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Assessment of Heavy Metal Contamination and Ecological Risk in Soil within the Zheng–Bian–Luo Urban Agglomeration

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Abstract: As urbanization accelerates, the contamination of urban soil and the consequent health implications stemming from urban expansion are increasingly salient. In recent years, a plethora of cities and regions nationwide have embarked on rigorous soil geological surveys with a focus on environmental quality, yielding invaluable foundational data. This research aims to develop scientifically robust and rational land-use planning strategies while assessing the levels of heavy metal pollution and associated risks. The urban agglomeration encompassing Zhengzhou, Luoyang, and Kaifeng (referred to as Zheng–Bian–Luo Urban Agglomeration) in Henan Province was designated as the study area. Leveraging the Nemerow comprehensive index method alongside the Hakanson potential ecological risk assessment method, this study delved into the pollution levels and potential ecological ramifications of nine heavy metals, namely Cr, Mn, Ni, Cu, Zn, As, Cd, Pb, and Co. Research indicates that the hierarchy of individual potential ecological risks ranges from most to least significant as follows: Cd > Pb > Cr > Ni > Cu > Zn > As > Mn > Co. The concentrations of Cd in both Zhengzhou and Kaifeng surpassed the established background levels. Furthermore, the mean single-factor pollution index values for the heavy metals Cd and Zn exceeded 1, signifying a state of minor pollution. The Nemerow comprehensive index P of Cd and Zn is between $1 < P_{comp} \leq 2$, which is considered mild pollution. The comprehensive P values of the other seven metal elements are all less than 0.7, reaching a clean (alert) level. Predominantly, the primary potential risk factor in the superficial soil of the Zheng–Bian–Luo urban agglomeration is Cd, while the ecological risk implications associated with other heavy metal elements are comparatively minimal. The soil environmental quality within the designated study area remains secure, although certain localized areas pose potential risks of heavy metal pollution. A comprehensive assessment of the current state of soil heavy metal pollution is essential to establish a theoretical foundation and provide technical support for soil environmental protection, pollution mitigation, and sustainable utilization.

Keywords: heavy metals; pollution levels; risk assessment; Zheng–Bian–Luo urban agglomeration

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Citation: Chen, X.; Zhang, H.; Wong, C.U.I.; Li, F.; Xie, S. Assessment of Heavy Metal Contamination and Ecological Risk in Soil within the Zheng–Bian–Luo Urban Agglomeration. *Processes* **2024**, *12*, 996. https://doi.org/10.3390/pr12050996

Academic Editor: Aldo Muntoni

Received: 14 April 2024
Revised: 7 May 2024
Accepted: 11 May 2024
Published: 14 May 2024

1. Introduction

With the advancement of economic development and the escalation of population growth, the intensity of land use has significantly increased. Emissions from vehicular exhausts, industrial waste gases, agricultural practices, industrial mining operations, and the irrigation of crops with industrial wastewater have collectively contributed to the accumulation of heavy metals in the soil [1,2]. Urban soil, profoundly influenced by anthropogenic activities, constitutes an integral component of the ecosystem. It serves not only as a repository for pollutants but also as a potential source of contamination. Throughout the process of urbanization, relentless and recurrent human interventions have subjected urban soil to significant disturbances, culminating in pronounced environmental pollution challenges [3–5]. The ramifications of this trend are undeniable, surpassing the inherent resilience of soil ecosystems and posing significant socio-ecological challenges.

The progression has intensified the pressure on atmospheric and aquatic resources, exerting a significant impact on the health and quality of life of city dwellers [6–8]. Moreover, because of widespread and complex human interventions in urban soils, their ecological functions and biodiversity encounter significant challenges. These pressures could lead to irreversible ecological catastrophes over time. Therefore, proactive measures are essential to improve the quality of urban soil and reduce the pollution burdens it faces. This is essential not only to ensure the sustainable progression of urbanization but also to cultivate a more resilient and habitable urban environment for forthcoming generations.

The "National Soil Pollution Situation Survey Bulletin" unveiled in April 2023 reveals that the current exceedance rate of soil pollutant thresholds in Chinese urban areas stands at 16.1%. The predominant pollutants encompass a range of metal elements, notably Cd, Ni, As, Cu, Hg, Pb, among others [9,10]. As heavy metal elements infiltrate the soil, remediation efforts become more complex and challenging. These metals persist within the soil matrix, severely impairing both its physical and chemical properties. Furthermore, they inflict significant harm on soil enzyme and microbial activities. Such toxic contamination markedly undermines soil productivity. The most concerning aspect of heavy metal pollution lies in its latent and enduring nature [11–13]. The escalating severity of heavy metal pollution in soil poses threatens not only the ecological environment but also affects organisms across the food chain, thereby leading to potential risks to human health. Therefore, it is crucial to obtain a comprehensive understanding of the content and distribution of heavy metals in the soil [14,15]. Although China's exploration into heavy metals in urban soil commenced relatively recently, contemporary scholars have diligently investigated the content, distribution, and sources of soil heavy metal pollution in numerous large- and medium-sized cities, including Haikou, Beijing, Nanjing, and Shanghai [16–23]. The single factor index method was employed to assess the heavy metal pollution of the soil near the river, revealing severe pollution in the area, particularly from Cd [24]. An investigation into eight heavy metals within Beijing's urban green spaces revealed that Cd, Cu, Zn, and Ni are markedly influenced by anthropogenic activities. Pollution assessment outcomes indicate that, while Beijing's green spaces are predominantly clean, there exist minor potential ecological risks [25]. Utilizing Pb isotopes and multivariate statistical analyses to investigate the origins of heavy metals in the alluvial plain soil of the Pearl River Delta, the study determined that Pb primarily originates from gasoline combustion emissions. Furthermore, the sources of As, Cd, Hg, and Pb predominantly stem from coal combustion and the lead-zinc industry [26].

With global attention turning towards the soil environment, the presence of heavy metals in urban soil has become a central focus of research for both domestic and international scholars. Presently, numerous studies delve into the content, distribution, and sources of heavy metals in the soils of major urban centers such as Shanghai, Beijing, and Nanjing. However, research on smaller urban agglomerations is relatively limited. Positioned as the core of the rapidly growing regional economy within the Central Plains Economic Zone, the Zheng–Bian–Luo urban agglomeration has witnessed significant urban expansion and an increase in townships. Concurrently, this growth has intensified significant urban security challenges.

In recent years, Henan has undergone rapid urbanization, leading to the establishment of an industrial economic framework centered around sectors including medicine, textiles, chemicals, machinery, electronics, food, light industry, and building materials. Consequently, urban surface soils have been subjected to the discernible anthropogenic pollution. Notably, certain heavy metal elements, including Cd, Hg, Zn, and Cr, have manifested contamination [27,28]. The escalation of industrial development and urbanization within the Zheng–Bian–Luo urban agglomeration has amplified the influence of urban soil on both residents' living environments and human health [29,30]. Consequently, there is a pressing need to undertake pollution assessments and potential ecological hazard evaluations of heavy metals in the surface soil of the Zheng–Bian–Luo urban agglomeration. These efforts are crucial for improving the ecological environment of the soil in this urban conglomeration, carefully planning urban soil usage, establishing a resilient urban ecosystem, and safeguarding residents' health. This research provides essential foundational data and a scientific framework. Given these imperatives, investigating the sources, geochemical migration patterns, and the ecological impacts of heavy metals in urban soils is of paramount practical significance.

With the ongoing integration of the Zheng–Bian–Luo urban agglomeration, the regional urban ecological environment is facing escalating pressures, particularly from heavy metal pollution. Recent investigations indicate that specific zones within the Zheng–Bian–Luo urban agglomeration, encompassing soil, sediment, water, and near-surface dust, exhibit varying degrees of contamination by heavy metal elements such as Cd, Cu, Pb, and Zn. However, there is still a noticeable gap in comprehensive studies regarding the distribution characteristics of heavy metals across various functional zones—such as industrial, agricultural, and residential areas—in this region.

To address this research gap, the present study examines the soil of the Zheng–Bian–Luo urban agglomeration. We performed an in-depth analysis of the contents of Cd, Cr, Cu, Ni, Pb, and Zn, and further clarified the distribution characteristics of these heavy metals across various functional zones. Our objective is to establish a scientific foundation for the planning and development of the Central Plains urban agglomeration, with a particular emphasis on early warning systems for environmental pollution.

2. Materials and Methods

2.1. Study Area Overview

The Zheng–Bian–Luo urban agglomeration includes the three cities of Zhengzhou, Kaifeng, and Luoyang in Henan Province. Acting as the nucleus of Central Plains culture, it is also a key point within the "three points and one line" tourism corridor along the Yellow River in Henan Province (Figure 1). Geographically situated between 112°42′ and 114°14′ east longitude and between 34°16′ and 34°58′ north latitude, the region experiences a warm temperate continental-monsoon climate. It has an annual temperature of 14.3 °C and an annual rainfall of 640 mm [31,32].

The Zheng–Bian–Luo urban agglomeration strategically occupies a position in the Central Plains region, intersecting both the Beijing–Guangzhou Railway and the Longhai Railway. It acts as a crucial link connecting the Central Plains Economic Zone to the Yangtze River Delta Economic Zone. Situated in eastern China's heartland, this region is adjacent to the plains of the middle and lower reaches of the Yellow River, enjoying an advantageous location and superior transportation infrastructure. Since the advent of economic reforms and opening-up policies, the Zheng–Bian–Luo region has expedited its industrialization and urbanization processes, capitalizing on its advantageous geographical position. Currently, the "two cities and one prefecture" consisting of Zhengzhou, Kaifeng, and Luoyang have merged to form the central urban hub within the Central Plains region [33–35].

The Zheng–Bian–Luo urban agglomeration is located in the middle and lower reaches of the Yellow River Basin, characterized by intricate geological formations. Over the past two decades, the rapid industrialization and urbanization of the Zheng–Bian–Luo urban agglomeration have led to extensive industrial developments, exerting substantial environmental pressures on the region [36–39]. Situated in the "Central Plains", the Zheng–Bian–Luo conurbation hosts numerous metal mineral processing enterprises. Consequently, the sources of heavy metal contamination in its soil may differ from those observed in comparable urban areas domestically and internationally, that have been studied similarly.

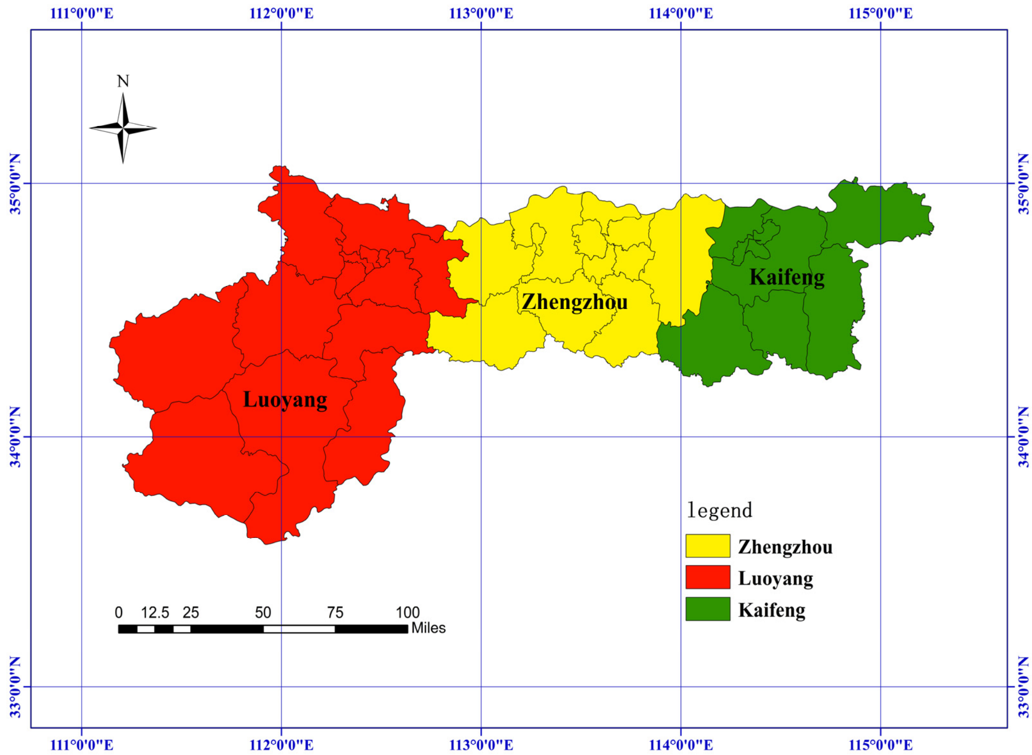

Figure 1. Geographic location map of Zheng–Bian–Luo urban agglomeration. (The illustration was crafted utilizing ArcGIS software, version 10.2. For further reference, the URL link is provided: https://www.arcgis.com/index.html, accessed on 1 March 2024).

2.2. Selection and Processing of Sampling Points

The research areas selected encompass Zhengzhou City, Luoyang City, and Kaifeng City, constituting the prominent "Three Points and One Line" tourist hub along the Yellow River in Henan Province. Based on land use classifications, these regions were demarcated into industrial zones, agricultural belts (adjacent to industrial zones), and residential precincts (encompassing urban green spaces).

The strategic placement of sampling points primarily adhered to two guiding principles: (1) variation in land use categories; and (2) sampling feasibility and convenience.

Taking into full consideration the relationship between rainfall and sampling depth, the annual rainfall in the area amounts to 640 mm. To avoid the direct impact of the physical and chemical properties of the surface soil on the surface runoff and pollutants caused by rainfall, the soil sampling points in the Zheng–Kai–Luo urban agglomeration were chosen to sample the 0–30 cm surface soil. In 2023, surface soil samples (0–30 cm depth) were meticulously procured from diverse functional zones across the aforementioned cities, culminating in a total of 300 samples. The distribution of these sampling points is as follows: Zhengzhou (100 sample points), Luoyang (100 sample points), and Kaifeng (100 sample points) (Figure 2). Each sampling point is uniquely numbered, ranging from 1 to 300.

2.3. Sample Processing

From March to July 2023, we meticulously collected soil samples using the plum blossom pile fixed-point technique. At each designated sampling point, three samples were procured from the surface soil layer spanning from 0 to 30 cm and subsequently blended to achieve homogeneity. Each collection yielded approximately 500 g of soil, meticulously stored in light-resistant plastic ziplock pouches to maintain the samples' integrity during preservation.

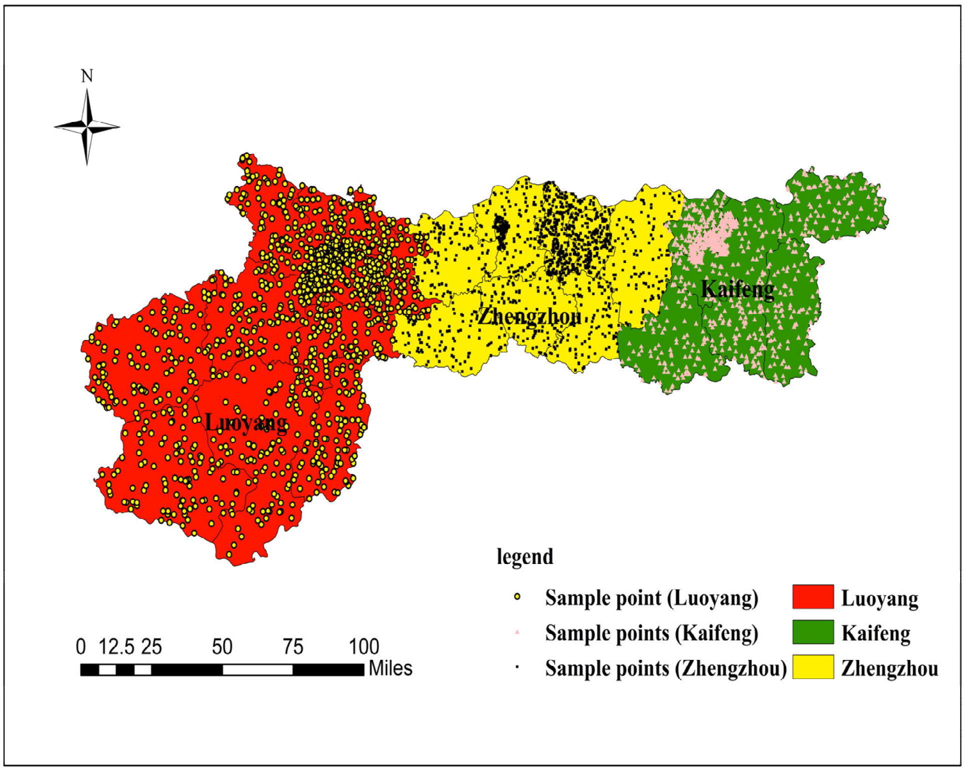

Figure 2. Spatial Distribution Map of Soil Sampling Sites in the Zheng–Bian–Luo Urban Agglomeration. (The illustration was crafted utilizing ArcGIS software, version 10.2. For further reference, the URL link is provided: https://www.arcgis.com/index.html, accessed on 1 March 2024).

After collection, the soil samples were transported to the laboratory and naturally dried in a shaded, cool environment. Subsequently, they were stored in a refrigerator maintained at 4 °C, protected from light exposure. Prior to analysis, the samples were ground using a mortar, filtered through a 0.15 mm mesh, placed in ziplock bags, and stored at −20 °C.

The concentrations of heavy metals in the soil samples were determined using the digestion combined with inductively coupled plasma-optical emission spectrometry (ICP-OES) methodology. In order to evaluate the effectiveness and accuracy of the sample digestion method, the author conducted a recovery rate test. By comparing the difference between the measured value and the certified value, the efficiency and reliability of the digestion method can be evaluated.

The digestion procedure is delineated as follows:

(1) Utilize a precision balance calibrated to one-ten-thousandth of a gram to weigh (0.1000 ± 0.0005) g of sediment sample, transferring it to a 25 mL digestion vessel made of polytetrafluoroethylene;
(2) In an acid-resistant fume hood, add 6 mL of nitric acid, 3 mL of hydrochloric acid, and 2 mL of hydrofluoric acid to the vessel. Allow the mixture to stand for 24 h to ensure the thorough mixing of the sample with these reagents;
(3) Execute the digestion process in accordance with the temperature ramping protocol detailed in Table 1, and subsequently allow the solution to cool upon the completion of the program;
(4) Once the temperature inside the digestion vessel has returned to ambient levels, pour all remaining substances into a 25 mL volumetric flask filled with distilled water. Rinse the digestion vessel and its lid with a small amount of distilled water, and then add these rinses to the volumetric flask. Fill the flask to the 25 mL mark with distilled water, allow it to stand for one hour, decant the supernatant, and proceed with measurements using ICP-OES.

ICP-OES analysis was used for the quantification of nine heavy metals in the samples, namely Cr, Mn, Ni, Cu, Zn, As, Cd, Pb, and Co.

Table 1. Digestion heating protocol.

Heating Duration/Minutes	Digestion Temperature/°C	Hold Time/Minutes
5	room temperature → 120	5
5	120 → 150	5
5	150 → 180	20

Note: The symbol "→" signifies the heating phase.

When performing ICP-OES (inductively coupled plasma–atomic emission spectrometry) analysis, the calculation of the limit of detection (LOD) and the limit of quantification (LOQ) is crucial to evaluate the sensitivity and suitability of the analytical method. And under the selected working conditions, the 2% nitric acid blank solution was measured 10 times in parallel according to the test method, and 3 times the standard deviation of the 10 measurement results was taken as the detection limit of each element. It can be seen that the detection limit of each element is 0.000214~5.578 μg/L, and the quantification limit is 0.000714~18.593 μg/L.

2.4. Research Methodology

2.4.1. Nemerow Comprehensive Index Methodology

The approach is based on the single-factor index methodology, but it has been refined to overcome its inherent limitation of only being applicable to areas contaminated by a single contaminant. Through the utilization of a single-factor pollution index, we can comprehensively assess the cumulative pollution magnitude of multiple contaminants in soil, enabling a detailed analysis of the multifaceted influence exerted by various pollutants on soil quality [40,41]. The mathematical expression for this integrated assessment is articulated as follows:

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

$$P_{\text{comp}} = \frac{\sqrt{(C_i/S_i)^2_{\max} + (C_i/S_i)^2_{ave}}}{2} \tag{2}$$

Within the formula: P_i represents the pollution value attributable to pollutant i; C_i represents the concentration of pollutant i; S_i represents the background level of pollutant i in the soil; $(C_i/S_i)_{max}$ stands for the peak single-factor pollution value; $(C_i/S_i)_{ave}$ corresponds to the average single-factor pollution value in the soil. The assessment criteria for are both shown in Tables 2 and 3.

Table 2. Criteria for single-factor index evaluation.

Rank	Single Factor Index	Pollution Level
I	$P_i \leq 1$	No pollution
II	$1 < P_i \leq 2$	slight pollution
III	$2 < P_i \leq 3$	light pollution
IV	$3 < P_i \leq 5$	Moderately polluted
V	$P_i > 5$	Heavy pollution

Table 3. Nemerow comprehensive index evaluation criteria.

Rank	Nemerow Comprehensive Index	Grade of Land Environmental Quality
I	$P_{comp} \leq 0.7$	Clean (Safe)
II	$0.7 < P_{comp} \leq 1$	Still clean (alert)
III	$1 < P_{comp} \leq 2$	light pollution
IV	$2 < P_{comp} \leq 3$	Moderately polluted
V	$P_{comp} > 3$	heavy pollution

2.4.2. Hakanson Potential Ecological Risk Assessment Methodology

The Hakanson methodology offers an efficient and effective approach for assessing the potential ecological consequences of heavy metal contamination in soil. Esteemed for its efficacy, this method finds extensive application in the realms of soil environmental quality assessment and research on soil pollution mitigation [42–44]. The formal expression for this methodology is articulated as follows:

$$RI = \sum_{i=1}^{n} E_f^i \tag{3}$$

$$E_f^i = T_f^i \times C_f^i \tag{4}$$

Within this framework, the subsequent evaluation metrics are encompassed:

$$C_f^i = C_d^i / C_n^i \tag{5}$$

$$C_H = \sum_{i=1}^{n} C_f^i \tag{6}$$

Let E_i^f denote the potential risk index associated with an individual metal; C_d^i represents the concentration of pollutant i in the soil; C_n^i signify the reference value for pollutant i in pollution assessment; C_H stand for the heavy metal pollution index; C_f^i indicates the index for pollution by a single metal; and T_f^i reflects the coefficient for the biotoxic response to various metals. The indices and corresponding degrees of harm are delineated in Table 4.

Table 4. Index of potential risk and classification of hazard degree.

Degree of Hazard	T_f^i	C_H	RI
Minor ecological risk	≤40	≤5	≤150
Moderate ecological risk	40–80	5–10	150–300
Significant ecological risk	80–160	10–20	300–600
High ecological risk	160–320	≥20	≥600
Severe ecological risk	≥320		

2.5. Data Processing and Analysis

The data were subjected to statistical analysis utilizing Excel 2019 and Origin 9.1, while spatial data and sampling points were visualized using ArcGIS 10.2.

3. Results and Analysis

3.1. Assessment of Soil Metal Content in the Zheng–Bian–Luo Urban Agglomeration

The findings regarding the heavy metal content across all samples are outlined in Table 5. Among soils sourced from diverse cities, only in Luoyang did the average arsenic (As) content surpass the background level [45,46], registering at 0.2 mg/kg. In Zhengzhou, especially in densely populated zones, concentrations of cadmium (Cd), copper (Cu), nickel (Ni), and zinc (Zn) surpassed the established background values. However, at other sampling sites, the heavy metal levels remained below the background thresholds [47,48]. In Kaifeng, the mean concentrations of Cd, chromium (Cr), Cu, and Zn all exceeded the background values [49]. Given the agricultural focus of this study, we employed risk screening values specific to agricultural soil pollution to evaluate the soil quality. The data revealed that the average Cd concentrations in Zhengzhou and Kaifeng exceeded the background levels by 1.77-fold and 10.37-fold, respectively. In conclusion, the Cd contamination in the soils across these cities is a matter of significant concern.

Table 5. Heavy metal concentrations in the soil of the Zheng–Bian–Luo urban agglomeration.

Area	Style	As	Cd	Co	Cr	Cu	Mn	Ni	Pb	Zn
Zhengzhou	Max	6.05	3.50	11.84	62.80	57.54	559.20	39.51	18.03	212.40
	Min	0.99	0.10	0.59	57.75	10.37	176.20	12.62	5.07	40.33
	Avg	2.79	0.11	3.65	60.27	25.34	373.40	24.63	14.64	106.80
Luoyang	Max	12.30	0.45	3.13	48.84	14.17	277	13.80	29.60	65.30
	Min	6.07	0.10	0.23	48.84	8.75	102	9.60	4.70	32.10
	Avg	9.20	0.24	1.68	48.84	10.07	166.70	11.08	14.90	43.70
Kaifeng	Max	10.90	5.79	4.22	96.30	118.3	731.60	26.02	124.50	750.00
	Min	2.60	1.40	2.15	38.40	25.90	310.80	17.11	15.20	150.30
	Avg	6.67	3.41	2.96	70.60	55.10	451.20	21.45	46.90	364.40
Agricultural land soil screening value		40	0.30	-	150	50	-	60	70	200
Soil background value		9	1.10	-	65	39	583	25	51	172

3.2. Correlation Assessment of Soil Heavy Metals in the Zheng–Bian–Luo Urban Agglomeration

Heavy metals in soil mainly originate from a variety of sources, including soil parent materials, agricultural practices, atmospheric deposition, and industrial emissions [50,51].

There is a potential correlation among heavy metals originating from the same sources. To ascertain the similarity in sources of these heavy metals, we conducted an analysis by calculating the correlation coefficients between them. The Spearman correlation analysis method was used to analyze the heavy metals in the soil of the Zheng–Kai-Luo urban agglomeration (Table 6). A high correlation coefficient suggests a common origin for these elements or the occurrence of composite pollution phenomena, whereas a low correlation coefficient implies a more intricate array of sources for these elements [52].

Table 6. Correlation assessment of heavy metals in the soil of the Zheng–Bian–Luo urban agglomeration.

Heavy Metal	As	Cd	Cr	Cu	Zn	Pb	Mn	Ni	Co
As	1								
Cd	0.03	1							
Cr	0.63 **	0.03	1						
Cu	0.45 **	0.2	0.62 **	1					
Zn	0.15	0.24	−0.12	0.15	0.28	1			
Pb	0.09	0.89 **	0.10 **	0.21	0.21	0.19 **	1		
Mn	0.25	0.06	0.13	0.35	0.26	0.06	0.13	1	
Ni	0.15	0.34	0.04	0.18	0.25	0.03	0.23	0.15	1
Co	0.03	0.21	0.16	0.05	0.17	0.04	0.28	0.33	0.27

Note: '**' denotes an extremely significant correlation at the 0.01 level, while '*' represents a significant correlation at the 0.05 level.

The assessment results of correlation coefficients for heavy metals in the soil of the Zheng–Bian–Luo urban agglomeration have been consolidated in Table 6. Within our study sample, lead (Pb) and cadmium (Cd) exhibited a pronounced correlation, registering a coefficient of 0.89. This suggests, at a significance level of 0.01, a shared source of contamination for these two elements. Furthermore, chromium (Cr) demonstrated a correlation of 0.63 with arsenic (As), copper (Cu) displayed a correlation of 0.45 with As, and the correlation between Cu and Cr stood at 0.62. These findings suggest a potential commonality in the pollution sources for these elements. Conversely, no significant correlations were observed between Cr and Cd, Cu and Cd, or As and Cd, indicating substantial disparities in their respective pollution sources.

3.3. Assessment and Analysis of Heavy Metal Pollution in the Soil of the Zheng–Bian–Lu Urban Agglomeration

The calculation results of both the single-factor index and the Nemerow comprehensive index for heavy metals in the soil of the Zheng–Bian–Luo urban agglomeration were recorded in Table 7. Upon scrutinizing the data, it is evident that the average single-factor pollution indices for Cd and Zn surpass a value of 1, suggesting a slight contamination by these two heavy metals. In contrast, the average index for Cu hovers near unity, specifically at 0.92. In terms of pollution severity, the average indices for Cd and Zn indicate mild pollution according to Level II criteria.

Table 7. Assessment index for heavy metal pollution in soil.

Area	Style	As	Cd	Co	Cr	Cu	Mn	Ni	Pb	Zn
Single-factor index	Max	0.46	0.87	0.78	0.69	0.69	0.41	0.26	0.16	0.39
	Min	1.35	1.84	1.51	1.23	1.85	1.74	1.33	0.76	0.75
	Avg	0.68	1.26	0.54	0.92	1.09	0.73	0.42	0.31	0.46
Nemerow composite index	P_{comp}	0.63	1.21	0.79	0.69	1.01	0.66	0.33	0.26	0.63
	Soil environmental quality classification	Clean (safe)	Light pollution	Still clean (alert)	Still clean (alert)	Light pollution	Clean (safe)	Clean (safe)	Clean (safe)	Clean (safe)

Additionally, upon computing the Nemerow comprehensive index, denoted by P comprehensive, it was observed that the P comprehensive values for Cd and Zn fell within the range of $1 < P_{comp} \leq 2$. This suggests a mild degree of pollution for these particular heavy metals. Conversely, the P values for the remaining seven metal elements all registered below 0.7, signifying a relatively clean or cautionary status.

3.4. Potential Ecological Risks of Heavy Metals in the Soil of Zheng–Bian–Luo Urban Agglomeration

According to the potential ecological risk index used for evaluating heavy metal contamination in surface soil (Table 8), the hierarchy of individual ecological risks, ranked in descending order, are as follows: Cd > Pb > Cr > Ni > Cu > Zn > As > Mn > Co. Across all sampling sites, the ecological risk index values for Pb, Cr, Ni, Cu, Zn, As, Mn, and Co are below 40, indicating minimal ecological risks. In particular, the ecological risk index for Cd ranges from 34.62 to 196.73, with 83.6% of the sampled sites exhibiting moderate ecological risks, while only a minority show severe risks.

Table 8. Potential ecological risk index for soil heavy metals.

Style	E_i^f									RI
	As	Cd	Cr	Cu	Zn	Pb	Mn	Ni	Co	
Max	0.81	34.62	4.747	2.01	1.09	5.38	0.43	3.67	0.34	50.79
Min	1.72	196.73	6.22	5.71	3.21	12.06	0.72	5.11	0.72	213.60
Avg	0.12	12.14	3.07	1.07	0.57	3.42	0.18	2.21	0.14	20.63
Mean risk level	Slight ecological risk	Slight ecological risk	Slight ecological risk	Slight ecological risk	Slight ecological risk	Slight ecological risk	Slight ecological risk	Slight ecological risk	Slight ecological risk	Slight ecological risk

The comprehensive potential ecological risk index (RI) spans from 20.63 to 213.60, mainly reflecting minor ecological risks that make up 98.4% of the total. These findings elucidate that cadmium (Cd) stands as the predominant risk factor in the surface soil of the Zheng–Bian–Luo urban agglomeration. In contrast, the ecological impacts of other heavy metal elements seem comparatively negligible. Collectively, the overall ecological risk within this region is assessed as moderate, albeit predominantly mild.

The bio-toxicity response coefficient of metals is a crucial metric used to evaluate the harmful effects of metals on various organisms, including humans, animals, and plants [53–55]. This coefficient primarily elucidates the correlation between the toxicological effects induced by specific metals and their concentrations. Leveraging this coefficient allows us to systematically quantify the potential health risks associated with exposure to these metals.

The biological toxicity response coefficients and associated potential hazard levels for various metals examined in this study are meticulously detailed in Table 9. Analysis of the data reveals that the toxicity response coefficients for the nine metallic elements listed therein all register below 40. Such findings signify that these metals can exert toxicological effects on organisms even at comparatively low concentrations, thereby suggesting a minimal ecological risk associated with their presence.

Table 9. Biotoxicity response coefficients of various metals.

Heavy Metal	As	Cd	Cr	Cu	Zn	Pb	Mn	Ni	Co	Degree
T_f^i	5	30	5	5	20	20	2	20	1	Slight ecological risk

This observation suggests that potential health hazards for humans or other organisms in everyday life or occupational settings may only become apparent when metal concentrations reach elevated levels [56–58]. Nonetheless, it remains imperative to acknowledge that even when the toxicity response coefficient falls below 40, metal exposure can still elicit detrimental effects on particularly vulnerable populations or ecosystems. Consequently, despite the reduced toxicity exhibited by these metals, a comprehensive risk assessment and management strategy is indispensable to safeguard both organisms and the environment.

4. Discussion

Upon examining the levels of heavy metals in the soil of the Zheng–Bian–Luo urban agglomeration, our findings indicate predominantly favorable soil quality within the study area. In isolated locations exhibiting moderate-to-severe pollution, the primary contaminants manifest as residues and oxidation states of iron and manganese, which exhibit limited mobility and absorption by plants. Currently, the potential adverse effects of these pollutants on both human health and environmental integrity appear to be relatively minimal.

The computed results for the single-factor index and the Nemerow comprehensive index pertaining to heavy metals in the soil of the Zheng–Bian–Luo urban agglomeration are presented below. The analysis reveals that the average single-factor pollution index values for the heavy metals Cd and Zn both exceed 1, signifying mild pollution levels, with an average value corresponding to Level II of mild pollution. Furthermore, the Nemerow comprehensive index (P) values for Cd and Zn range between $1 < P_{comp} \leq 2$, indicative of mild pollution. In contrast, the comprehensive P values for the remaining seven metal elements are all below 0.7, categorizing them at a relatively clean or alert level.

Elevated Cd concentrations in soil are often associated with anthropogenic activities, including sectors such as the chemical industry, battery manufacturing, mineral processing, and improper waste disposal practices. Specifically, the Luoyang Jianxi Industrial Zone, densely populated regions, and areas rich in historical human activity relics emerge as the most heavily contaminated zones. Noteworthy examples include the Luoyang Copper Processing Factory, Datang Power Plant, Luoyang Glass Factory, Baima Temple, and the Ru'ao areas. Contamination in the former locations may be attributed to mineral processing activities, whereas the latter encompasses remnants of ancient human settlements dating back to the Han and Wei dynasties, as well as activities from the Sui, Tang, and Song dynasties. Consequently, persistent or large-scale industrial emissions, illicit waste disposal, and improper application of pesticides and fertilizers are potential contributors to the heightened Cd levels observed in the soil.

Among the individual potential ecological risks assessed, Cd poses the most substantial risk, whereas Co presents a comparatively minor risk. Elevated Cd concentrations are often associated with specific anthropogenic activities, including the chemical industry, mineral processing, battery manufacturing, and improper waste disposal. Such activities can lead to the substantial release and accumulation of cadmium, thereby augmenting the risk of cadmium contamination within soils and ecosystems. In contrast, the primary sources of Co typically stem from natural geological processes, such as the inherent weathering and decomposition of cobalt ores. Given the relatively stable migration and transformation properties of Co within soil, its accumulation and enrichment in the environment are less pronounced.

The concentration of heavy metals in soil is influenced by a myriad of factors, resulting in a multifaceted array of sources. To enhance our comprehension and management of heavy metal pollution in soil, it is imperative to intensify relevant investigations and meticulously trace the origins of pollution. These efforts will provide a scientific foundation for the judicious utilization of soil resources and facilitate effective strategies for mitigating soil pollution amidst the backdrop of urbanization.

5. Conclusions

(1) In soil samples collected from Zhengzhou and Kaifeng, the average cadmium (Cd) concentrations surpassed the background values by 1.77-fold and 10.37-fold, respectively. Such pronounced cadmium contamination in these urban soil matrices warrants meticulous scrutiny and underscores the imperative for heightened attention to this environmental concern.

(2) Upon examining the correlation coefficients of heavy metals in the soil of the Zheng–Bian–Luo urban agglomeration, our findings unveil a significant association between Pb and Cd, yielding a coefficient of 0.89 at a significance level of 0.01. Such results suggest a common source of contamination for these two elements. Furthermore, the correlations between Cr and As, Cu and As, and Cu and Cr are determined to be 0.63, 0.45, and 0.62, respectively, implying potential shared sources of contamination for these elements. Conversely, the correlations between Cr and Cd, Cu and Cd, as well as As and Cd, are notably weak or even absent, indicating distinct sources of pollution for these metals.

(3) The average single factor pollution index for Cd and Zn surpasses 1, suggesting a state of slight pollution categorizing them under Level II mild pollution. Moreover, the Nemerow comprehensive index places the P comprehensive value for Cd and Zn within the $1 < P_{comp} \leq 2$ range, signifying a mild pollution level for these metals. In contrast, the comprehensive P values for the remaining seven metal elements fall below 0.7, suggesting pollution levels that either reach a clean state or warrant warning.

(4) In terms of individual potential ecological risks, the hierarchy, ranging from most to least significant, is as follows: Cd > Pb > Cr > Ni > Cu > Zn > As > Mn > Co. The ecological risk index for Cd oscillates between 34.62 and 196.73, suggesting a condition of mild ecological risk. The comprehensive potential ecological risk index, denoted by RI, spans from 20.63 to 213.60, predominantly signifying minimal potential ecological risks. Research findings elucidate that the predominant risk factor influencing the surface soil of the Zheng–Bian–Luo urban agglomeration is cadmium (Cd), with the remaining heavy metal elements exerting relatively negligible impacts on ecological risk levels.

6. Limitations and Future Directions

This study conducted a comprehensive exploration and assessment of heavy metal pollution levels in the soil of the Zheng–Bian–Luo urban agglomeration; however, several limitations warrant acknowledgment. Primarily, constrained by resources and scope, our investigation was confined to select heavy metal elements, thus failing to encompass all potential contributors to heavy metal pollution. Secondly, our study predominantly focused on a static pollution assessment, lacking a comprehensive exploration into the dynamic fluctuations of soil contamination over time.

In future research endeavors, it would be advisable to expand the range of heavy metal detection by incorporating additional trace elements or emerging pollutants. Moreover, the geographical scope of our study should include a broader array of counties surrounding urban agglomerations. By integrating soil types, topographical features, and other pertinent factors, our aspiration is to formulate a more sophisticated soil pollution assessment model. Such advancements aim to furnish robust foundational support for soil ecological sustainability research across various urban agglomerations nationwide.

Author Contributions: Conceptualization, X.C., H.Z., F.L. and C.U.I.W.; Data curation, X.C.; Formal analysis, X.C., H.Z. and F.L.; Methodology, X.C., H.Z. and C.U.I.W.; Software, X.C., F.L. and S.X.; Writing—original draft, X.C., H.Z. and C.U.I.W.; Writing—review and editing, X.C., H.Z., S.X. and C.U.I.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author/s.

Conflicts of Interest: The authors declare no conflicts of interest.

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