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Heavy metal synergistic pollution risk assessment in the soil-crop system of the nanyang basin

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The enrichment law of heavy metals and pollution assessment in the soil-crop system have become the focus of research on environmental pollution issues. Evaluating the co-pollution risk of heavy metals in the soil-crop system of the Nanyang Basin is of great significance for food safety and the governance of regional heavy metal environmental pollution. This study collected 5778 surface soil samples, 185 wheat samples, 75 corn samples, 114 peanut samples, and 374 corresponding root soil samples from each crop in the Nanyang Basin. The concentrations of arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hq), and lead (Pb) were measured. The pollution index and potential ecological risk assessment methods were utilized to assess the pollution of heavy metals in the soil. The bioconcentration factor (BCF) method was employed to analyze the metal transfer dynamics. The synergistic risk of heavy metals in the soil-crop system was assessed utilizing the soil-crop comprehensive quality index (IICQ). The results revealed that most of the study areas had low levels of soil pollution, with unpolluted and lightly polluted areas predominating. The crops of wheat, corn and peanuts in the study area are generally at a safe level, with the crop pollution index less than 1, while the crop pollution index at some other points is greater than 1. Wheat, peanuts, and corn showed strong bioaccumulation capacity for Cd, with peanuts exhibiting the highest accumulation ability. The largest proportion of sampling points was categorized under unpolluted soil and crops, with peanuts being the most affected crop.

Keywords Heavy metals, Soil-crop system, Pollution evaluation, Synergistic pollution risk

The increasing problem of heavy metal pollution poses a critical environmental issue demanding effective solutions^{1–3}. Heavy metal pollution can result from natural factors such as soil erosion, rock weathering, and volcanic eruptions⁴. However, it is primarily caused by human activities, including mining, manufacturing, wastewater irrigation, and the use of metal-based products or pollutants^{5]–[6}. The accumulation of heavy metals in soil often results in their transfer to crops, contributing to contamination. However, not all crop-related heavy metal pollution originates from soil sources⁷. The patterns of heavy metal accumulation and pollution assessment within the soil-crop system have become focal points in environmental pollution research^{8–10}. Investigating the risks of co-contamination in soil and crops is essential for protecting local ecosystems and food safety, ultimately providing a theoretical foundation for soil remediation and ecological conservation in affected areas.

The overall soil environment in China remains concerning, with 16.1% of surveyed sites exceeding safety standards and a non-compliance rate of 19.4% among cultivated land sites, mainly due to multi-metal pollution involving lead, cadmium, and arsenic. Heavy metal contamination is a global issue, with numerous regions worldwide facing levels that surpass safety thresholds¹¹. Scholars have developed various evaluation methods for assessing heavy metal pollution, including the single factor index, geo-accumulation index¹², Nemerow integrated inde¹³, enrichment factor method¹⁴, and environmental risk index¹⁵. El-Sorog used both the single-factor pollution index and the Nemerow composite index to analyze heavy metal contamination in coastal sediments of Hurghada, northwest Red Sea¹⁶. Hintsa Gitet applied the bioconcentration factor to study heavy metal accumulation in crops cultivated near the Almeda textile factory in Adwa, Ethiopia.

To address soil-crop co-contamination, researchers have introduced the Integrated Impact of Contamination Quality (IICQ) inde^{17,18}. This method combines soil and crop heavy metal concentrations while accounting for

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soil quality standards, natural element background levels, specific soil load capacities, and regulatory pollutant limits for agricultural products, resulting in more comprehensive and rational assessment outcomes. Using the IICQ index, Xiang Mingtao assessed pollution risks in the soil-crop systems of the southeastern Yangtze River Delta, identifying a trend of increasing co-contamination from the periphery towards the center¹⁹. Similarly, Wang Ying applied the IICQ index in Shizuishan to assess the cumulative risk of heavy metals within the soil-crop system. The study revealed that cropland soils in the region exhibited a mild level of contamination²⁰.

The complex industrial and agricultural structure and intense mineral extraction activities in the Nanyang Basin have increased heavy metal content in soils, impacting agriculture and natural ecosystems. However, no comprehensive study has investigated the extent of heavy metal pollution across the entire Nanyang Basin or assessed co-contamination within the soil-crop system. Therefore, it is essential to examine the distribution of heavy metal pollution in the soils of the Nanyang Basin, understand the accumulation patterns within the soil-crop system, and conduct a co-contamination risk evaluation for this system.

In this study, the pollution index method is applied to identify soil heavy metal contamination areas. The potential ecological risk index (PERI) is utilized to evaluate the ecological risks posed by heavy metals, while the bioconcentration factor method examines the movement and accumulation of heavy metals within the soil-crop system. Finally, the IICQ index is employed to determine the co-contamination risk of the soil-crop system in the study area.

Materials and methods Overview of the study area

The Nanyang Basin is situated in the southwestern part of Henan Province, spanning Nanyang and Zhumadian cities, with geographic coordinates ranging from 110°00′ to 113°15′E and 32°00′ to 33°20′N (Fig. 1). The region features extensive Quaternary strata at the eastern section of the Qinling Fold Belt. As a major national grain-producing area, the Nanyang Basin, often referred to as the "Granary of Central China," is known for its diverse agricultural output, including wheat, corn, rice, and peanuts. The basin also supports a strong industrial economy with various sectors, establishing a diversified industrial profile focused on optoelectronics, machinery, light industry, food processing, metallurgy, construction materials, chemical packaging, and mineral extraction. Emerging industries such as renewable energy, new materials, and textile manufacturing further strengthen their industrial clusters. Both industrial and agricultural activities contribute to heavy metal accumulation in soil and crops, leading to potential ecological and environmental pollution.

Sample collection and processing

In this study, 5,778 surface soil samples were systematically gathered from the Nanyang Basin, following the sampling procedures outlined in our previous study²⁰. Additionally, 185 wheat samples, 75 corn samples, 114 peanut samples, and 374 root-zone soil samples corresponding to these three crops were gathered. The specific sampling locations are illustrated in Fig. 1. Wheat samples were primarily collected from Tanghe County,



Fig. 1. Location of the study area and the sampling site.

Dengzhou City, Neixiang County, Zhenping County, Xichuan County, and the Tongbai-Miyang border area. Corn samples were collected mainly from Tanghe County, Dengzhou City, and the Tongbai-Miyang border area, while peanut samples were obtained primarily from Tanghe County, Dengzhou City, Neixiang County, Zhenping County, and Xichuan County.

Crop samples were collected during the harvest season on windless days. Healthy, intact wheat, corn, and peanut plants were carefully uprooted, and the soil attached to the roots was shaken off into sampling bags. The grains from each crop were then separated. For wheat and corn, debris was removed from the grain samples, rinsed thoroughly with deionized water and air-dried at room temperature. Once dried, the samples were bagged and sent to the laboratory for analysis. Peanut samples were first cleared of external soil on the shells and then sun-dried for three days to remove moisture. The dried peanuts were shelled, and the kernels were packaged in sampling bags for subsequent laboratory measurements. Root-zone soil samples were processed following the same protocol as the surface soil samples.

As and Hg concentrations in soil heavy metals were determined using an AF-2000 atomic fluorescence photometer, while the concentrations of Cr were determined using an ASXPrimus II gamma ray fluorescence spectrometer. Additionally, the concentrations of Cd and Pb were determined utilizing the United States thermoelectric XSERIES2 inductively coupled plasma mass spectrometer. The analysis and detection procedures for As, Cr, and pH followed the guidelines outlined in the "Regional Geochemical Sample Analysis Method" (DZ/T0279-2016), and the detection method for Cd and Pb complied with the requirements of the chemical analysis method for silicate rocks (GB/T14506-2010).

As, Cd, Cr, and Pb concentrations in crop samples were measured utilizing inductively coupled plasma mass spectrometry (ICP-MS), while Hg was determined using cold atomic absorption spectrometry. The analytical procedures followed the protocols specified in the Ecological and Geochemical Assessment Methods for Plant and Animal Samples (DZ/T 0253–2014). Detection limits were set at 0.01 mg/kg for As, 0.005 mg/kg for Cr, 0.0002 mg/kg for Cd, 0.005 mg/kg for Pb, and 0.0005 mg/kg for Hg. The quality indicators for detection limits, reporting rates, accuracy, and precision met or exceeded the standards of the Specification for Multi-target Regional Geochemical Surveys (1:250,000) (DZ/T 0258–2014).

Data processing and analysis

GIS Spatial interpolation method

The fundamental principle of Inverse Distance Weighting (IDW) interpolation is based on the concept that "nearer things are more similar than distant ones" (Tobler's First Law of Geography). As a widely used interpolation method, it leverages spatial autocorrelation by estimating values at unsampled locations through the inverse of distances to known data points. IDW assumes that each sampled point exerts local influence, which diminishes as distance increases. The calculation process of Inverse Distance Weighting is as follows:

$$d_{i} = \sqrt[2]{(x - x_{i})^{2} + (y - y_{i})^{2}}$$
$$W_{i} = \frac{\frac{1}{d_{i}}}{\sum_{i=1}^{n} \frac{1}{d_{i}}}$$
$$Z_{0} = \sum_{i=1}^{i=n} W_{i}^{*} Z(X_{i}, Y_{i})$$

(x, y) represents the coordinates of the interpolation point; (xi, yi) denotes the coordinates of the discrete/ sampled points; di is the distance between the two points; and wi refers to the distance weight.

Soil heavy metal pollution levels

The single-factor index method was applied to analyze soil heavy metal pollution, determining their accumulation levels by comparing the measured concentrations to the standard limit values. The formula is as follows¹³:

$$P_i = \frac{C_i}{S_i}$$

Where $\rm P_i$ represents the pollution index of the heavy metal in soil, $\rm C_i$ denotes the detected concentration of the heavy metal within the soil sample, $\rm S_i$ is the standard evaluation value for pollutant i in the soil, based on the Soil Environmental Quality: Risk Control Standard for Soil Contamination of Agricultural Land (Trial) (GB 15618 – 2018). The evaluation standard values for heavy metals in soil are 40 mg·kg^{-1} for As, 150 mg·kg^{-1} for Cr, 0.3 mg·kg^{-1} for Cd, 90 mg·k^{-1} for Pb, and 1.8 mg·kg^{-1} for Hg.

Based on the single-factor index method, the Nemerow composite index method is applied to reflect the overall pollution level of multiple pollutants. The formula is as follows²¹:

$$CP_i = \sqrt{\frac{(maxP_i)^2 + (\overline{P_i})^2}{2}}$$

Where CP_i represents the comprehensive pollution index of heavy metals in the soil; $maxP_i$ is the maximum single factor index among all pollutants at a given sampling point; P_i signifies the mean value of all single-factor indices.

The classification of soil heavy metal pollution levels is displayed in Table 1.

	Single fa	actor pollution	Nemerow pollution index			
Level	P _i	Pollution degree	CP _i	Pollution degree		
Ι	≤1.0	No pollution	≤0.7	Clean (safe)		
II	1.0-2.0	Slight pollution	0.7-1.0	Fairly clean (alert)		
III	2.0-3.0	Moderate pollution	1.0-2.0	Slight pollution		
IV	> 3.0	Heavy pollution	2.0-3.0	Moderate pollution		
V			> 3.0	Heavy pollution		

Table 1. Soil pollution level evaluation.

Index	Slight	Moderate	Strong	Very strong	Extremely strong
E _{ri}	< 40	40-80	80-160	160-320	> 320
RI	<150	150-300	300-600		>600

Table 2. Classification standards for potential ecological risk levels.

Peri

The PERI method, introduced by Hakanson in 1980, is widely used domestically and internationally to assess the ecological risks of heavy metals in soi²². The formula is as follows¹⁵:

$$\begin{split} E^i_r = T^i_r \times \ C^i_r = T^i_r \times \ C/C^i_n \\ RI = \sum\nolimits_i^n E^i_r \end{split}$$

Where E_i^i is the ecological risk index for each heavy metal; RI represents the total PERI; The toxic response factor T_r^i assigned to each metal is as follows²³: As = 10, Cr = 2, Cd = 30, Hg = 40, and Pb = 5; C_r^i denotes the contamination factor for a single heavy metal; C indicates the measured concentration of the heavy metal in the soil; C_n^l is the reference value, which corresponds to the soil pollution risk screening threshold in this study. The classification standards for potential ecological risk levels are provided in Table 2.

Crop pollution index

The crop pollution index method is utilized to characterize the heavy metal pollution risk in crops. This method is similar to the single-factor pollution index, representing the ratio of heavy metal concentration in crops to the national food safety standard limit. The formula is as follows²⁴:

$$CPI_i = \frac{CC}{CS}$$

Where CPI_i represents the crop pollution index for element i; CC_i denotes the measured concentration of the pollutant in the crop; CS_i is the standard limit for pollutant i in crops, based on the National Food Safety Standard: Maximum Levels of Contaminants in Foods (GB 2762-2017).

Bioconcentration factor (BCF)

The Bioconcentration Factor (BCF) is used to measure the ability of crops to absorb and accumulate heavy metals from soil, providing a direct indication of an element's bioavailability. This factor is calculated as the ratio of heavy metal content in the crop to the corresponding heavy metal content in root-zone soil. The formula is as follows²⁵:

$$BCF = \frac{C_p}{C_r}$$

Where BCF is the bioconcentration factor for a specific element; C_p indicates the heavy metal concentration in the crop; C_s denotes the heavy metal concentration in the root-zone soil.

Soil-crop heavy metal co-contamination evaluation

The Integrated Impact of Contamination Quality(IICQ) effectively integrates soil heavy metal content with crop heavy metal concentrations, accounting for soil environmental quality standards, elemental background values, specific soil loading capacities, and pollutant limits for agricultural products. In this study, a soil-crop integrated quality index method is applied to evaluate the study area, introducing three indicators formulated as follows¹⁷:

Relative Influence Equivalent (RIE) of soil:

$$RIE = \left[\sum_{i=1}^{N} (P_{ssi})^{1/n}\right] / N = \left[\sum_{i=1}^{N} (C_i/C_{si})^{1/n}\right] / N$$

Deviation Degree of Determined Background (DDDB) for soil elements:

$$DDDB = \left[\sum_{i=1}^{N} (P_{SBi})^{1/n}\right] / N = \left[\sum_{i=1}^{N} (C_i / C_{Bi})^{1/n}\right] / N$$

Deviation Degree of Standard Background (DDSB) for soil:

$$DDSB = \left[\sum {}_{i=1}^{N} (C_{Si}/C_{Bi})^{1/n}\right]$$

Crop Quality Index (QIAP) is a parameter used to evaluate the influence of heavy metal contamination on crop quality. A lower QIAP value signifies better agricultural product quality:

$$QIAP = \left[\sum_{i=1}^{N} (P_{APi})^{1/n}\right] / N = \left[\sum_{i=1}^{N} (C_{APi} / C_{LSi})^{1/n}\right] / N$$

Where n represents the oxidation state of element i; N indicates the total number of elements analyzed; C_i denotes the concentration of element i; C_{Si} denotes the soil environmental quality standard for the respective element; C_{Bi} denotes the background value of element; P_{SSi} is the index value of the measured element concentration relative to the standard value; P_{SBi} is the index value of the measured concentration relative to the background. C_{APi} represents the concentration of element i in the crop; C_{LSi} is the permissible limit of element i in crops; P_{APi} is the index value of crop heavy metal content relative to the regulatory limit.

IICQs represent the Integrated Impact Index of Soil Quality.

$$IICQ_s = X \times (1 + RIE) + Y \times DDDB/DDSB$$

Where X represents the number of soil measurements that surpass the national limit values, RIE represents the Relative Influence Equivalent for soil, Y is the count of measurements exceeding local background levels, DDDB denotes the extent of deviation of soil element concentrations from their natural background levels, and DDSB indicates the deviation of standards from background values.

IICQ_{AP} represents the Integrated Impact Index of Agricultural Product Quality.

$$IICQ_{Ap} = Z \times (1 + QIAP/k) + QIAP/(K \times DDSB)$$

Where Z represents the number of crop measurements that exceed the established regulatory limits, QIAP is the Crop Quality Index, k is the background correction factor, and DDSB represents the deviation of soil standards from background values.

IICQ represents the Comprehensive Quality Impact Index.

$$IICQ = IICQ_s + IICQ_{AP}$$

Based on the range of IICQ values, the quality is categorized into five levels (Table 3) : clean, mildly polluted, moderately polluted, heavily polluted, and extremely polluted. This classification yields 13 distinct soil and crop quality statuses, allowing for the determination of each sampling point's IICQ level and corresponding soil-crop quality status.

Results and discussion

Levels and pollution characteristics of soil heavy metals

Descriptive statistics of heavy metals in soil

Table 4 presents the statistical results of the mean, median, and standard difference of soil heavy metals across the 5778 sampling points in the study area, along with the background values for Henan Province and the national background values. The average concentrations of As, Cd, Cr, Hg, and Pb were determined to be 10.80 mg/kg, 0.17 mg/kg, 70.71 mg/kg, 0.05 mg/kg, and 29.49 mg/kg, respectively. The average values of all the elements, except for As and Hg, were observed to exceed the national soil background values. Furthermore, the concentrations of As (56.70%), Cd (99.60%), Cr (69.60%), Hg (71.30%), and Pb (92.60%) surpassed the background values specific to Henan Province.

IICQ ranges	Grade	Both soil and crop are uncontaminated	Only soil or crop is contaminatedr	Both soil and crop are contaminated
IICQ≤1	Clean	I		
$1 < IICQ \le 2$	Slightly contaminated		sub-II	II
2 <iicq≤2< td=""><td>Moderately contaminated</td><td></td><td>sub-III</td><td>III</td></iicq≤2<>	Moderately contaminated		sub-III	III
$3 < IICQ \le 5$	Heavily contaminated		sub-IV	IV
IICQ>5	Extremely contaminated		sub-V	V

Table 3. Grades of IICQ and soil environmental quality descriptions.

Items	As	Cd	Cr	Hg	Pb
Sample size	5778	5778	5778	5778	5778
Mean value	10.80	0.17	70.71	0.05	29.49
Median	10.40	0.15	70.60	0.04	28.30
Standard deviation	4.15	0.20	20.98	0.08	16.24
Skewness	1.78	33.79	2.83	19.32	43.71
Kurtosis	15.66	1499.37	24.21	566.90	2549.27
Minimum value	0.24	0.04	6.80	0.01	12.30
Maximum value	71.70	10.50	354.00	3.31	1030.00
Variable coefficient	0.39	1.19	0.30	1.60	0.55
Background values in Henan Province	9.80	0.07	63.20	0.03	22.30
National soil background values	11.20	0.10	61.00	0.07	27.00

Table 4. Description of heavy metals in soil statistical characteristics $/mg \cdot kg^{-1}$.

Crop type	Parameter	As	Cr	Cd	Hg	Pb
	Sample size	185	185	185	185	185
	Mean	13.57	79.42	0.19	0.04	29.58
Wheat root soil	Standard deviation	3.84	18.71	0.19	0.02	12.59
	Minimum	2.92	35.20	0.08	0.003	12.30
	Maximum	26.50	169.00	2.20	0.15	150.00
	Sample size	75	75	75	75	75
	Mean	11.83	87.08	0.55	0.04	38.45
Corn root soil	Standard deviation	3.72	75.31	2.51	0.04	34.27
	Minimum	1.89	45.90	0.09	0.002	20.20
	Maximum	19.90	631	21.60	0.30	263
	Sample size	114	114	114	114	114
	Mean	14.17	83.93	0.18	0.04	28.54
Peanut root soil	Standard deviation	5.16	28.83	0.13	0.01	6.06
	Minimum	4.65	42.30	0.08	0.02	9.00
	Maximum	35.10	264	1.05	0.09	44.50
	the average values for Henan Province ^a	10.00	45.00	0.15	0.05	23.60
	National background value ^b	11.20	61.00	0.10	0.07	27.00

Table 5. Characteristics of heavy metal content in root zone soils.

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Characteristics of soil heavy metal content

Table 5 summarizes the statistical analysis of heavy metal concentrations in the root-zone soils of wheat, corn, and peanuts within the study area. The data include mean, standard deviation, maximum, and minimum values, and are compared with the average concentrations reported for Henan Provinc²⁶ and the national background levels²⁷. In the root-zone soils of wheat, the average concentrations of arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hg), and lead (Pb) were 13.57 mg/kg, 0.19 mg/kg, 79.42 mg/kg, 0.04 mg/kg, and 29.58 mg/kg, respectively. For corn, the corresponding mean concentrations were 11.83 mg/kg for As, 0.55 mg/kg for Cd, 87.08 mg/kg for Cr, 0.04 mg/kg for Hg, and 38.45 mg/kg for Pb. In the case of peanuts, the mean levels of these metals were 14.17 mg/kg for As, 0.18 mg/kg for Cd, 83.93 mg/kg for Cr, 0.04 mg/kg for Hg, and 28.54 mg/kg for Pb. Except for Hg, the average concentrations of the other four heavy metals surpassed both the Henan Province averages and the national background values.

Soil heavy metal pollution levels

Pollution index

The pollution index and corresponding assessment levels for the five heavy metal elements As, Cr, Cd, Hg, and Pb are illustrated in Fig. 2. The findings indicate that the mean single-factor pollution indices for these metals follow the order of Cd (0.55) > Cr (0.47) > Pb (0.33) > As (0.27) > Hg (0.47). Among these, Cd and Cr exhibit the highest levels of pollution. Cr contamination is primarily concentrated in the northwest and southeast parts of the study area, while Cd pollution is mostly located in the central and southeastern regions, as illustrated in Fig. 2a. The spatial distribution of the Nemerow composite pollution index is depicted in Fig. 2b, with index values ranging from 0.18 to 25.27 and an average value of 0.482, indicating an overall non-polluted status. However, polluted areas are present, primarily centered in the Wancheng District of Nanyang City, in the southeastern mining zone near the Miyang-Tongbai border, and the western and north-central regions of Nanzhao County. In areas





				Sample count by pollution Level				
Heavy metal	Minimum value	Maximum value	Mean value	E _{ri} ≤40	$40 < E_{ri} \le 80$	$80 < E_{ri} \le 160$	$160 < E_{ri} \le 320$	E _{ri} >320
				Slight	Moderate	Strong	Very strong	Extremely strong
As	0.06	17.93	2.70	5778	0	0	0	0
Cr	0.09	4.72	0.94	5778	0	0	0	0
Cd	3.5	1050	16.62	5701	53	18	2	4
Hg	0.22	73.53	1.17	5777	1	0	0	0
Pb	0.68	57.21	1.64	5775	3	0	0	0

Table o.	Single element	n potentia	ecological	LISK	assessment	results.

Ecological Risk Level (RI)	RI < 150	$150{\leq}RI{<}300$	$300{\leq}RI{<}600$	RI>600
Hazard degree	Low	Moderate	Strong	Very strong
Sample count	5769	5	2	2

Table 7. Comprehensive evaluation results of potential ecological risk levels.

with high Nemerow pollution index values, both Cr and Cd single-factor pollution indices are elevated, making Cd and Cr pollution significant contributors to the Nemerow pollution index. The average value of the internal Merro comprehensive pollution index of heavy metals in the farmland soil around the copper mining area in Anhui Province was 2.59, and the average value of the internal Merro comprehensive pollution index of heavy metals in the plough layer soil of the farmland in the Wuwei Plain area of Gansu Province was 2.16^{28]-[29}. Compared with them, the soil heavy metal pollution index in the Nanyang Basin was lower.

Potential ecological risk assessment

The potential ecological risks of surface soils in the study area are summarized in Tables 6 and 7 and illustrated in Fig. 3. The average potential ecological risk indices for the five heavy metals As, Cr, Cd, Hg, and Pb are 2.70, 0.94, 16.62, 1.17, and 1.64, respectively, ranked in descending order as Cd > As > Pb > Hg > Cr. The potential ecological risk indices for As and Cr are below 40 at all sampling points, indicating a low ecological risk level. In contrast, Cd poses a higher ecological risk, with 53 locations classified as moderate risk, 18 as considerable risk, 2 as high risk, and 4 as very high risk. For Hg and Pb, only one and three points falls under the moderate risk category, while the remainder is at a low-risk level. In summary, Cr and Hg exhibit the lowest potential ecological risks, while Cd presents the greatest ecological threat.

The comprehensive PERI ranges from 6.45 to 1058.09, with an average of 23.10, suggesting that most areas in the study region present a low ecological risk for soil heavy metals, with most sampling points falling under the low-risk category. As shown in the spatial distribution map (Fig. 3), areas with high ecological risk are primarily located in the southeastern, central, and north-central regions, closely matching areas with elevated Cd concentrations and high Cd single-factor pollution indices (Fig. 2), making Cd the main contributor to ecological risk. Pang Guotao found that the comprehensive potential ecological risk index of soil heavy metals in the typical cultivated land area of Xinxiang City, Henan Province, ranged from 128.14 to 2696.06, with an



Fig. 3. Spatial distribution map of potential ecological risk index.

Crop type	Parameter	As	Cr	Cd	Hg	Pb
	Sample size	185	185	185	185	185
	Mean	0.001	0.064	0.054	0.0006	0.108
Wheat	Standard deviation	10.27	0.089	0.052	0.0006	0.025
	Minimum value	0.000	0.000	0.08	0.000	0.000
	Maximum value	0.036	0.557	0.614	0.0048	0.108
	Sample size	75	75	75	75	75
	Mean	0.009	0.169	0.018	0.0014	0.021
Corn	Standard deviation	11.43	0.25	32.39	0.0010	0.019
	Minimum value	0.000	0.000	0.000	0.000	0.000
	Maximum value	0.026	0.829	0.467	0.0032	0.078
	Sample size	114	114	114	114	114
	Mean	0.019	0.232	0.241	0.0011	0.016
Peanut	Standard deviation	0.022	0.432	0.152	0.0011	0.020
	Minimum value	0.005	0.000	0.026	0.000	0.000
	Maximum value	0.167	3.06	0.744	0.0060	0.105
Grains	Limit value	0.5	1.0	0.1	0.02	0.2
Peanut	Limit value	-		0.5	-	-

Table 8. Heavy metal content in crops.

average of 543.02³⁰. Obviously, the overall ecological risk degree of this area was higher than that of our study area. Although most areas remain within safe limits, some points have reached critical risk levels, necessitating targeted remediation at these sensitive sites.

Levels of heavy metal pollution in crops

Heavy metal content characteristics in crops

Table 8 presents the statistical results for heavy metal content in the wheat, corn, and peanut grains in the study area, including mean, standard deviation, maximum, and minimum values. For wheat grains, the average levels of these metals were recorded as 0.001 mg/kg, 0.054 mg/kg, 0.064 mg/kg, 0.0006 mg/kg, and 0.108 mg/kg, respectively. In corn grains, the mean concentrations of the same metals were found to be 0.0091 mg/kg, 0.018 mg/kg, 0.169 mg/kg, 0.0010 mg/kg, and 0.019 mg/kg, respectively. Peanut grains exhibited average values of 0.019 mg/kg for As, 0.241 mg/kg for Cd, 0.232 mg/kg for Cr, 0.0011 mg/kg for Hg, and 0.016 mg/kg for Pb. The heavy metal concentrations in both wheat and corn grains generally complied with the thresholds outlined in the National Food Safety Standard for Contaminants in Food (GB2762-2017), with all values for As, Cr, Hg, and Pb falling within acceptable limits. Currently, there are no established national contaminant limits for As, Cr, Hg, and Pb in peanuts, but the average Cd concentration in peanut grains was below the limit, while the maximum value exceeded it, indicating that some peanut samples were contaminated with Cd.

Crop type	Parameter	As	Cr	Cd	Hg	Pb	Evaluation
	Mean	0.020	0.063	0.534	0.028	0.096	
Wheat	Minimum	0.000	0.000	0.000	0.000	0.000	
	Maximum	0.072	0.557	6.140	0.238	0.540	
	Mean	0.018	0.169	0.178	0.072	0.107	
Corn	Minimum	0.000	0.000	0.000	0.000	0.000	
	Maximum	0.051	0.829	4.674	0.159	0.392	
	Mean			0.483			
Peanut	Minimum			0.052			
	Maximum			1.488			

Table 9. Crop pollution index.



Fig. 4. Distribution map of crop pollution index.

Levels of heavy metal pollution in crops

The crop pollution indices and corresponding assessment levels for As, Cr, Cd, Hg, and Pb in wheat and corn grains and for Cd in peanut grains are summarized in Table 9. The mean crop pollution indices for As, Cr, Cd, Hg, and Pb in wheat grains were 0.020, 0.063, 0.534, 0.028, and 0.096, respectively. For corn grains, the mean indices for these elements were 0.018, 0.169, 0.178, 0.072, and 0.107, respectively, while the mean crop pollution index for Cd in peanut grains was 0.483. All mean crop pollution indices for wheat and corn and Cd in peanuts were below 1, indicating that the crops are generally in an unpolluted state. However, the maximum crop pollution indices for Cd in wheat, corn, and peanut grains reached 6.140, 4.674, and 1.488, respectively, suggesting heavy metal pollution in some crop samples.

The distribution diagram of crop pollution index is shown in Fig. 4. In Neixiang County, Zhenping County, Dengzhou City, and Tongbai County, the Cd pollution index was significantly higher than other elements, with the highest Cd indices observed in Dengzhou City and Tongbai County. In Tanghe County, the Cr pollution index in corn grains was notably higher than other elements and significantly exceeded values in Tongbai County.

Bioaccumulation coefficient of heavy metals

BCF of heavy metals reflects the ability of crops to accumulate heavy metals from the soil^{31–32}. The BCF values for wheat, corn, and peanuts are shown in Fig. 5. In Tanghe County, the average BCF values for As, Cd, Cr, Hg, and Pb in wheat were 0.0012, 0.4368, 0.0028, 0.0356, and 0.0015, respectively, indicating that the bioaccumulation capacity in wheat for these metals followed the order Cd > Hg > Cr > Pb > As. For corn in the same region, the average BCF values were 0.0117 for As, 0.1586 for Cd, 0.0077 for Cr, 0.0372 for Hg, and 0.0012 for Pb, with Cd > Hg > As > Cr > Pb in terms of bioaccumulation capacity. In peanuts, the average BCF values were 0.0165 for As, 2.1969 for Cd, 0.0104 for Cr, 0.0083 for Hg, and 0.0012 for Pb, indicating that peanut bioaccumulation capacity ranked as Cd > As > Cr > Hg > Pb. In Dengzhou City, the average BCF values for As and Cd in wheat were 0.0007 and 0.2968, respectively. For corn, the average values for As and Cd were 0.0006 and 0.0695, while in peanuts, the BCF values for As and Cd were 0.0054 and 2.1665. In Neixiang County, wheat showed average BCF values of 0.0004 for As and 0.1811 for Cd, while peanuts had BCF averages of 0.0006 for As and 1.3174 for Cd. In Zhenping County, the average BCF values for As and Cd in wheat showed BCF averages of 0.0009 for As, 0.2412 for Cd, 0.0012 for Cr, 0.0421 for Hg, and 0.0021 for Pb, with Cd > Hg > Pb > Cr > As in bioaccumulation. Peanuts showed average BCF values of 0.0010 for As, 0.5820 for Cd,



Fig. 5. Enrichment coefficients of different crops in different regions.

0.0050 for Cr, 0.0200 for Hg, and 0.0010 for Pb, ranking as Cd > Hg > Cr > Pb = As. At the Tongbai-Miyang border, wheat exhibited average BCF values of 0.0010 for As, 0.4255 for Cd, 0.0003 for Cr, 0.0165 for Hg, and 0.0005 for Pb, with bioaccumulation capacity following Cd > Hg > As > Pb > Cr. In corn, the average BCF values for these metals were 0.0016 for As, 0.1163 for Cd, 0.0014 for Cr, 0.0274 for Hg, and 0.0441 for Pb, following the order Cd > Pb > Hg > As > Cr. A study by Yu Fei on the central part of Nanchuan District, Chongqing Municipality, also revealed that cadmium (Cd) exhibits strong migration and enrichment capacity in the soil-crop system³³. Similarly, Xiao Kaiqi investigated Fenghuang County, Xiangxi Tujia and Miao Autonomous Prefecture, and found that Cd had the highest enrichment factor among heavy metals in the edible parts of crops³⁴.

The BCF results across the study area indicate that for all regions, wheat, corn, and peanuts have the highest bioaccumulation capacity for Cd, significantly exceeding that for other metals. Among crops, peanuts show a notably higher capacity for Cd accumulation than wheat and corn.

Soil-crop coordinated heavy metal pollution levels

A comprehensive quality index method was employed to assess the coordinated pollution risk in the soil-crop system across the study area and at individual sampling points, resulting in soil quality indices, crop quality indices, and combined soil-crop quality indices, as detailed in Table 10. Additionally, the spatial distribution of these indices is visualized in Fig. 6.

In wheat samples, Level I points comprised a substantial proportion at 90.27%, indicating that the majority of soils were in a clean and healthy state. Nine sampling points showed instances where the soil was contaminated while the crops remained uncontaminated. Only three points exhibited contaminated crops with uncontaminated soil, all classified as sub-Level II. There was only one point where both the crops and soil were contaminated. In corn samples, Level I points were still predominant, accounting for 81.30%, indicating mostly clean and healthy soil. Twelve sampling points had contaminated soil with uncontaminated crops, while only one point showed contaminated crops with uncontaminated soil. Additionally, only one point exhibited contamination in both soil and crops. For peanut samples, the most significant proportion (71.93%) was found in the category where crops were contaminated but soil remained uncontaminated. The next most common category, with 15.79%, included samples where both soil and crops were unpolluted. There were five points where the soil was contaminated but the soil was uncontaminated, and five points where both soil and crops were contaminated.

The distribution of the comprehensive pollution index in wheat and corn samples was similar, with most sampling points classified as having unpolluted soil and crops. The next most frequent category included points with contaminated soil but uncontaminated crops, while only a few points exhibited either contaminated crops

Collaborative quality status	IICQ grade	Wheat Number	Proportion (%)	Corn Number	Proportion (%)	Peanut Number	Proportion (%)
Both uncontaminated	Ι	167	90.27	61	81.30	18	15.79
	sub-II	3	1.62	6	8.00	0	0.00
Soil contaminated and gran uncontaminated	sub-III	5	2.70	2	2.67	2	1.75
son containinated and crop uncontaininated	sub-IV	1	0.54	3	4.00	3	2.63
	Sub-V	0	0.00	1	1.30	0	0.00
	sub-II	3	1.62	1	1.30	82	71.93
Cross contaminated and acil uncontaminated	sub-III	0	0.00	0	0.00	4	3.51
Crop contaminated and soil uncontaminated	sub-IV	0	0.00	0	0.00	0	0.00
	sub-V	0	0.00	0	0.00	0	0.00
Poth contaminated	VV	5	2.70	0	0.00	1	0.88
both containmated	V	1	0.54	1	1.30	4	3.51

Table 10. The numbers and proportions of collaborative quality status and IICQ grade for wheat, corn and peanut in the study region.

with uncontaminated soil or contamination in both soil and crops. Unlike wheat and corn, peanuts showed the highest proportion of points with crop contamination despite uncontaminated soil. Peanuts also had a relatively higher proportion of points where soil and crops were contaminated.

The largest proportion of sampling points (65.78%) were classified as having unpolluted soil and crops, indicating that most soils were clean and healthy. In the study area, 34.22% of points showed pollution, with 3.21% exhibiting simultaneous contamination of both soil and crops, primarily concentrated in Tongbai-Biyang and Xichuan counties, which require increased attention. Additionally, 6.95% of points had polluted soil but uncontaminated crops, emphasizing the need for careful monitoring of soil quality at these locations. A notable 24.06% of points had contaminated crops with uncontaminated soil, with peanuts being the most affected crop. The majority of these points were classified as sub-Level II, predominantly located in Tanghe, Dengzhou, Neixiang, Zhenping, and Xichuan counties.

Conclusion

The average single-factor pollution index for the study area was below 1. The Nemerow Pollution Index ranged from 0.18 to 25.27, averaging 0.482. The majority of the study area exhibited low soil pollution levels, dominated by unpolluted and lightly polluted zones. However, moderate to severe pollution was observed in some areas, with Cd being the most significant contaminant. The evaluation of potential ecological risks from soil heavy metals revealed average single-element risks for As, Cr, Cd, Hg, and Pb of 2.70, 0.94, 16.62, 1.17, and 1.64, respectively. The overall average ecological risk index was 23.10. Most areas in the study region showed low ecological risks for heavy metals, with most sampling points classified under the low-risk category. However, higher ecological risk values were observed in the southeastern, central, and northern-central regions, with Cd being the primary contributor to the elevated risk levels. The heavy metal content in the vast majority of sample sites of crops such as wheat, corn and peanuts in the study area was less than the national food safety limits, while the content in only one other sample site exceeded this limit value.Cd was the primary contaminant in wheat grain samples, with minimal contamination from As, Cr, Hg, and Pb. In different administrative regions, wheat, corn, and peanuts showed the strongest bioaccumulation capacity for Cd, significantly higher than other elements. Among these crops, peanuts exhibited a higher ability to absorb and accumulate Cd than wheat and corn. The evaluation of the soil-crop comprehensive quality index indicated that the largest proportion of sampling points were classified as having both unpolluted soil and crops. The next most common condition was crops being contaminated while the soil remained unpolluted, with peanuts being the primary crop affected. By visualizing the spatial distribution of soil heavy metal pollution in the Nanyang Basin and regional division of the risk levels of soil and crops, this has reference value for preventing and controlling soil heavy metal pollution and optimizing the layout of land use. Through the analysis of this research, it is possible to precisely monitor and establish a governance system for areas with risks, and control the further deepening of pollution. The absorption and enrichment of heavy metals by crops can be influenced by many external factors, such as climate, soil properties, and the growth stage of crops. These factors should be further considered in future research. This study conducted a risk assessment of the co-pollution of heavy metals in soil and agricultural crops. Next, it further explored the co-pollution situations of the soil-groundwater and soil-atmospheric environments to form a complete systematic research work.





Fig. 6. Results of soil-crop comprehensive quality index.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Declarations

Competing interests

The authors declare no competing interests.

Declaration of competing interest

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

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