectively indicate spatial and temporal differences in environmental pollution and provide a scientific basis for urban air quality monitoring. Other scholars have investigated the purification role of green plants and green belts near highways against heavy metals and the selection and screening of heavy metal-resistant plants. By comparing the level of contamination, it was found that green belts have a protective effect on heavy metal migration, and biodetectability of plants can be utilized to detect the distribution pattern of heavy metals in roadside soils [8, 9]. Guan's experimental studies revealed that different vegetation types have varying focuses on heavy metal absorption [10]. Sobik-Szoltysek and Jablonska [11] mixed sewage sludge with chemically active dolomite post-flotation waste to form a soil mixture and found that the two, in certain mixing ratios, effectively prevented the transfer of heavy metals to plants, as well as eliminating the nuisance and threat due to the specificity of the two wastes. Yang et al. [12] have proven that wetland plants significantly affect the migration and chemical forms of Pb and Zn in the rhizosphere soil. Some scholars have utilised the use of phytoremediation to clean cadmium and lead content in polluted soil by changing soil pH [13]. The use of residues including a variety of biochar to help contaminated soils can be an effective and sustainable way to purify lead-contaminated soils and increase food safety and health.

Pb, Zn, Cu, and Cr are common traffic-derived pollutants in soils alongside highways. Pb content in soil mainly originates from vehicle exhaust, brake pad friction, and tire wear. The wear and corrosion of vehicle tires, brake pads, and galvanised steel plates, as well as the combustion of lubricating oil, increase roadside soil Zn content. Cu pollution mainly arises from the wear of vehicle brake pads and radiators, while Cr pollution primarily originates from vehicle exhaust and tire-ground friction [14].

At present, the research on soil heavy metal pollution mainly focuses on the content of many kinds of heavy metals, mainly Cd, Ni, Cu, As and Hg, in the soil as well as the impact on soil microorganisms and plants, etc. Analysing the source and degree of soil heavy metal pollution and evaluating the potential ecological risk value are the hotspots in this field, based on which, a series of related researches, including soil remediation and pollution control, have been spawned. For example, the study by Lindh and Lemenkova

demonstrates that stabilizing contaminated soils using Portland cement and slag can effectively reduce the leaching of heavy metals, offering a viable technical solution for the safe handling of polluted soils [15]. This paper evaluates the ecological and health risks of heavy metal contamination in soils adjacent to highways, and provides a basis for the effective prevention and control of heavy metal contamination and the rational planning and construction of land for safe agricultural production.

The hazards of heavy metal pollution to human health include Cu and Zn, which are integral to metabolic processes in organisms, but excessive levels can cause toxicity and even plant necrosis [16]. Pb and Cr, known for their carcinogenic properties, are among the most toxic pollutants [17]. To analyse the characteristics of heavy metal content in soil and potential ecological risks, many scholars have conducted extensive research on the types of soil heavy metal pollution in highway green belts, the extent of pollution, and preventive and remedial measures [18-22], exploring the impact of different barriers (vegetation cover, green belts, protective forests, iron fences, etc.) and distances on soil heavy metal content. This provides more reference data for subsequent studies on the application of plant remediation technologies in soil heavy metal pollution [23]. Some researchers have found that metal-tolerant and hyperaccumulator plants in protective belts can reduce the mobility of heavy metals, and Ammophila breviligulata Fernald has a strong comprehensive remediation capacity and can be used as a remediation plant species for multiple metal compound pollution sites [24].

This study focuses on soil sampling and analysis along the Jinggang Line (National Highway 107), from the intersection of Provincial Road s103 and National Highway 107 to the crossroads of Zijing Mountain South Road. This road has huge traffic flow, many pedestrians, dense residential areas and agricultural land within 100 meters on both sides of the road, and improper control of the heavy metal content of the surrounding soil will lead to a great potential danger to the production and life of the surrounding residents, therefore, the evaluation of the health pollution of this road is essential for the subsequent soil remediation and management of the site and the health of the people. It involves determining the soil content of five heavy metals including Cu, Cd, Cr, Pb, and Zn. Based on soil environmental quality standards, the types of heavy metals in contaminated soil are identified, and the degree of soil pollution is evaluated. The sources of soil heavy metal pollution are analysed to provide a scientific basis for the prevention and treatment of heavy metal contamination in highway soil areas [25].

Research methods

Overview of the study site

Soil testing unit type: Comprehensive pollution-type soil monitoring unit. Sources of pollution include: 1) Atmospheric Pollution-Type Soil Monitoring Unit - contaminants such as automobile exhaust and other atmospheric pollutants; 2) Agricultural Chemicals Pollution-Type Soil Monitoring Unit - contaminants from agricultural herbicides or pesticides. The soil type is yellow-brown soil, with an average pH value of 7.65. Monitoring points were selected along a stretch of the Jinggang Line (National Highway 107) from the intersection of Provincial Road s103 and National Highway 107 to the crossroads of Zijing Mountain South Road. This section spans approximately 3.5 kilometers, consisting of a two-lane roadway with a two-way traffic flow of 2052 vehicles per hour. Protective forests, predominantly consisting of evergreen trees such as

Ligustrum and Photinia, deciduous trees like Cercis, and low-growing evergreen shrubs, are planted along both sides of the road. Adjacent to the roadbed, annual crops such as rapeseed are cultivated. Near some of the sampling points are vegetable gardens, and scattered around some points are discarded red bricks. The protective forest is arranged in a terraced layout, with samples collected from the flat vegetated soil behind the forest on the leeward side of the highway (Fig. 1).

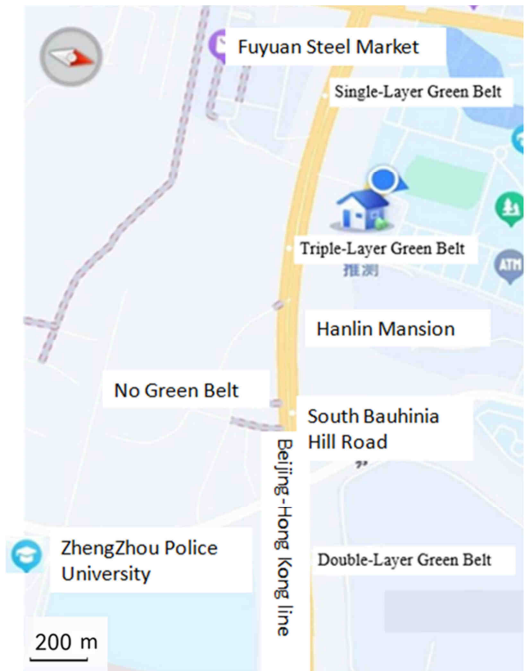


Fig. 1. Sampling area map (extracted from Baidu map, scale 1 : 20000)

Research questions and hypotheses

With the increase in the extensive coverage of highway traffic in China, the aspect of soil heavy metal pollution around the road has also begun to attract people's attention, the purpose of this paper is to evaluate the ecological risk of pollution and the health risk of soil heavy metals in the agricultural land and residential areas in the study area, and to explore the pollution level of different heavy metals in the study area as well as the effect of roadside greening measures on the content of heavy metals in the soil.

Based on the summary of the previous research results, there are the following assumptions: 1) This paper predicts that the existence of green belts next to the highway has a blocking effect on the migration of heavy metals in roadside soil, and it is related to the density of the green belts. 2) The level of heavy metal content in the roadside soil is related to the distance from the roadbed. 3) The study area of the Cu, Cd, Cr, Pb, Zn, and several other heavy metals may exist in the content of the exceeding standard or the problem of higher health risk.

Sampling and analysis

Soil samples were collected along the left side of the highway, with sampling lines laid out parallel to the road at distances of 8 m and 20 m from it. The sampling points were divided into eight categories based on the different layers of protective forest vegetation. These categories included a control group with only rapeseed planted (representing no protective forest), single-layer protective forest (rapeseed + Photinia), double-layer protective forest (rapeseed + Rohdea + Photinia), and triple-layer protective forest (rapeseed + Rohdea + Photinia + low shrubs). To minimise sampling error, samples were taken every 5 m along each line, with five replicates per sampling line. A soil sampler (1 m/50 mm soil auger, produced by Hongguang Instruments) was used to collect samples from a depth of 15 cm. At each specific sampling point, the 0 cm - 15 cm topsoil was sampled using a five-point sampling method and then mixed together. The quartering method was employed to discard excess samples, retaining 50 g of the mixed sample for analysis. This resulted in a total of eight mixed soil samples. Each sample was thoroughly mixed and then divided into two portions: one for pH and soil particle size analysis, and the other for determining heavy metal content. Soil samples were processed with duplicate samples, and the logarithmic error (ΔlgC) and relative standard deviation (*RSD*) between the average value of the measured element content and the standard value of each standard substance were counted, and the values of logarithmic deviation and relative standard deviation were within 5 %, and the limits of detection, precision, and accuracy of each analytical method were in accordance with or better than the requirements of the "Specification for Geochemical Evaluation of Land Quality" (DZ/T 0295-2016) [26].

Sample processing and analysis

(1) Pretreatment: The collected soil samples were poured onto a tray and allowed to air-dry to a semi-dry state. While semi-dry, the soil clumps were crushed, and debris such as plant roots and fallen leaves were removed. The soil was then spread into a thin layer and frequently turned over in a shaded area to dry slowly. Once dry, the soil was crushed with plexiglass (or a wooden rod) and sieved through a 2 mm mesh to remove particles larger than 2 mm and plant residues. The crushed soil was then passed through a 1 mm sieve (standard sieve, produced by Cangzhou Bokuan Testing Instrument Co., Ltd.) to obtain soil with a particle size of 1 mm, which was then thoroughly mixed. Approximately 10 g of soil was sampled from multiple points, ground in an agate mortar, and passed through a 0.15 mm sieve. The sieved soil was stored in a ground glass bottle in a cool, dry place for analysis.

(2) Sample pretreatment method: Microwave digestion method, as per the national standard HJ-832-2017, in an acid-resistant fume hood, 6 mL of nitric acid, 3 mL of hydrochloric acid, and 2 mL of hydrofluoric acid were added sequentially into the sample, which was is then placed in the chamber of a microwave digestion device, heated to 150 °C for 10 minutes, continued to 180 °C for 5 minutes, and finally to 200 °C for 25 minutes.

(3) Acid removal: 1 ml of perchloric acid was added using a pipette to remove excess hydrofluoric acid (to prevent excessive hydrofluoric acid from destroying the heavy metal in the sample). The sample was then heated to 170 °C for 30 minutes to evaporate the acid, reducing the sample solution to about 2 ml, followed by cooling and diluting with water to a final volume of 25 mL.

(4) Detection: The sample solutions (B11, B12, B13, B14, B15, B16, B17, B18) were analysed for heavy metals Cu, Cd, Cr, Zn, and Pb using ICP-MS. The specific instrument used is Model ICP-MS Aglient 7850.
(5) pH measurement method: The pH of the soil was measured using an electrode method. The procedure involves weighing 10 g of the sample and dissolving it in 25 g of water (1 : 2.5 ratio), shaking the mixture well, allowing it to settle, and then measuring the pH of the mixture using a pH meter. The primary instrument used for this is the Model FE28 pH meter.

Data processing and analysis

Experimental results

The results of the heavy metal contents of five heavy metals in the sampling area based on two different variables, namely, different distances from the roadbed and different layers of shelterbelts, are shown in Tables 1 and 2. Table 1 is the original data of heavy metal contents in the soil, and according to the relevant standards of data processing of heavy metal pollution in the soil, in order to facilitate the analysis of the subsequent calculations, the unit of μg/L of the heavy metal contents in the original data is now uniformly converted into mg/kg in Table 2.

Table 1

Soil heavy metal content in different green belt types and distance from subgrade

Item	Unit	Control group (No green belt)		Single layer		Double layer		Triple layer	
		8 m (B15)	20 m (B16)	8 m (B11)	20 m (B12)	8 m (B17)	20 m (B18)	8 m (B13)	20 m (B14)
Cu	μg/L	52.82	51.298	51.514	50.422	50.889	47.453	48.726	53.753
Cd	μg/L	1.564	1.009	0.422	0.443	1.603	0.423	0.388	1.133
Pb	μg/L	66.451	67.449	68.26	65.849	66.244	66.331	62.287	65.725
Cr	μg/L	40.839	52.24	38.634	40.43	42.279	42.262	43.106	39.993
Zn	μg/L	34.278	37.704	34.559	39.304	35.569	34.253	33.749	36.38
pH	-	8.22	8.25	8	8.27	8.39	8.17	8.32	8.32

Table 2

Soil heavy metal content in different green belt types and distance from subgrade

Item	Unit	Control group (No green belt)		Single layer		Double layer		Triple layer	
		8 m (B15)	20 m (B16)	8 m (B11)	20 m (B12)	8 m (B17)	20 m (B18)	8 m (B13)	20 m (B14)
Cu	mg/kg	12.08	12.03	12.02	11.86	11.83	10.88	11.34	12.74
Cd	mg/kg	0.36	0.24	0.10	0.10	0.37	0.10	0.09	0.27
Pb	mg/kg	15.20	15.82	15.93	15.49	15.41	15.21	14.50	15.57
Cr	mg/kg	46.71	61.26	45.09	47.54	49.16	48.47	50.17	47.39
Zn	mg/kg	39.20	44.21	40.33	46.22	41.36	39.28	39.28	43.10
pH	-	8.22	8.25	8.00	8.27	8.39	8.17	8.32	8.32

Distribution and characteristics of heavy metals in highway soil

Since the sampling points in the study area span within 4 kilometers, the ambient temperature, humidity, rainfall, soil type, and the degree of vegetation cover in this area are very different, based on the above environmental variables caused by the environmental

error is negligible, so this paper does not include environmental variables in the scope of the analysis of the impact of heavy metals in the soil. Then based on the experimental results of heavy metal content, the national standard GB15618-2018: Soil environmental quality risk control standard for soil contamination of agricultural land specifies screening and control values for soil pollution in agricultural land [27]. These standards are used to determine whether the heavy metal and certain organic substance content in the soil meets the safety standards for the crops grown there for consumption. Subsequently, appropriate measures are taken for remediation. The known screening values for heavy metals in agricultural land are: Cu: 100 mg/kg; Cd: 0.3 mg/kg; Pb: 120 mg/kg; Cr: 200 mg/kg; Zn: 250 mg/kg.

Graphical analyses are conducted to examine the effectiveness of different barrier types in blocking various heavy metals. Comparative charts are used to analyse the trends in the concentration of the five heavy metals under the conditions of four different types of protective barriers.

(1) Soil heavy metal distribution map

The results of the changes in the content of different heavy metals are shown in Figures 2-6.

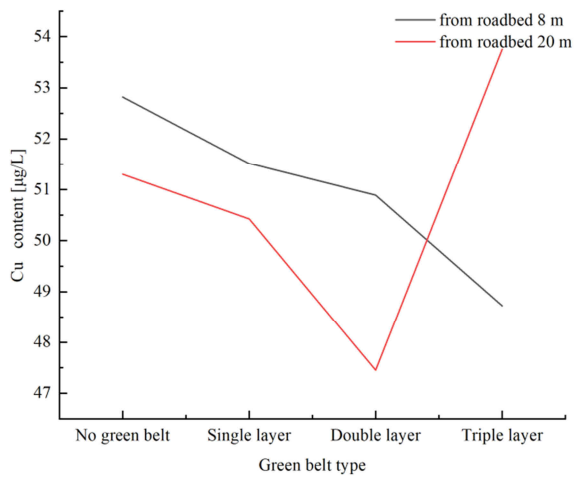


Fig. 2. Trend of Cu content variation with different green belt type and distance from the roadbed

(2) Soil heavy metal analysis results

Through the longitudinal comparison of the relevant heavy metal contents in the soil at different distances from the roadbed and the horizontal comparison of the number of layers of different protection zones for the same heavy metal element in Figures 2-6, the following trends were observed: 1) Under the premise of being within the 0 cm - 15 cm topsoil layer and at the same distance from the roadbed, the content of heavy metals Cu, Cd, Pb, Cr, and Zn varied with different types of green belts. It was observed that with an increase in the number of green belt layers, the overall content of Cu, Cd, Cr, Pb, and Zn showed a declining trend. Notably, the gap in the content of Cu, Cr, and Zn between areas with no green belt and single-layer green belt was significant, indicating that the presence of green belts plays a substantial role in blocking the migration of heavy metals from the road.

2) For the same heavy metal element at different distances from the roadbed, the content of Cu and Cd decreased with increasing distance from the roadbed, while the content of Cr, Pb, and Zn showed a negative correlation with the distance from the roadbed. This is related to the different adsorption capacities of metals on different particle sizes. For particulate matter in automobile exhaust, particles larger than 9 μm (accounting for 40 % of the total) tend to settle on both sides of the road in a short time; particles between 1 μm - 9 μm (20 % of the total) spread over short distances; and particles less than 1 μm (40 % of the total) remain suspended in the air and can travel longer distances. On the other hand, it has been shown that the physicochemical properties and ore composition of soil also affect the uptake of heavy metals by plants and thus the distribution and transport of heavy metals in soil.

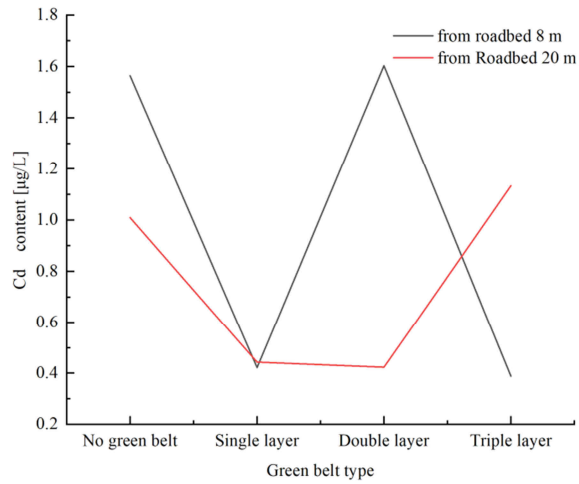


Fig. 3. Trend of Cd content variation with different green belt type and distance from the roadbed

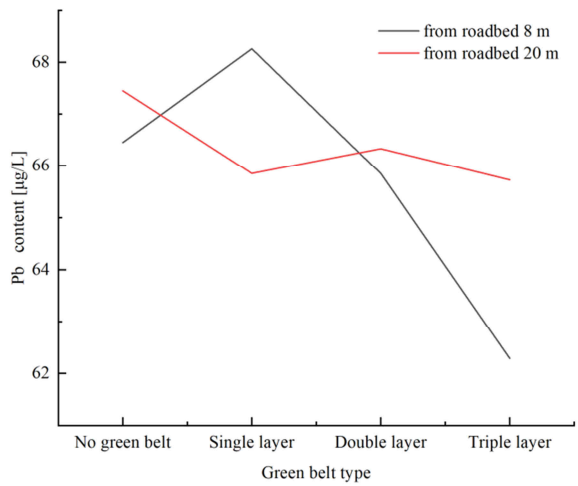


Fig. 4. Trend of Pb content variation with different green belt type and distance from the roadbed

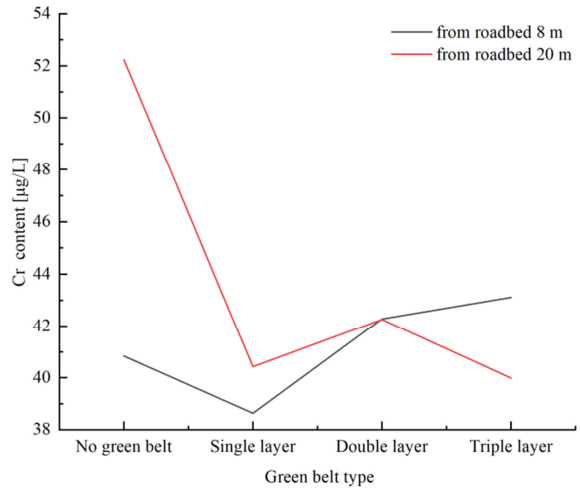


Fig. 5. Trend of Cr content variation with different green belt type and distance from the roadbed

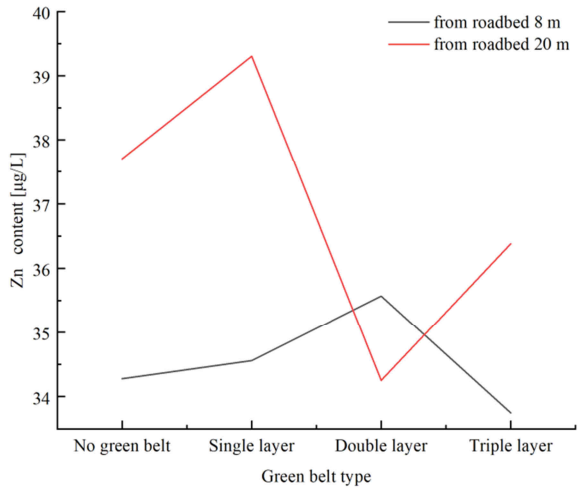


Fig. 6. Trend of Zn content variation with different green belt type and distance from the roadbed

Comparing the soil heavy metal content in Table 2 with the background values in the national standard GB 15618-2018 [27], it is found that the content of Cd element in the no-green-belt and double-layer green belt areas 8 m from the roadbed exceeds the risk screening value for agricultural land soil pollution risk control. This indicates potential risks to the quality and safety of crops grown in these areas, as well as to crop growth and the soil's ecological environment. Hence, there is a need for intensified soil environmental testing and coordinated agricultural product testing in and around these areas.

Correlation analysis: Based on the soil heavy metal content and corresponding pH values, a statistical chart of correlation coefficients for each heavy metal element is derived. The results of the analysis are shown in Figure 7.

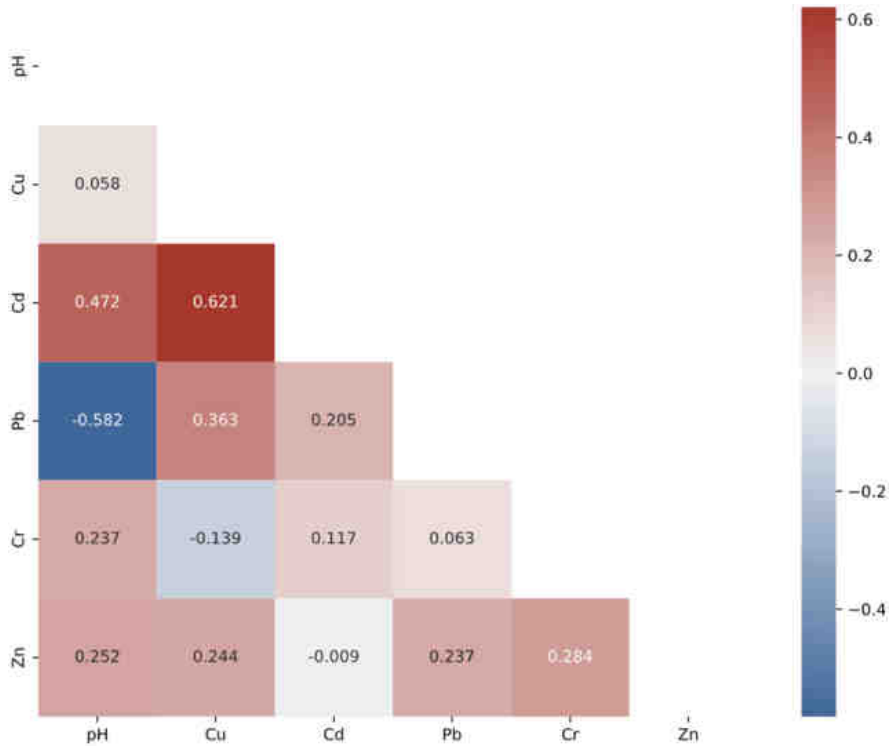


Fig. 7. Correlation statistics of heavy metals

The correlation among heavy metals can reflect the similarity of their sources. Metals with high correlation likely share similar sources, while those with low correlation have more diverse origins. The results mentioned above demonstrate that there is no strong correlation among the five heavy metals Cu, Cd, Pb, Cr, and Zn. However, a significant correlation is observed between Cd and Cu, suggesting that these two heavy metals have similar sources. Based on the location of the sampling points, it is inferred that these two metals are likely derived from vehicle exhaust emissions.

Highway soil heavy metal risk assessment

The overall soil heavy metal contamination level for the five heavy metals discussed in this paper was evaluated using the Geo-accumulation index method and the Nemerow pollution index method. These assessments help in determining the pollution levels of different heavy metals in the soil.

The extent of potential health hazards posed by heavy metals was assessed based on health risk assessment standards to determine whether the level of risk is within acceptable limits.

(1) Pollution risk assessment

The Geo-accumulation index method (I_{geo}) evaluates the extent of pollution by comparing the concentration of heavy metals with their geochemical background values. This method also considers the impact of human activities on the concentration of heavy

metals and quantifies the degree of pollution [28]. The Geo-accumulation index classifies pollution into seven levels (ranging from 0 to 6) (see Table 3).

Table 3

Classification criteria of geological accumulation index method

Level	I_{geo}	Degree of pollution
0	$I_{geo} \leq 0$	No pollution
1	$0 < I_{geo} \leq 1$	Light to moderate pollution
2	$1 < I_{geo} \leq 2$	Moderate pollution
3	$2 < I_{geo} \leq 3$	Moderate to severe pollution
4	$3 < I_{geo} \leq 4$	Severe pollution
5	$4 < I_{geo} \leq 5$	Severe to extreme pollution
6	$I_{geo} > 5$	Extreme pollution

The model for the Geo-accumulation index is:

$$I_{geo} = \log_2 \left[C_i / \left(KB_i \right) \right] \tag{1}$$

where, C_i is the measured concentration of the heavy metal (in [mg/kg]), K is a coefficient accounting for variations in background values due to differences in rock types, and B_i is the reference background value for the heavy metal. K is a conversion coefficient that adjusts for variations in soil characteristics across different areas, which may affect the background values [29, 30].

Based on the aforementioned model, the Geo-accumulation index (I_{geo}) for each sampling point was calculated. The results are presented in Table 4.

Table 4

Calculated values of geochemical accumulate index

Sampling point	Cu	Cd	Pb	Cr	Zn
B11	–1.32	0.06	–1.04	–1.07	–1.22
B12	–1.34	0.06	–1.08	–1.00	–1.02
B13	–1.40	–0.09	–1.17	–0.92	–1.26
B14	–1.24	1.49	–1.07	–1.00	–1.12
B15	–1.31	1.91	–1.11	–1.02	–1.26
B16	–1.32	1.32	–1.05	–0.63	–1.08
B17	–1.34	1.95	–1.09	–0.95	–1.18
B18	–1.46	0.06	–1.10	–0.97	–1.26
Average	–1.34	0.84	–1.09	–0.95	–1.17

Table 5

Soil heavy metal pollution in the study area

Sampling point	Cu	Cd	Pb	Cr	Zn
B11	Clean	Light	Clean	Clean	Clean
B12	Clean	Light	Clean	Clean	Clean
B13	Clean	Clean	Clean	Clean	Clean
B14	Clean	Moderate	Clean	Clean	Clean
B15	Clean	Moderate	Clean	Clean	Clean
B16	Clean	Moderate	Clean	Clean	Clean
B17	Clean	Moderate	Clean	Clean	Clean
B18	Clean	Moderate	Clean	Clean	Clean
Average	Clean	Light	Clean	Clean	Clean

Using the environmental background values for brown soil in Zhengzhou City (Cu: 20.0 mg/kg; Cd: 0.064 mg/kg; Pb: 21.8 mg/kg; Cr: 63.3 mg/kg; Zn: 62.5 mg/kg), the heavy metal pollution status of the highway soil in the study area and the regional pollution situation were analysed and summarised. The findings are presented in the Table 5, which details the pollution status based on the above evaluation results.

As shown in Table 5, using the Geo-accumulation index method, within a 20 m distance from the highway roadbed in the study area, the order of heavy metal pollution levels is Cd > Cr > Pb > Zn > Cu. Among these, the elements Cr, Pb, Cu, and Zn show no pollution. However, for the element Cd, some sampling points in the study area reach light and moderate pollution levels, indicating an overall trend towards light pollution or higher. Given the proximity of residential areas to the study site and the discovery of a large number of discarded red bricks at some sampling points, it is important to note that the main component of red bricks is Fe_2O_3. Iron oxides are a significant factor in the accumulation of heavy metals like Cd in the soil [31]. Soil organic matter, rich in functional groups, provides numerous sites for the adsorption of heavy metals. The high vegetation cover in the sampling area contributes to rich organic matter in the soil, which is conducive to the accumulation of heavy metals such as Cd. The average Geo-accumulation index of Cd in the study area is 0.84, making it the heavy metal with the highest average I_{geo} index among those tested. This indicates that the area is most severely polluted by Cd.

The Nemerow index method [32] is a commonly used approach for evaluating comprehensive pollution indices. This method not only reflects the impact of various types of pollution in a specific environment but also the combined effects of multiple pollutants acting synergistically. It provides an assessment of the level of heavy metal pollution. The classification of heavy metal pollution levels according to the Nemerow index is shown in Table 6.

Table 6

Evaluation criteria for Nemerow pollution index in soil

P_i	Pollution level	P	Pollution level
< 1	Clean	< 0.7	Clean
1-2	Warning	0.7-1	Warning
2-3	Light pollution	1-2	Light pollution
3-5	Severe pollution	2-3	Severe pollution
> 5	Extreme pollution	> 3	Extreme pollution

The model for the Nemerow index method is as follows:

- Single pollution index:

$$P_i = C_i / S_i \tag{2}$$

where, P_i is the pollution index for each heavy metal, C_i is the measured concentration of each heavy metal [mg/kg], and S_i is the corresponding environmental background value for each heavy metal [mg/kg].

- The comprehensive pollution index adopts the Nemerow index method:

$$P = \left\{ \left[\left(C_i / S_i \right)^2_{\max} + \left(C_i / S_i \right)^2_{\text{ave}} \right] / 2 \right\}^{1/2} \tag{3}$$

where, P is the Nemerow comprehensive cumulative index, $(C_i/S_i)^2_{\max}$ is the maximum value of the heavy metal pollution indices, and $(C_i/S_i)^2_{\text{ave}}$ is the average value of the heavy metal pollution indices.

Based on the aforementioned models, the Nemerow index for each sampling point was calculated. The results are presented in Table 7.

Table 7

Original evaluation results using the Nemerow index method

Sampling point	Cu	Cd	Pb	Cr	Zn
B11	0.60	1.56	0.73	0.71	0.65
B12	0.59	1.56	0.71	0.75	0.74
B13	0.57	1.41	0.67	0.79	0.63
B14	0.64	4.22	0.71	0.75	0.69
B15	0.60	5.63	0.70	0.74	0.63
B16	0.60	3.75	0.73	0.97	0.71
B17	0.59	5.78	0.71	0.78	0.66
B18	0.54	1.56	0.70	0.77	0.63
$(C_i/S_i)_{max}$	0.60	5.78	0.73	0.97	0.74
$(C_i/S_i)_{ave}$	0.59	3.18	0.71	0.78	0.67
P	0.60	4.67	0.72	0.88	0.70

Table 8

Soil heavy metal pollution status in the study area

Sampling point	Cu	Cd	Pb	Cr	Zn
B11	Clean	Warning	Clean	Clean	Clean
B12	Clean	Warning	Clean	Clean	Clean
B13	Clean	Warning	Clean	Clean	Clean
B14	Clean	Severe	Clean	Clean	Clean
B15	Clean	Extreme	Clean	Clean	Clean
B16	Clean	Severe	Clean	Clean	Clean
B17	Clean	Extreme	Clean	Clean	Clean
B18	Clean	Warning	Clean	Clean	Clean
$(C_i/S_i)_{max}$	Clean	Extreme	Clean	Clean	Clean
$(C_i/S_i)_{ave}$	Clean	Light	Clean	Clean	Clean
P	Clean	Severe	Warning	Warning	Clean

For the evaluation of heavy metal pollution, the corresponding environmental background values for agricultural land soil pollution risk screening are selected as follows: Cu: 20.0 mg/kg; Cd: 0.0809 mg/kg; Pb: 21.3 mg/kg; Cr: 63.3 mg/kg; Zn: 62.5 mg/kg. Based on the results of the aforementioned assessments, a comprehensive analysis of the heavy metal pollution in the highway soil of the study area and the regional pollution status was conducted. The summarised pollution situation is presented in the Table 8.

As shown in Table 8, the Nemerow comprehensive evaluation method indicates that within a 20 m distance from the roadbed in the study area, Cd is the primary pollutant. In 50 % of the samples from the study area, the concentration of Cd exceeds three times the background value, with the highest single-factor pollution index reaching 5.78. Some sampling locations in the study area reach an extreme level of Cd pollution. The average Nemerow index (P) value is 4.67, suggesting that the soil in the study area of Yunnan is at an extreme pollution level overall, posing the highest ecological risk according to the ecological risk warning index. It indicates an extremely high ecological risk. Meanwhile, the Nemerow comprehensive evaluation indices for heavy metal elements Pb and Cr are at a warning level, not causing significant harm overall, but attention should be paid to prevention and control measures. For Cu and Zn, both the single-factor index and the

Nemerow index are below the warning values of the evaluation standards, indicating a clean level. The risk assessment of the five soil heavy metals aligns with the conclusions derived from the Geo-accumulation index method.

(2) Health risk assessment

Using the health risk assessment model proposed by the United States Environmental Protection Agency (USEPA) and combining it with the actual health conditions of the Chinese population, a study was conducted on the exposure doses of heavy metals in road dust and leaf surface dust in Longhu Town, Xinzheng City. This study calculated exposure doses for three different pathways: ingestion (hand-to-mouth), dermal (skin contact), and inhalation.

Hand-to-mouth exposure calculation model:

$$ADD_{ing} = \frac{C_i \cdot IR \cdot CF \cdot EF \cdot ED}{BW \cdot AT} \tag{4}$$

Dermal contact exposure dose calculation model:

$$ADD_{derm} = \frac{C_i \cdot SA \cdot ABS \cdot CF \cdot EF \cdot ED}{AT \cdot BW} \tag{5}$$

Inhalation exposure calculation model:

$$ADD_{inh} = \frac{C_i \cdot \mathrm{PM10} \cdot DAIR \cdot PLAF \cdot FSPO \cdot CF \cdot EF \cdot ED}{AT \cdot BW} \tag{6}$$

ADD represents the exposure dose for different pathways; C_i is the actual measured concentration of heavy metals. The parameters used in the three models and the reference exposure doses are presented in the Tables 9 and 10.

Table 9

Health risk parameters of soil heavy metals

Symbol	Meaning	Unit	Adult	Child
IR	Soil ingestion rate	$mg \cdot d^{-1}$	100	200
CF	Conversion factor	$kg \cdot mg^{-1}$	10^{-6}	10^{-6}
EF	Exposure frequency	$d \cdot a^{-1}$	350	350
ED	Exposure duration	a	24	6
BW	Average body weight	kg	61.8	19.2
SA	Exposed skin surface area	cm^2	5075	2448
SF	Skin adhesion coefficient	$mg \cdot cm^{-2}d$	0.07	0.2
ABS	Skin absorption factor	-	0.001	0.001
PM10	Inhalable suspended particulates in air	$mg \cdot cm^{-3}$	0.15	0.15
DAIR	Daily air inhalation rate	$m^3 \cdot d^{-1}$	14.5	7.5
PLAF	Particle inhalation and retention ratio in body	-	0.75	0.75
FSPO	Proportion of soil particles in air	-	0.5	0.5
AT (*Carcinogenic*)	Average exposure time (Carcinogenic)	d	70 · 365	70 · 365
AT (*Non-carcinogenic*)	Average exposure time (Non-carcinogenic)	d	*ED* · 365	*ED* · 365

Health risk assessment includes both carcinogenic and non-carcinogenic health risk evaluations. The non-carcinogenic effects are represented by the non-carcinogenic risk index (*HQ*) and the total non-carcinogenic risk index (*HI*). Carcinogenic effects are indicated by the carcinogenic risk index (*CR*) and the total carcinogenic risk index (*TCR*). The models for calculating the health risk indices for carcinogenic and non-carcinogenic effects of heavy metals are as follows:

Carcinogenic health risk index formula:

$$TCR = \sum CR_{nm} = \sum ADD_{nm} \cdot SF_{nm} \quad (7)$$

Non-carcinogenic health risk index formula:

$$HI = \sum HQ_{\mathrm{n}} = \sum ADD_{nm} / RFD_{nm} \quad (8)$$

where, ADD_{nm} is the average daily dose of element n through exposure pathway *m*; SF_{nm} is the cancer slope factor for element *n* (see Table 9); *TCR* is the total carcinogenic risk index for element n across all three exposure pathways; CR_n is the carcinogenic risk index for element *n* for a single exposure pathway; RFD_{nm} is the reference dose for element *n* for exposure pathway *m*; *HI* is the total non-carcinogenic risk index for element *n* across all three exposure pathways; and HQ_n is the non-carcinogenic risk index for element *n* for a single exposure pathway.

Table 10

RFD and *SF* of soil heavy metals exposed by different pathways

Heavy metal	Inhalation			Dermal contact		Ingestion	
	***RFD* (adult)**	***RFD* (child)**	***SF***	***RFD***	***SF***	***RFD***	***SF***
Cu	$1.20 \cdot 10^{-2}$	-	-	$4.00 \cdot 10^{-2}$	-	$4.00 \cdot 10^{-2}$	-
Pb	$3.52 \cdot 10^{-3}$	$1.37 \cdot 10^{-4}$	0.042	$5.25 \cdot 10^{-4}$	$1.70 \cdot 10^{-2}$	$3.50 \cdot 10^{-3}$	$8.50 \cdot 10^{-3}$
Zn	$3.00 \cdot 10^{-1}$	-	-	$6.00 \cdot 10^{-2}$	-	$3.00 \cdot 10^{-1}$	-
Cr	$2.86 \cdot 10^{-5}$	$3.91 \cdot 10^{-5}$	42	$6.00 \cdot 10^{-5}$	20	$3.00 \cdot 10^{-3}$	$5.01 \cdot 10^{-1}$
Cd	$2.40 \cdot 10^{-6}$	$3.91 \cdot 10^{-6}$	6.3	$1.00 \cdot 10^{-5}$	6.1	$1.00 \cdot 10^{-3}$	6.1

It is established that when the *HI* is less than or equal to 1, the non-carcinogenic risk is considered to be within an acceptable range. If *HI* is greater than 1, it indicates potential non-carcinogenic health risks due to exposure to specific toxic elements. As for the *TCR*, if it is less than $1.0 \cdot 10^{-6}$, it is generally considered not to pose a carcinogenic risk to humans. When *TCR* is between $1.0 \cdot 10^{-6}$ and $1.0 \cdot 10^{-4}$, the carcinogenic risk is within an acceptable range. However, if *TCR* is greater than $1.0 \cdot 10^{-4}$, the carcinogenic risk is deemed unacceptable, and it is believed to pose a significant cancer risk to humans.

Using the parameters from the aforementioned models and the data on soil heavy metal concentrations, the average daily exposure amounts for carcinogenic and non-carcinogenic risks of soil heavy metals were calculated. The results are presented in Tables 11 and 12.

Based on the health risk assessment model and exposure parameters, the daily exposure amounts to soil heavy metals in the study area were calculated for both carcinogenic and non-carcinogenic risks. The results are shown in Tables 11 and 12: For adults, the order of average daily intake for both carcinogenic and non-carcinogenic risks is ingestion (ADD_{ing}) > dermal contact (ADD_{derm}) > inhalation (ADD_{inh}). Similarly, for children, the order is ingestion (ADD_{ing}) > dermal contact (ADD_{derm}) > inhalation (ADD_{inh}). Ingestion is the primary route of exposure for both carcinogenic and non-carcinogenic risks. A comparison of exposure amounts through different pathways reveals that children have higher non-carcinogenic risk exposures through all routes compared to adults. In the case of carcinogenic risk, children's exposure through ingestion is higher than adults, while dermal contact and inhalation exposures are lower. The higher exposure levels in children compared to adults in both carcinogenic and non-carcinogenic risks can be attributed to children's physiological and behavioral characteristics. These include behaviours like hand-to-mouth actions, as well as their less developed detoxification and excretion capabilities, making children more susceptible to health threats from environmental

contaminants. And according to the survey, it was found that for both adults and children, acute or chronic exposure to heavy metals can probability cause irreversible damage to many organs and tissues of the body (gastrointestinal tract, liver, lungs, kidneys, bladder, central nervous system, reproductive system, etc.) [33].

Table 11

Average daily exposure amounts for non-carcinogenic risks of soil heavy metals in soil [mg/(kg·d)]

Item	ADD_{ing} adult	ADD_{ing} child	ADD_{inh} adult	ADD_{inh} child	ADD_{derm} adult	ADD_{derm} child	*ADD*
Cu	$1.84 \cdot 10^{-5}$	$1.18 \cdot 10^{-4}$	$1.50 \cdot 10^{-7}$	$2.50 \cdot 10^{-7}$	$9.33 \cdot 10^{-7}$	$1.45 \cdot 10^{-6}$	$1.40 \cdot 10^{-4}$
Cd	$3.16 \cdot 10^{-7}$	$2.04 \cdot 10^{-6}$	$2.58 \cdot 10^{-9}$	$4.29 \cdot 10^{-9}$	$1.60 \cdot 10^{-8}$	$2.49 \cdot 10^{-8}$	$2.40 \cdot 10^{-6}$
Pb	$2.39 \cdot 10^{-5}$	$1.54 \cdot 10^{-4}$	$1.95 \cdot 10^{-7}$	$3.24 \cdot 10^{-7}$	$1.21 \cdot 10^{-6}$	$1.88 \cdot 10^{-6}$	$1.81 \cdot 10^{-4}$
Cr	$7.68 \cdot 10^{-5}$	$4.94 \cdot 10^{-4}$	$6.26 \cdot 10^{-7}$	$1.04 \cdot 10^{-6}$	$3.90 \cdot 10^{-6}$	$6.05 \cdot 10^{-6}$	$5.83 \cdot 10^{-4}$
Zn	$6.46 \cdot 10^{-5}$	$4.16 \cdot 10^{-4}$	$5.27 \cdot 10^{-7}$	$8.77 \cdot 10^{-7}$	$3.28 \cdot 10^{-6}$	$5.09 \cdot 10^{-6}$	$4.90 \cdot 10^{-4}$
ADD	$1.84 \cdot 10^{-4}$	$1.18 \cdot 10^{-3}$	$1.50 \cdot 10^{-6}$	$2.50 \cdot 10^{-6}$	$9.33 \cdot 10^{-6}$	$1.45 \cdot 10^{-5}$	$1.40 \cdot 10^{-3}$

Table 12

Average daily exposure amounts for carcinogenic risks of soil heavy metals in soil [mg/(kg·d)]

Item	ADD_{ing} adult	ADD_{ing} child	ADD_{inh} adult	ADD_{inh} child	ADD_{derm} adult	ADD_{derm} child	*ADD*
Cu	$5.81 \cdot 10^{-6}$	$9.34 \cdot 10^{-6}$	$4.73 \cdot 10^{-8}$	$1.97 \cdot 10^{-8}$	$2.95 \cdot 10^{-7}$	$1.14 \cdot 10^{-7}$	$1.56 \cdot 10^{-5}$
Cd	$9.98 \cdot 10^{-8}$	$1.61 \cdot 10^{-7}$	$8.14 \cdot 10^{-10}$	$3.39 \cdot 10^{-10}$	$5.07 \cdot 10^{-9}$	$1.97 \cdot 10^{-9}$	$2.69 \cdot 10^{-7}$
Pb	$7.54 \cdot 10^{-6}$	$1.21 \cdot 10^{-5}$	$6.15 \cdot 10^{-8}$	$2.56 \cdot 10^{-8}$	$3.83 \cdot 10^{-7}$	$1.49 \cdot 10^{-7}$	$2.03 \cdot 10^{-5}$
Cr	$2.42 \cdot 10^{-5}$	$3.90 \cdot 10^{-5}$	$1.98 \cdot 10^{-7}$	$8.23 \cdot 10^{-8}$	$1.23 \cdot 10^{-6}$	$4.78 \cdot 10^{-7}$	$6.52 \cdot 10^{-5}$
Zn	$2.04 \cdot 10^{-5}$	$3.28 \cdot 10^{-5}$	$1.66 \cdot 10^{-7}$	$6.92 \cdot 10^{-8}$	$1.04 \cdot 10^{-6}$	$4.02 \cdot 10^{-7}$	$5.49 \cdot 10^{-5}$
ADD	$5.81 \cdot 10^{-5}$	$9.35 \cdot 10^{-5}$	$4.74 \cdot 10^{-7}$	$1.97 \cdot 10^{-7}$	$2.95 \cdot 10^{-6}$	$1.14 \cdot 10^{-6}$	$1.56 \cdot 10^{-4}$

Based on the calculated daily exposure amounts and reference doses, the health risk indices for non-carcinogenic and carcinogenic effects of the five heavy metals studied in the area were assessed. This includes calculating the individual non-carcinogenic risk indices, carcinogenic risk indices for each heavy metal, as well as the total non-carcinogenic risk index and total carcinogenic risk index. The results of these calculations are presented in Tables 13-15.

Table 13

Non-carcinogenic health risk indices of soil heavy metals

Item	HQ_{ing} adult	HQ_{ing} child	HQ_{inh} adult	HQ_{inh} child	HQ_{derm} adult	HQ_{derm} child	Cumulative
Cu	$4.60 \cdot 10^{-4}$	$2.96 \cdot 10^{-3}$	$1.25 \cdot 10^{-5}$	$2.08 \cdot 10^{-5}$	$2.33 \cdot 10^{-5}$	$3.62 \cdot 10^{-5}$	$3.51 \cdot 10^{-3}$
Cd	$3.16 \cdot 10^{-4}$	$2.04 \cdot 10^{-3}$	$1.07 \cdot 10^{-3}$	$1.10 \cdot 10^{-3}$	$1.60 \cdot 10^{-3}$	$2.49 \cdot 10^{-3}$	$8.62 \cdot 10^{-3}$
Pb	$6.82 \cdot 10^{-3}$	$4.39 \cdot 10^{-2}$	$5.53 \cdot 10^{-5}$	$2.37 \cdot 10^{-3}$	$2.31 \cdot 10^{-3}$	$3.58 \cdot 10^{-3}$	$5.91 \cdot 10^{-2}$
Cr	$2.56 \cdot 10^{-2}$	$1.65 \cdot 10^{-1}$	$2.19 \cdot 10^{-2}$	$2.67 \cdot 10^{-1}$	$6.49 \cdot 10^{-2}$	$1.01 \cdot 10^{-1}$	$6.45 \cdot 10^{-1}$
Zn	$2.15 \cdot 10^{-4}$	$1.39 \cdot 10^{-3}$	$1.76 \cdot 10^{-6}$	$2.92 \cdot 10^{-6}$	$1.09 \cdot 10^{-5}$	$1.70 \cdot 10^{-5}$	$1.63 \cdot 10^{-3}$
Cumulative	$3.34 \cdot 10^{-2}$	$2.15 \cdot 10^{-1}$	$2.30 \cdot 10^{-2}$	$2.70 \cdot 10^{-1}$	$6.89 \cdot 10^{-2}$	$1.07 \cdot 10^{-1}$	$7.17 \cdot 10^{-1}$

For adults, the order of risk is $HQ_{derm} > HQ_{ing} > HQ_{inh}$, indicating that dermal contact is the primary pathway for non-carcinogenic risk in adults. For children, the order is $HQ_{inh} > HQ_{ing} > HQ_{derm}$, with inhalation being the main source of non-carcinogenic risk. Across different exposure routes for both adults and children, the order of non-carcinogenic risk from heavy metals is Cr > Pb > Cd > Cu > Zn. The total non-carcinogenic exposure index

for all five heavy metals (Cr, Pb, Cd, Cu, Zn) is less than 1, suggesting that these metals pose a relatively small health impact through ingestion, dermal contact, and inhalation. However, the non-carcinogenic risk index for Cr is significantly higher than for the other metals, indicating a need for focused management and control of Cr and Cd pollution in the study area, especially to protect local residents, particularly children.

Table 14

Carcinogenic health risk indices of soil heavy metals

Item	CR_{ing} adult	CR_{ing} child	CR_{inh} adult	CR_{inh} child	CR_{derm} adult	CR_{derm} child
Cu	-	-	-	-	-	-
Cd	$6.09 \cdot 10^{-7}$	$9.80 \cdot 10^{-7}$	$5.13 \cdot 10^{-9}$	$2.14 \cdot 10^{-9}$	$3.09 \cdot 10^{-8}$	$1.20 \cdot 10^{-8}$
Pb	$6.41 \cdot 10^{-8}$	$1.03 \cdot 10^{-7}$	$2.58 \cdot 10^{-9}$	$1.08 \cdot 10–^{9}$	$6.51 \cdot 10^{-9}$	$2.53 \cdot 10^{-9}$
Cr	$1.21 \cdot 10^{-5}$	$1.95 \cdot 10^{-5}$	$8.30 \cdot 10^{-6}$	$3.46 \cdot 10^{-6}$	$2.46 \cdot 10^{-5}$	$9.55 \cdot 10^{-6}$
Zn	-	-	-	-	-	-
Cumulative	$1.28 \cdot 10^{-5}$	$2.06 \cdot 10^{-5}$	$8.31 \cdot 10^{-6}$	$3.46 \cdot 10^{-6}$	$2.46 \cdot 10^{-5}$	$9.57 \cdot 10^{-6}$

Table 15

Total non-carcinogenic and carcinogenic health risk indices of soil heavy metals

Item	*HI*-adult	*HI*-child	Cumulative	*TCR*-adult	*TCR*-child	Cumulative
Cu	$4.95 \cdot 10^{-4}$	$2.99 \cdot 10^{-3}$	$3.49 \cdot 10^{-3}$	-	-	-
Cd	$2.99 \cdot 10^{-3}$	$5.62 \cdot 10^{-3}$	$8.62 \cdot 10^{-3}$	$6.45 \cdot 10^{-7}$	$9.94 \cdot 10^{-7}$	$1.64 \cdot 10^{-6}$
Pb	$9.19 \cdot 10^{-3}$	$4.99 \cdot 10^{-2}$	$5.91 \cdot 10^{-2}$	$7.32 \cdot 10^{-8}$	$1.06 \cdot 10^{-7}$	$1.80 \cdot 10^{-7}$
Cr	$1.12 \cdot 10^{-1}$	$5.32 \cdot 10^{-1}$	$6.45 \cdot 10^{-1}$	$4.50 \cdot 10^{-5}$	$3.25 \cdot 10^{-5}$	$7.76 \cdot 10^{-5}$
Zn	$2.28 \cdot 10^{-4}$	$1.40 \cdot 10^{-3}$	$1.63 \cdot 10^{-3}$	-	-	-

The carcinogenic health risk index shows: For adults, the risk order by different exposure pathways is $CR_{derm} > CR_{ing} > CR_{inh}$, suggesting that dermal contact is the main pathway for carcinogenic risk. For children, the order is $CR_{ing} > CR_{derm} > CR_{inh}$, indicating ingestion as the primary pathway for carcinogenic risk. The contribution to carcinogenic risk from heavy metals in the study area, for both adults and children, is in the order of Cr > Cd > Pb. The CR_{ing} values for Cr for adults and children are $1.21 \cdot 10^{-5}$ and $1.95 \cdot 10^{-5,}$ respectively. The average values of CR_{inh} are $8.30 \cdot 10^{-6}$ for adults and $3.46 \cdot 10^{-6}$ for children, while CR_{derm} averages are $2.46 \cdot 10^{-5}$ for adults and $9.55 \cdot 10^{-6}$ for children. This means that ingestion of Cr poses a carcinogenic risk within an acceptable range for human health, while inhalation and dermal contact do not pose a carcinogenic risk. The risk indices for Cd and Pb through all three pathways are less than 10^{-6}, indicating that the levels of Cd and Pb in the study area do not pose a carcinogenic risk to humans. Based on the *TCR* and the above analysis, it is evident that soil Cr in the study area presents a potential carcinogenic risk to human health, but the risk is relatively low and within acceptable limits.

Discussion

Soil heavy metal contamination is one of the primary issues currently faced in environmental and soil science fields, with urban areas, soils adjacent to highways, and industrial zones being high-risk zones for heavy metal pollution. Previous research results on soil heavy metal contamination of Zhengzhou highway/expressway roadside, Pb, Cd, Hg, Zn and as the main object of contamination, Cd has the highest potential level of contamination, the results of this paper show that the peak of the contamination indicators

of Cd in the study area has reached the degree of extremely heavy pollution, and the results of previous work on the level of Cd contamination, and the conclusions of the study of several other elements are different. According to the results of the existing research is presumed to be due to the element Cd content by the activities of personnel, and highway roadside Cd main source of automobile parts wear and tear, corrosion, the formation of a large base, so the cumulative content is high.

This study analysed the content, spatial distribution, and migration trends of soil heavy metals in the study area. The findings indicate that the content of Cd in the soil of the study area is significantly higher than the environmental background values, showing enrichment near the highways. The content of Cr is close to background levels, while Pb, Cu, and Zn are all below background values. Their spatial distribution characteristics vary, with the content of Cu and Cd decreasing with increasing distance from the road base, while the content of Cr, Pb, and Zn shows a negative correlation with the distance from the road base. The study also examined the distribution trends of these five heavy metals with different protective forest layers, showing an overall trend of No protective forest > Single-layer protective forest > Double-layer protective forest > Triple-layer protective forest.

Currently, it is known that the main non-carcinogenic exposure pathways of soil heavy metals are dermal contact and respiratory inhalation. Based on the experimental results in the study area, it is shown that the indices of carcinogenicity and non-carcinogenicity factors of Cr in the study area are much larger than those of other elements, and the highest carcinogenicity and health risk index for children is CR_{ing}, then the children are exposed mainly to indicating ingestion; and the highest carcinogenicity and health risk index for adults is *CRderm*, then the source of carcinogenicity risk for adults route is mainly dermal contact. From the data, the total noncarcinogenic factor index HI-child and the total carcinogenic risk index TCR-child for children were $5.32 \cdot 10^{-1}$ and $3.25 \cdot 10^{-5}$, respectively, and the total noncarcinogenic factor index HI-adult and the total carcinogenic risk index *TCR*-adult for adults were $1.12 \cdot 10^{-1}$ and $4.50 \cdot 10^{-5}$, the overall health risk to which children are exposed is greater than that of adults, and the Cr carcinogenic risk index for both children and adults in the study area exceeds the risk threshold of 10^{-6}, which poses a mild carcinogenic risk to humans within acceptable limits, However, from the perspective of soil environment and health, however, we need to be vigilant about the soil environment management in the research area.

Conclusion

(1) The analysis of the distribution characteristics of soil heavy metals behind protective forests shows that, with the increase in the layers of protective belts and at the same distance from the road base, the content of the same heavy metal in soils under multi-layer protective belts is significantly lower than that in soils with a single-layer protective belt or no green belt. In this experiment, the triple-layer green belt consisting of mixed tree species was most effective in preventing soil heavy metal pollution, significantly reducing highway Cu, Cd, Cr, Zn, and Pb contamination. The protective effect of mixed-species green belts, arranged from low to high height facing the road and consisting of evergreen species, is hypothesised to be related to the blocking and absorption by tree trunks and foliage, as well as the width of the green belt. Mixed-species plantings generally provide better heavy metal protection than single-species plantings, but the optimal combination of species for protective belts

requires further exploration. The results of this study show that planting green belts along highways and increasing the thickness of the green belts or enriching the tree species that make up the green belts can, to a certain extent, prevent the migration of heavy metals to agricultural fields and residential areas behind the green belts. Regarding the correlation of heavy metals, no strong correlation was observed among the five heavy metal elements Cu, Cd, Pb, Cr, and Zn; however, Cd and Cu showed a significant synergistic effect.

(2) The Geo-accumulation index evaluation results indicate that Cd pollution is the most prominent in the study area, presenting a light to moderate pollution level. Cu, Pb, Cr, and Zn show no pollution. The Nemerow index suggests that the potential ecological risk of heavy metals in the soil of the study area mainly ranges from moderate to extremely high risk, with Cd being the primary contributor to ecological risk. The Nemerow comprehensive evaluation indices for Pb and Cr are at a warning level. Cu and Zn in the study area are in a clean state.

(3) The human health risk assessment results show that children are more susceptible to heavy metal threats. The primary source of carcinogenic risk for children is oral intake, while non-carcinogenic risk mainly comes from inhalation. For adults, dermal contact is the main exposure pathway for both non-carcinogenic and carcinogenic risks of heavy metals. The total non-carcinogenic exposure indices for all five heavy metals (Cr, Pb, Cd, Cu, Zn) are less than 1, indicating a relatively low non-carcinogenic health risk to humans. However, some soil samples with Cr pose a potential non-carcinogenic health risk, and some samples with Cd pose a potential carcinogenic risk. The total carcinogenic risk index for Cr is greater than 10^{-6}, within an acceptable range, but due to its higher toxicity and higher total carcinogenic risk index compared to other heavy metals in the study area, monitoring and control of Cr should be emphasised.

(4) From the results of the above analysis, it can be seen that the contamination of heavy metals along the highway roadside studied in this paper is mainly concentrated in the areas of residential activities as well as soil heavy metal contamination of agricultural land, which may enter the human body through the air, drinking water, and edible plants, and thus potentially harm the human body. The focus of this study is mainly on the distribution pattern of heavy metals in soil in the sampling area, the ecological pollution risk situation and the health risk. Based on the conclusions of this study, the behaviour of heavy metals in different soil types, the differences in the uptake of heavy metals by different vegetation types, and the reasons for the enrichment of different heavy metal elements can be investigated in depth in the future.

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