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Source Analysis and Bioavailability of Soil Cadmium in Poyang Lake Plain of China Based on Principal Component Analysis and Positive Definite Matrix Factor

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Abstract: In order to identify the source and bioavailability of soil Cd in the alluvial geological high background area, 3799 topsoil samples and 140 root soil samples were collected from the Jiulong area on the south bank of Poyang Lake, Jiangxi Province. The results confidently indicate that the range of topsoil Cd content is 0.02~8.12 ppm, with an exceedance rate of 14.6%. It is noteworthy that exceedance points were mostly distributed in quaternary sediments. The geostatistical analysis clearly shows that the spatial distribution characteristic of topsoil Cd is higher in the north and lower in the south. The area with extremely high values (>90% quantile) is predominantly located in the tidal flat and low-lying areas of the mainstream of the Xinjiang River. The PCA analysis confirms that the main source of topsoil Cd is man-made activities related to industry and mining. Soil Cd is primarily derived from upstream industrial and mining discharge (58.5%), as revealed by the PMF model analysis. The active Cd content in root soil is 77 ppb, with higher levels observed in the north and lower levels in the south. These findings suggest a significant risk of Cd diffusion along the upstream stream and deposition in the low-lying parts of the north. It is worth noting that Cd's bioavailability and active forms in paddy fields are the highest, which can have a detrimental effect on food security. The correlation analysis suggests that genetic sources primarily control the bioavailability of soil Cd, followed by soil physicochemical properties such as SOC, Fe-Al oxides, and soil texture. Preventing source pollution and cutting off water system transmission are effective methods for preventing and controlling soil Cd pollution. These methods ensure the safety of cultivated land in the lakeside area of Poyang Lake Plain.

Keywords: cadmium; source analysis; geochemical fraction; bioavailability; PCA; PMF; soil; Poyang Lake Plain



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1. Introduction

As a thiophile element, Cadmium (Cd) is mainly stored in sulfide minerals such as sphalerite and galena in endogenous reduction environment [1]. Soil Cd originates from the weathering of parent rock and secondary enrichment of pedogenic processes under natural conditions [2]. However, it is important to note that continuous accumulation of heavy metal pollutants is mainly caused by external inputs such as mining, smelting, and agricultural production activities. Therefore, Cd has been identified as the primary factor contributing to soil pollution in China [3]. High background soil Cd is closely related to basalt [4], black shale [5], carbonate rock [6,7] and sulfide deposits [8]. In China, high background soil Cd is mainly distributed in southwest China [9–11], the middle and lower reaches of the Yangtze River [11,12], and the Pearl River Delta [13–15]. Soils with different geneses exhibit significant differences in the geochemical fractions, availability, and environmental risks of high background Cd. Soil with a high background developed from

carbonate rocks generally exhibits a ‘high content and low bioavailability’ characteristic, resulting in relatively low risk [6,7,9,16]. On the other hand, soil with a high background developed from black shale exhibits a ‘serious acidification and high bioavailability’ characteristic, resulting in relatively high risk [5,17,18]. Identifying the sources of heavy metal pollution in soil is a necessary prerequisite for controlling heavy metal pollution and remediating the ecological environment. Soil source analysis includes the identification process and quantitative analysis of pollution sources. The commonly used methods are geostatistical analysis, principal component analysis (PCA), the chemical mass balance model (CMB), unmixing (UNMIX), the positive definite matrix factor decomposition method (PMF), the isotope method, and so on [19].

As a seasonal shallow lake, Poyang Lake is the largest freshwater lake in China, and it plays an important role in maintaining the ecological security of the middle and lower reaches of the Yangtze River. Although the lake’s mineral-rich basin has earned the nickname ‘Copper Capital of China’ due to its significant non-ferrous and precious metal minerals, it is imperative to prioritize the preservation of the lake’s ecological balance. The accumulation of heavy metals and other pollutants in Poyang Lake through the river, as a result of the exploitation and smelting of mineral resources over a long period, poses a significant threat to the ecological security of the river basin. Heavy metal anomalies are evident in Poyang Lake’s surface water [20,21], sediment [22,23], and soil [24,25]. It is important to note that the current research samples are limited, and the focus of these is on the total heavy metal content in the basin. Few systematic studies have been conducted on the origin, geochemical fraction, and bioavailability of cadmium in cultivated land in lakeside areas [26]. This paper confidently analyses the enrichment characteristics and geochemical fractions of Cd in the Jiulong area on the south bank of Poyang Lake. Through the use of PCA and PMF, potential pollution sources were qualitatively speculated and their relative contributions quantified. Additionally, the bioavailability and influencing factors of Cd were thoroughly discussed. The findings provide a strong basis for the safe utilization of Cd-contaminated cultivated land and the safe production of agricultural products in the Poyang Lake area.

2. Materials and Methods

2.1. Study Area

The study area is located in the lakeside region on the southern bank of Poyang Lake in Jiangxi Province, China (Figure 1). It covers an extensive area of 190 km², including Jiulong Town and Fenggang Town, and boasts a subtropical humid climate with four distinct seasons, abundant rainfall, sufficient sunshine, and a short frost period. As a result, it plays a crucial role as a commercial grain base. The area is located in the Poyang Lake Plain, with a gently sloping terrain from the southern hills to the north, transitioning to the lakeside plain.

The Xinjiang River has a total length of about 300 km and a basin area of about 17,600 square kilometers. The study area is located in the lower reaches of the Xinjiang River into the Poyang lake, mainly growing rice and vegetables, without industrial production and mineral resources’ development. Yongping Copper Mine in the middle reaches of Xinjiang River is a large mine dominated by copper and sulfur, and is the second largest open pit copper mine in China. The Guixi Smelter in the middle reaches of Xinjiang River is the largest copper smelter in China and its production scale has become the second largest in the world. According to previous studies, Poyang Lake receives an annual contribution of 26.5 tons of cadmium, 123 tons of zinc, and 24.4 tons of lead from Xinjiang River [27].

Jiangxi Province belongs to the Yangtze stratigraphic area, as indicated by its regional geological records [28]. The area is mainly composed of the Qingbaikou system, Permian, Triassic, and Quaternary strata, with the Permian Leping formation and Triassic Anyuan formation being typical coal-bearing strata. The surface materials are derived from quaternary sediments, quaternary residues, black shale, metamorphic rocks, and magmatic rocks.

The primary soil types in this area are red soil and paddy soil, as identified by the second national soil survey [29].

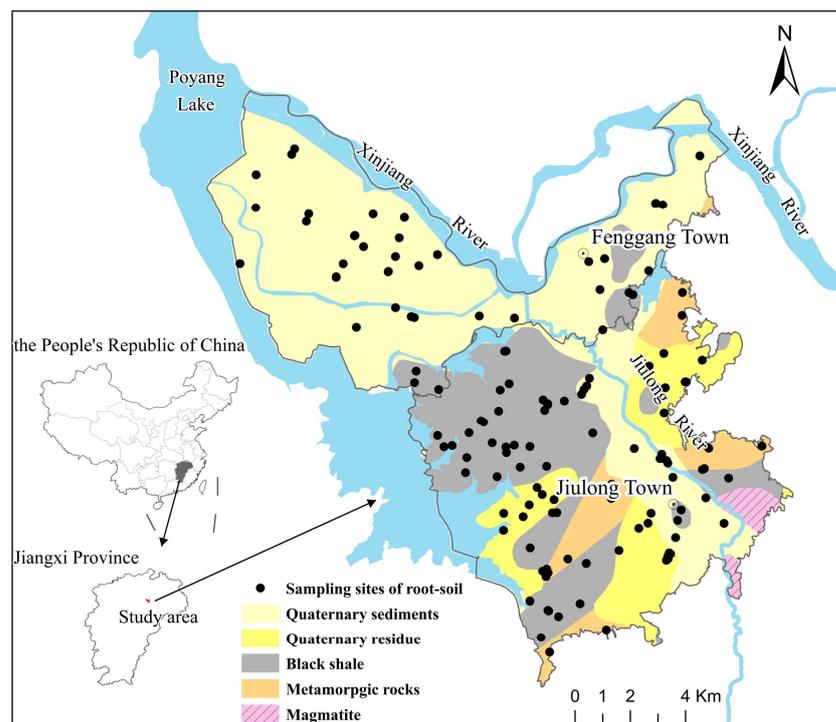


Figure 1. Map of the study area and sampling locations.

2.2. Sample and Analysis

The Arcgis 10.2 software was confidently utilized to arrange sample points based on the thorough analysis of water system distribution, land use, soil type, and regional geology. Sample points were expertly arranged according to a grid of $1.0 \text{ km} \times 1.0 \text{ km}$, with a density of 20 samples/ km^2 for topsoil and 1 sample/ $1\text{--}4 \text{ km}^2$ for root soil. A total of 3799 topsoil samples (including inland beach samples) and 140 root soil samples of crops (rice, sesame, corn, peanut, gorgon seed, oil tea camellia) were meticulously collected with precision and care. The soil sample (0–20 cm) was confidently classified as either ‘X’ or ‘S’-type based on the shape of the plot. The sample was expertly composited from 4 to 6 subsamples collected within 50 m of the sampling site. Any visible plant detritus and rock fragments were meticulously removed from the soil samples. Following air-drying, the samples were skillfully crumbled using a wooden hammer and precisely sieved through a 10 mesh ($< 2 \text{ mm}$) nylon sieve for analysis.

After digestion with mixed acids (HF , HNO_3 , HClO_4 , H_2SO_4), soil Cd and Pb were determined by an inductively coupled plasma mass spectrometer (ICP-MS), and soil Cr, Cu, Ni, and Zn were determined by inductively coupled plasma atomic emission spectrometry (ICP-AES). After (HNO_3 , HF , HClO_4) digestion, soil As and Hg were determined by atomic fluorescence spectrometry (AFS). Soil P, K_2O , Na_2O , CaO, MgO, SiO_2 , Al_2O_3 , and Fe_2O_3 were determined by an X-ray fluorescence spectrometer (XRF). Soil pH was determined by the electrode method, soil organic matter (OM) and N were determined by the volumetric method (VOL), soil S was measured by the high frequency infrared method, soil CEC was measured by the ammonium acetate exchange method, and soil mechanical composition was measured by the hydrometer method. The detection limits of As, Cd, Pb, Cr, Cu, Ni, Zn, Hg, N, P, and S were 0.24, 0.02, 2, 0.2, 0.5, 0.2, 1, 0.0005, 12.5, 6.4, and 20 ppm, respectively. The detection limits of OM, K_2O , Na_2O , CaO, MgO, SiO_2 , Al_2O_3 , and Fe_2O_3 and mechanical composition were 0.05%, 0.03%, 0.03%, 0.03%, 0.05%, 0.1%, 0.5%, 0.5%, and 0.1%, while the detection limit of pH was 0.01 and the detection limit of CEC was 1 cmol kg^{-1} . In the analysis process, the national first-class soil geochemical reference materials were tested

12 times, the qualification rate of the standard materials and monitoring samples was 100%, and the reporting rate was 100%.

The soil samples were sequentially extracted to determine seven fractions of Cd: F1—soluble fraction, F2—ion exchangeable fraction, F3—easily mobilizable fraction, F4—labile OM fraction, F5—Fe–Mn oxides fraction, F6—refractory OM fraction, and F7—residual fraction. The specific procedures and reagents are listed in Table 1. The element concentrations in the digests and extracts were measured using ICP-AES. Total digestion was performed on the samples as an internal check.

Table 1. Procedure of Tessier sequential extraction methods.

Fraction	Extractant	Extraction Method
Soluble fraction	Distilled water (pH = 7.0)	25 mL, shake 30 min at 25 °C
Ion exchangeable fraction	1 mol/L MgCl ₂ ·6H ₂ O (pH = 7.0)	25 mL, shake 30 min at 25 °C
Easily mobilizable fraction	1 mol/L NaAc–Hac (pH = 5.0)	25 mL, shake 1 h at 25 °C
Labile OM fraction	1 mol/L Na ₄ P ₂ O ₇ ·10H ₂ O (pH = 10.0)	25 mL, shake 40 min at 25 °C
Fe–Mn oxides fraction	0.25 mol/L HONH ₃ Cl–HCl	25 mL, shake 1 h at 25 °C
Refractory OM fraction	30% H ₂ O ₂ –HNO ₃ (pH = 2.0)	8 mL, water bath 3 h at 83 °C, shake 10 h at 25 °C
Residual fraction	HCl–HNO ₃ –HClO ₄ (1:1:1)	0.2 g residual sample + 5 mL HCl–HNO ₃ –HClO ₄ solution

To guarantee the very high quality of the achieved results, the sum of each element extracted in the seven-step sequential extraction was compared with the results obtained by a separate aqua regia digestion as follows:

$$Recovery = \frac{C_{sum} - C_{total}}{C_{total}} \times 100\%$$

where C_{sum} is the sum of each element extracted in the seven-step sequential extraction and C_{total} is the concentration obtained by a separate aqua regia digestion.

The maximum relative standard deviation between precision was less than 40%. The accuracy of calculating the soil Cd element speciation test data is less than 19.46%, which meets the needs of this study.

2.3. Statistical Analysis

Data analysis and statistical measures were performed using Excel 2021. The spatial interpolation map was created using the geostatistical analysis function of ArcGIS 10.2, and was graded based on quantile values (10%, 25%, 50%, 75%, 90%). The distribution characteristics of heavy metals in soil were visually represented, allowing for intuitive inference of their sources. The topsoil content in the lakeside area was analyzed for heavy metal content using SPSS 17. Factor analysis was employed to reduce the dimensionality of the data, explaining the main information of many variables using fewer representative factors and inferring pollution sources. Factor analysis was employed to reduce the dimensionality of the data, explaining the main information of many variables using fewer representative factors and inferring pollution sources. The analysis of the source of heavy metals in soil was conducted and its contribution rate was quantified using USEPA PMF 5.0. This software applies a non-negative constraint on the factorization matrix to ensure that the source component spectrum and source contribution rate are positive, resulting in a more accurate outcome [30]. The combined use of three source analysis methods is widely employed in the analysis of pollutant sources in the atmosphere, stream sediment, soil, and other pollutants [31–35]. This approach yields more accurate and effective results.

2.4. Risk Assessment Methods

The Nemiro comprehensive pollution index method is commonly used to evaluate the pollution level of heavy metals in the surface soil of a lakeside area.

The single factor pollution index is as follows:

$$P_i = C_i/S_i$$

The multi-factor comprehensive pollution index is as follows:

$$P_n = \sqrt{\frac{\max(P_i)^2 + \text{ave}(P_i)^2}{2}}$$

where P_i is the single factor pollution index of the element i in the soil, C_i represents the measured concentration of the element i , S_i represents the evaluation standard or background value of the element i , and P_n represents the comprehensive pollution index of soil i .

3. Results

3.1. Enrichment Characteristics and Spatial Distribution

The study area shows a wide range of topsoil Cd content, ranging from 0.02 to 8.12 ppm (Table 2). The average content is 0.21 ppm, which is higher than the background value of soil in Jiangxi Province (0.10 ppm) [36]. It is worth noting that 71.8% of the samples exceed this value. The Cd contents in soils developed from quaternary sediments, quaternary residues, black shale, metamorphic rocks, and magmatic rocks are 0.30 ppm, 0.10 ppm, 0.12 ppm, 0.10 ppm, and 0.10 ppm, respectively. These values are consistent with the high geological background characteristics of fluvial and lacustrine sediments. The average Cd content in root soil was 0.16 ppm, with a range of 0.03~0.65 ppm. Notably, 75.7% of the samples exceeded the background value.

Table 2. Statistics of soil Cd content in the study area (ppm).

Sample	Parent Material	N	Range	Average	Standard Deviation	CV (%)	Exceedance Rate (%)	P_n
Topsoil	Quaternary sediments	2014	0.02~8.12	0.30	0.56	170	26.3	19.2
	Quaternary residues	468	0.02~0.33	0.10	0.06	55	0.21	0.82
	Black shale	929	0.02~3.21	0.12	0.14	117	1.94	7.57
	Metamorphic rocks	344	0.02~0.32	0.10	0.06	55	0.30	0.80
	Magmatic rocks	44	0.03~0.53	0.10	0.08	80	2.27	1.27
	Study area	3799	0.02~8.12	0.21	0.39	183	14.6	19.2
Root soil	/	140	0.03~0.65	0.16	0.09	56	6.43	1.58

The topsoil Cd is higher in the north and lower in the south of the study area (Figure 2). The high-value area (>75% quantile) is mainly distributed in the sedimentary area of the Xinjiang River mainstream and its tributary river and lake. The extremely high-value area (>90% quantile) is particularly concentrated in the tidal flat and low-lying areas of the Xinjiang River mainstream. This concentration may be closely related to the man-made pollution imported by the industrial and mining industries in the upper reaches [22,27]. The concentration of Cd in the soil of the southern Jiulong River watershed is similar to the background value of soil in Jiangxi Province, indicating that it is not significantly affected by human activities. Furthermore, there is a clear distinction in soil pH between the north and south regions, with the south being more acidic.

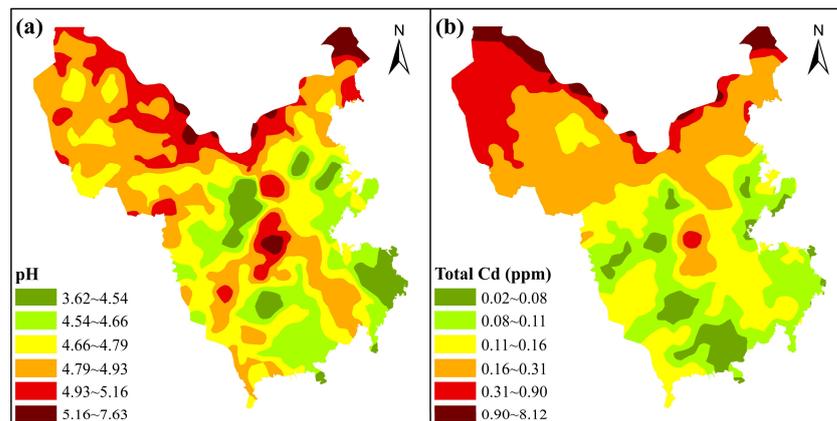


Figure 2. Spatial distribution of pH (a) and Cd content (b) in topsoil.

The level of Cd pollution in the topsoil was evaluated using the soil environmental quality standard (GB 15618-2018) [37]. The pollution index was found to be 19.2, with an exceedance rate of 14.6%, indicating a high level of pollution. The pollution index of soils, in terms of geological genesis, follows this order: quaternary sediment > black shale > root soil > magmatic rock > quaternary residual > metamorphic rock. The study area has a high pollution index due to the high values of a few samples found in quaternary fluvial and lacustrine sediments. Nevertheless, the root soil's pollution index is relatively slight at 1.58, with an exceedance rate of 6.43%.

3.2. Geochemical Fractions and Bioavailability Characteristics

The distribution of Cd among the different geochemical fractions in the studied soils varies greatly and is strongly influenced by soil texture, pH, Eh, CEC, organic matter, and other factors. The order of Cd geochemical fraction in root soils is as follows: F2 (64 ppb) > F7 (29 ppb) > F4 (21 ppb) > F5 (15 ppb) > F3 (11 ppb) > F6 (5.6 ppb) > F1 (1.9 ppb) (Figure 3).

F2 accounts for 43.2% of the main geochemical fraction of Cd in the root soil, which is consistent with the findings of most studies. For example, the proportion of F2 in the soil developed from black shale in Chongqing is 40.6% [38], while that of paddy soils in the high geological background area of the Pearl River Delta is 35.7% [39]. Moreover, the F2 of soils in the geological high background area of gold deposits in Shaanxi Province is 54.4% [40]. The performance of the karst area in the southwest differs significantly, with both the soil F2 and F7 measuring at 26.8% [9].

The active fraction of Cd was determined in this study by considering the available state of Tessier extraction as $\sum F1-F3$, and calculating the ratio of the active fraction to the sum of each extracted in the seven-step sequential extraction ($\sum F1-F7$) to determine the bioavailability of the element [41]. The results showed that the active fraction of root soil Cd in the study area was 77 ppb, and its bioavailability was 48.9%, respectively. The active fraction of root soil Cd is higher in the north than in the south (Figure 4). This suggests that the risk of Cd diffusing along the upstream water system and depositing in the low-lying parts of the north is higher. Conversely, the available fraction is lower in the south, where human activities have less impact, resulting in a lower risk.

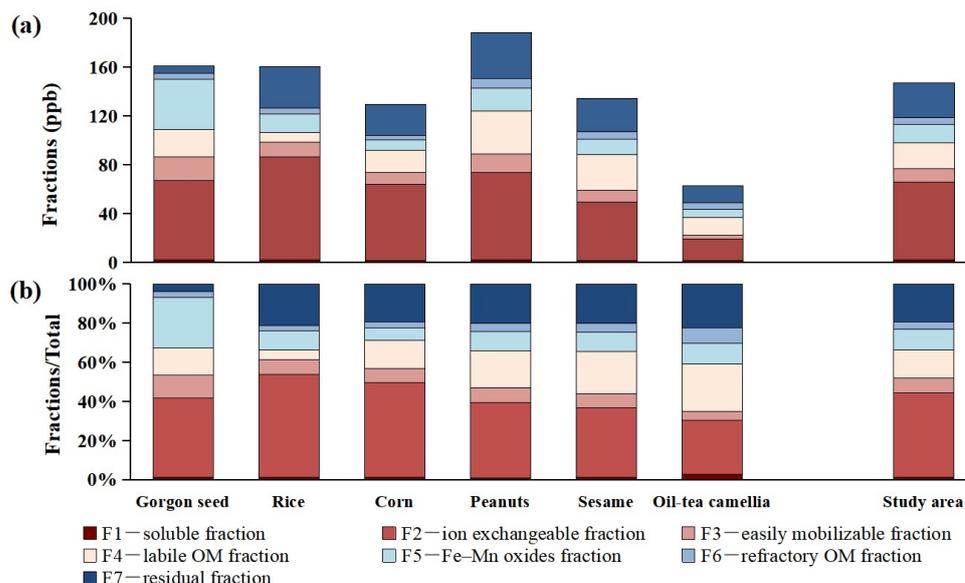


Figure 3. Characteristics of Cd geochemical fractions in root soils of different crops. (a) The content of geochemical fractions. (b) Distributions of Cd in various geochemical fractions.

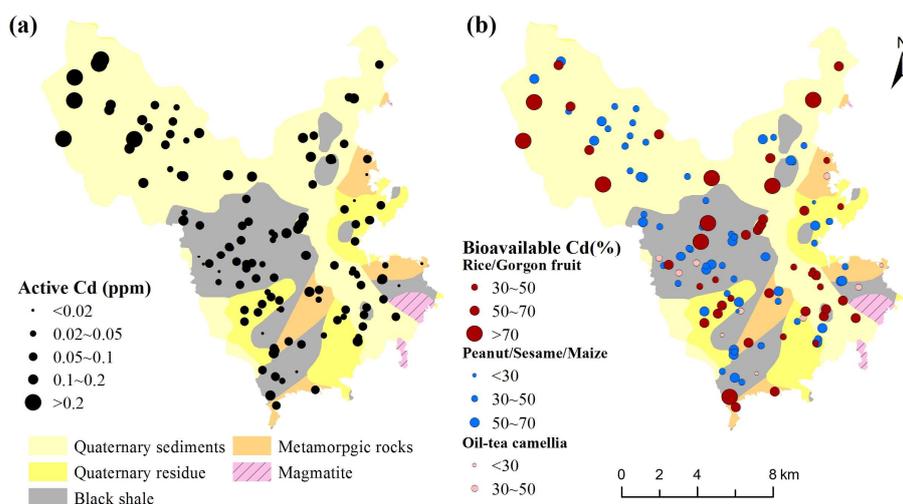


Figure 4. Spatial distribution of active Cd (a) and bioavailable Cd (b) in root soil.

Paddy fields exhibit significantly higher levels of active Cd and bioavailable Cd in root soil (Figure 4). The bioavailable Cd of root soil in paddy fields is highest; that is, the bioavailability is strong, where rice root soil Cd is 59.9%, while dryland root soil availability of Cd is in the middle, for example, sesame root soil availability Cd is 40.9%, and woodland is the lowest, for example, camellia oleifera is 32.5%.

4. Discussion

4.1. Source Analysis

4.1.1. Inference Analysis Based on PCA

The characteristics and composition of soil elements are influenced not only by their geochemical properties but also by epigenetic geochemical conditions and human activities. This study confidently employed principal component analysis to examine the combination of 15 indexes, including major and heavy metal elements, to explain the characteristics of soil Cd and other elements. PCA was deemed appropriate for this study as indicated by the KMO value of 0.754. Bartlett’s sphericity test was significant at $p < 0.001$. A cumulative

contribution rate of 74.4% was explained by the four factors selected based on initial eigenvalues greater than 1 (Table 3).

Table 3. Rotating loadings of soil indexes by PCA.

Indexes	PC1	PC2	PC3	PC4
Cd	−0.17	0.63	−0.07	0.54
Pb	−0.07	0.87	0.20	0.01
Zn	0.28	0.87	0.01	0.19
As	0.71	−0.02	−0.19	0.34
Cr	0.82	−0.29	−0.02	0.17
Ni	0.88	0.11	−0.01	−0.03
Cu	0.36	0.44	0.00	0.11
Hg	0.15	−0.03	0.23	0.76
N	−0.24	0.05	0.91	0.09
P	−0.02	0.11	0.53	0.37
S	0.08	−0.01	0.85	−0.07
K	−0.22	0.82	−0.01	−0.29
Fe	0.87	0.07	−0.29	−0.13
Al	0.68	0.58	−0.04	−0.30
SOC	−0.25	0.02	0.92	0.11
Initial Eigenvalue	4.15	3.38	2.40	1.23
Cumulative Variance (%)	24.1	45.7	65.0	74.4

PC1 had strong positive loadings of Cr, Ni, and Fe and moderate positive loadings of As and Al, explaining about 24.1% of the total variance. The study area experiences a subtropical humid climate with abundant rainfall. The parent rock undergoes strong decomposition during the process of rock weathering and soil formation, resulting in the leaching of silicon and base materials, and the accumulation of less mobile Fe-Al oxides [29]. Typical siderophile elements, such as As, Cr, and Ni, are commonly found in association with Fe-Al oxides in epigenetic geochemical environments.

PC2 had strong positive loadings of Pb, Zn, and K and moderate positive loadings of Cd and Al, explaining about 21.6% of the total variance. K is known for its highly active chemical properties and is easily lost in water systems, resulting in its deposition in downstream rivers and lakes, making it a valuable indicator element. Copper mines and smelters are located in the middle reaches of the Xinjiang River. Unfortunately, their early mining and smelting practices were found to be disorderly, leading to the continuous diffusion of heavy metals through the surface water system. This poses a significant threat to downstream ecology [22,23].

PC3 had strong positive loadings of N, S, and soil organic carbon (SOC) and moderate positive loadings of P, explaining about 19.3% of the total variance. The weathering of black shale continues to release heavy metals into the soil [36], and human agricultural production activities will continue to import heavy metals.

PC4 had moderate positive loadings of Cd and Hg, explaining about 9.44% of the total variance. It is well known that the combustion of fossil fuels and metal smelting are the main sources of Hg emissions [42]. With rapid economic growth, industrial enterprises consume a large amount of coal, which is likely to be the primary source of Hg in atmospheric sediments.

4.1.2. Contribution Rate Based on PMF

Fifteen indexes from 3799 topsoil samples were analyzed using EPA PMF 5.0. Setting factors 2 to 7, using Robust mode, and running 20 times, PMF confidently identified three significant factors with relative contribution rates of 14.2%, 21.4%, and 64.4%, respectively (Figure 5).

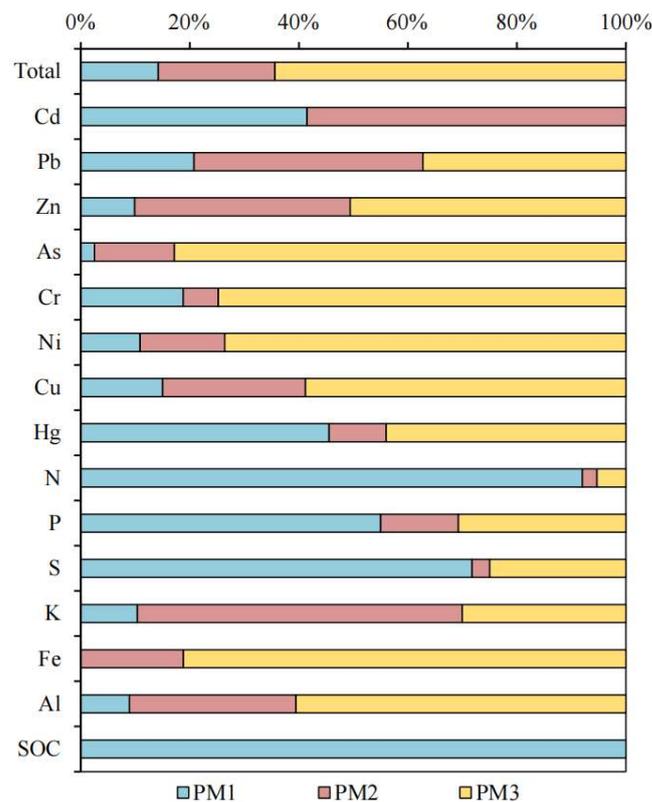


Figure 5. Source contribution for soil indexes by PMF (%).

PM1 has a high load of SOC (100%), N (92%), S (71.6%), P (55%), Cd (41.5%), and Hg (45.5%), which is similar to the previous PC3. The sedimentary rocks in the study area have the primary composition of shale with layers of coal or coal lines. These rocks not only contain ore but also provide ore-forming materials for the formation of epigenetic deposits [43]. The weathering of the parent rock continuously releases a significant amount of heavy metals such as Cd and Hg.

PM2 has a high load of K (59.6%), Cd (58.5%), Pb (42%), and Zn (39.5%), which is similar to the previous PC2. Thiophile elements Cd, Pb, and Zn are commonly found together in sulfide deposits. Heavy metal pollution from mining, separating these deposits, and industrial metal smelting is a major concern.

PM3 has a high load of As (82.9%), Fe (81.2%), Cr (74.8%), Al (60.5%), Ni (73.6%), Cu (58.8%), Zn (50.6%), Hg (44%), and Pb (37.3%), which is similar to the previous PC1. Red soil is a zonal soil in the subtropical region, which is characterized by desilication and iron-rich aluminization [28]. Siderophile elements such as As, Cr, Ni, Cu, Pb, and Zn are easily absorbed and enriched by negatively charged Fe-Al oxide colloids.

4.2. Effect Factors on Bioavailable Cd

Soil metal elements' geochemical fractions and bioavailability depend on their geochemical behavior, genetic sources, and soil physicochemical conditions, including pH, organic matter, Fe-Al oxides, soil texture, and the effects of the plant rhizosphere [44–52]. Under natural conditions, heavy metals such as Cd are retained in primary minerals, activated and released during primary mineral decomposition, leached into water bodies, or absorbed by secondary minerals. The increase in total Cd content in soil is mainly due to the increase in steady fractions ($\Sigma F4-F7$). It is important to note that the ecological risk does not increase with the increase in total content [44,45].

Pearson correlation analysis (Figure 6) showed that the content of active Cd in root soil was significantly positively correlated with total Cd and K_2O . At the same time, the bioavailable Cd of root soil was significantly positively correlated with the total Cd, which

meant that its biological activity increased with the increase in the total Cd. It can be considered that the exogenous input Cd in the soil is mainly active, which has a great influence on the safety of the ecosystem.

	Total Cd	pH	SOC	CEC	Al ₂ O ₃	Fe ₂ O ₃	SiO ₂	K ₂ O	Sand	Silt	Clay
Total Cd	1	0.23**	0.13	0.02	-0.24**	-0.42**	0.27**	0.47**	0.03	0.22*	-0.25**
Active Cd	0.95**	0.21*	0.29**	-0.13	-0.24**	-0.43**	0.26**	0.45**	0.08	0.22*	-0.3**
Bioavailable Cd	0.51**	0.17*	0.58**	-0.21*	-0.28**	-0.39**	0.27**	0.17*	0.1*	0.27**	-0.39**

Figure 6. Correlation analysis of influencing factors of active Cd and bioavailable Cd. * $0.01 < p \leq 0.05$, ** $p \leq 0.01$.

Soil Cd’s solubility and mobility are significantly influenced by various physicochemical properties, including soil organic matter (SOM), pH, CEC, and Fe-Al oxides. These factors play a crucial role in determining the geochemical fractions of Cd in soil [44,47]. In the study area, the active Cd and bioavailable Cd of root soil showed a significant positive correlation with SOC and SiO₂ while exhibiting a negative correlation with Al₂O₃ and Fe₂O₃. The soil organic matter (SOM) possesses a negative charge and can effectively adsorb Cd. Furthermore, the organic matter (OM) comprises numerous oxygen-containing functional groups that readily complex or chelate with Cd. As a result, the quantity of Cd adsorbed in soil rises proportionally with the increase in OM content [45,50]. The zonal red soil exhibits desilication and is rich in Fe-Al, making it an ideal soil for fixing Cd.

The geochemical behavior of heavy metals in soil is largely influenced by soil texture, with metal elements being generally more bioavailable in fine-grained soil than in coarse-grained soil. In the study area, the bioavailable Cd in the root soil showed a significant negative correlation with clay and a significant positive correlation with silt. Sand did not show any significant correlation. The colloidal properties, humus, and Fe-Al oxides present in clay make it easier to absorb Cd [45,46].

5. Conclusions

In this paper, the sources of soil Cd contamination in the study area were analysed by geostatistical spatial analysis, PCA, and PMF. The results showed that the Cd content in the topsoil ranged from 0.02 to 8.12 ppm, which was high in the north and low in the south. The above-standard points were mainly distributed in the mudflats and low-lying areas of the mainstream of the Xinjiang River in the north of the study area, which was caused by the transport and accumulation of industrial and mineral pollutants in the upstream with the river system, and the relative contribution rate was 58.5%. This can be used as a reference for the analysis of heavy metal pollution sources in high background areas.

The morphological analysis showed that the active Cd content of the crop root soil in the study area was 77 ppb, which was high in the north and low in the south, meaning that the risk was highest in the low-lying areas in the north. The correlation showed that the active state content of Cd in root soil was controlled by genetic sources, which was related to the high activity of exogenously imported Cd. The bioavailability of Cd in root soil is 48.9%, of which that of rice fields is the highest (59.9%), dryland is in the middle, and woodland is low, which is a major threat to food security. Bioavailability is mainly controlled by genetic sources, followed by soil physical and chemical properties such as SOC, Fe-Al oxides, and soil texture. This provides an effective basis for the safe use of Cd-contaminated farmland and the safe production of agricultural products in the Poyang Lake area.

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