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Original Research

Study on Influencing Factors of Cadmium Accumulation in Wheat and Soil Risk Threshold in Karst Geogenic High-Background Areas

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Abstract

Wheat is the most widely cultivated food crop globally and is susceptible to the accumulation of cadmium (Cd). The risk screening value for soil Cd concerning wheat as specified in the national standard of China ("Safety thresholds of Cd, Pb, Cr, Hg, As in soil for wheat production", GB/T 41685-2022) is lower than the national standard ("Soil environmental quality - Risk control standard for soil contamination of agricultural land", GB 15618-2018) in China. However, its applicability in karst regions with high geogenic backgrounds remains uncertain. This study focuses on 3 counties in the karst core of southwest China: HZ (heavily polluted), DF (moderately polluted), and NY (unpolluted). A total of 203 paired soil–wheat samples were collected to determine the concentrations of Cd, Hg, As, Pb, and Cr, examine the factors influencing wheat Cd accumulation, and derive soil Cd risk thresholds. Results showed that 54.67% of wheat samples exceeded the food limit for Cd, with exceedance rates of 84.49%, 64.44%, and 26.14% in HZ, DF, and NY, respectively. Wheat Cd is extremely negatively correlated with pH, with a correlation coefficient of -0.24 ($p<0.01$). In NY County, wheat Cd was strongly correlated with soil Cd ($p<0.01$), whereas this relationship was weaker in polluted areas. The variety Fengyou 5 exhibited low Cd accumulation (BCF = 0.105). The soil Cd risk thresholds were estimated at 0.28, 0.13, and 0.45 $mg \cdot kg^{-1}$ for HZ, DF, and NY, respectively. Overall, soil Cd content and pH were identified as the key factors regulating wheat Cd accumulation. We should pay more attention to controlling Cd

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accumulation in polluted areas, and planting low-Cd varieties could ensure safe production in unpolluted karst high-background regions.

Keywords: karst high-background area, wheat, risk elements, variety, soil safety threshold

Introduction

Cadmium (Cd), a representative toxic risk element, has long attracted considerable attention in environmental science due to its strong tendency to migrate and accumulate within soil–plant systems. As one of the world's most extensively cultivated staple crops, wheat tends to accumulate Cd in its grains, which is closely linked to food safety and poses potential risks to human health [1, 2]. The karst landscape, characterized by unique geological structures and soil conditions, exerts a strong influence on agricultural productivity and the ecological stability of the surrounding environment. In regions with naturally high heavy-metal backgrounds, elevated soil Cd levels pose a considerable risk to the safe cultivation of crops [3, 4]. The study area represents a key part of the karst region widely distributed in southwest China, where the geochemical background levels of soil risk elements are markedly higher than the national average [5]. Although China's main wheat production areas are concentrated in the north, with smaller planting areas in the south, and previous studies on wheat Cd accumulation have mainly focused on northern regions, the karst areas, as one of the major wheat production regions in southwest China, face a critical issue of Cd pollution. This is mainly attributed to wheat's strong ability to accumulate Cd, making Cd contamination an urgent problem that must be addressed to ensure safe wheat production in the region [6, 7]. Currently, risk elements contamination in soils has become a major environmental concern in karst regions. The primary sources of pollution originate from long-term zinc smelting activities and the disposal of waste residues from lead-zinc mining, resulting in markedly elevated concentrations of Cd, Pb, As, Cr, and Hg in surface soils compared with their natural background levels. Moreover, the concentrations of risk elements derived from zinc smelting are substantially higher in surface dust than in the surrounding agricultural soils [8, 9]. At the same time, notable variations in soil heavy-metal concentrations are observed among different geological units within the region. The high geochemical background further exacerbates the risk of heavy-metal accumulation [10]. From a source perspective, Cd includes geological origins such as the weathering of mineralized ores and the release of metals from rock erosion [11, 12], along with human-induced inputs, including industrial operations and the use of fertilizers and pesticides, mineral extraction, and atmospheric deposition [13-15]. Identifying its sources is essential for developing effective control measures and mitigating environmental impacts [16]. In karst regions with elevated geogenic heavy-metal backgrounds, soil characteristics and wheat cultivars have been identified as key factors governing Cd uptake in the crop [17, 18]. However, it remains unclear whether total soil Cd concentration and pH consistently act as the primary determinants of Cd accumulation in wheat across different pollution gradients. Additionally, the Chinese national standard "Safety thresholds of Cd, Pb, Cr, Hg, As in soil for wheat production" (GB/T 41685-2022) specifies lower Cd risk screening values for wheat-producing soils than those in another national standard, the "Soil environmental quality – Risk control standard for soil pollution in agricultural land" (GB 15618-2018). However, due to the complexity of soil systems, significant regional differences in farmland environments, and the diverse sources of heavy-metal pollution, the applicability of this standard to karst regions with high geological backgrounds of risk elements is limited [19, 20]. As a result, local governments face challenges in achieving precise classification and management of agricultural land.

In light of this, the present study focuses on the research areas of HZ County (heavily polluted), DF County (moderately polluted), and NY County (unpolluted) in the core karst region of southwest China. A total of 203 paired soil-wheat samples were collected for analysis. Based on a comprehensive analysis of the main factors influencing wheat Cd accumulation in the region, the study examines the suitability of the current "National Food Safety Standard for Food Contaminant Limits" (GB 2762-2025) for evaluating safe wheat production soils in the area. Furthermore, the study derives the health risk threshold for Cd in wheat production soils in the study areas through species sensitivity distribution curves. The aim is to provide scientific evidence and new insights for safe wheat cultivation in the region and offer a reference for managing Cd contamination risks in agricultural land in similar geological background areas globally.

Materials and Methods

Overview of the Study Area

The research area is situated in the northwestern region of Bijie City, Guizhou Province, with geographic coordinates ranging from 103°36′ to 106°43′ east longitude and 26°21′ to 27°46′ north latitude. The area is characterized by a northern subtropical monsoon humid climate. The dominant soil type in the study area is yellow soil, a zonal soil formed under perennially humid subtropical bioclimatic conditions. Its primary texture is loam, accounting for 39.92% of the total soil area. All monitoring sites in the NY, HZ, and DF regions exhibit loam-textured soils and are situated within typical karst landscapes, which are recognized as geochemically anomalous zones for elements such as Cd, Pb, As, and Cr. Among these, the geochemical background value of soil Cd is particularly elevated compared with the national average. NY, HZ, and DF counties are the main wheat production areas within the study region, with a total wheat planting area of nearly 2 million acres. As a local specialty crop, the wheat industry has become a pillar supporting rural revitalization. The soil risk elements pollution characteristics in the three counties differ significantly. Among them, HZ County is one of the areas with high-risk elements content in China. Not only is the geological background of this area characterized by high risk elements background values, but it is also a historical center for traditional zinc smelting, a practice that has developed for over 300 years [21]. Currently, there are still large-scale abandoned mining areas within the county. Historical zinc smelting operations have caused substantial accumulation of risk elements, particularly cadmium (Cd), in nearby soils and sediments, resulting in a high potential risk of soil contamination [22]. DF County was historically supported by traditional sulfur smelting as a pillar of the local economy. However, over a million tons of waste slag were left behind from the extensive, workshop-based sulfur smelting production. There are also large amounts of open sulfur furnaces and slag piles, which have caused severe ecological damage and led to soil risk elements pollution in the region, with Cd contamination being particularly prominent. NY County's soil exhibits high geochemical background levels of Cd and Hg, but the risk elements content in agricultural soils is generally at a non-polluted or moderately polluted level [8, 23]. Studies have shown that the cadmium (Cd) content in agricultural soils of this region mainly derives from the parent material, with risk elements contamination largely governed by geogenic background factors [24].

Sample Collection and Testing Methods

In this study, extensive field surveys were conducted in HZ, DF, and NY counties in Bijie City. Because the wheat planting areas differed substantially among the three regions (approximately 17 km^2 in HZ, 13 km^2 in DF, and 33 km^2 in NY), the sampling design was adjusted accordingly. Regions with larger planting areas and more spatially dispersed farmland required more sampling sites to ensure adequate representation of different cultivation zones, whereas smaller and more spatially concentrated planting areas could be sufficiently characterized with fewer sites. The number of sampling sites was also determined based on the expected complexity of pollution sources and the degree of geological heterogeneity within each region. Areas with more complex contamination patterns or greater geological variability were assigned more sampling points to better capture spatial variation. A total of 203 sampling points were established, with 70, 45,

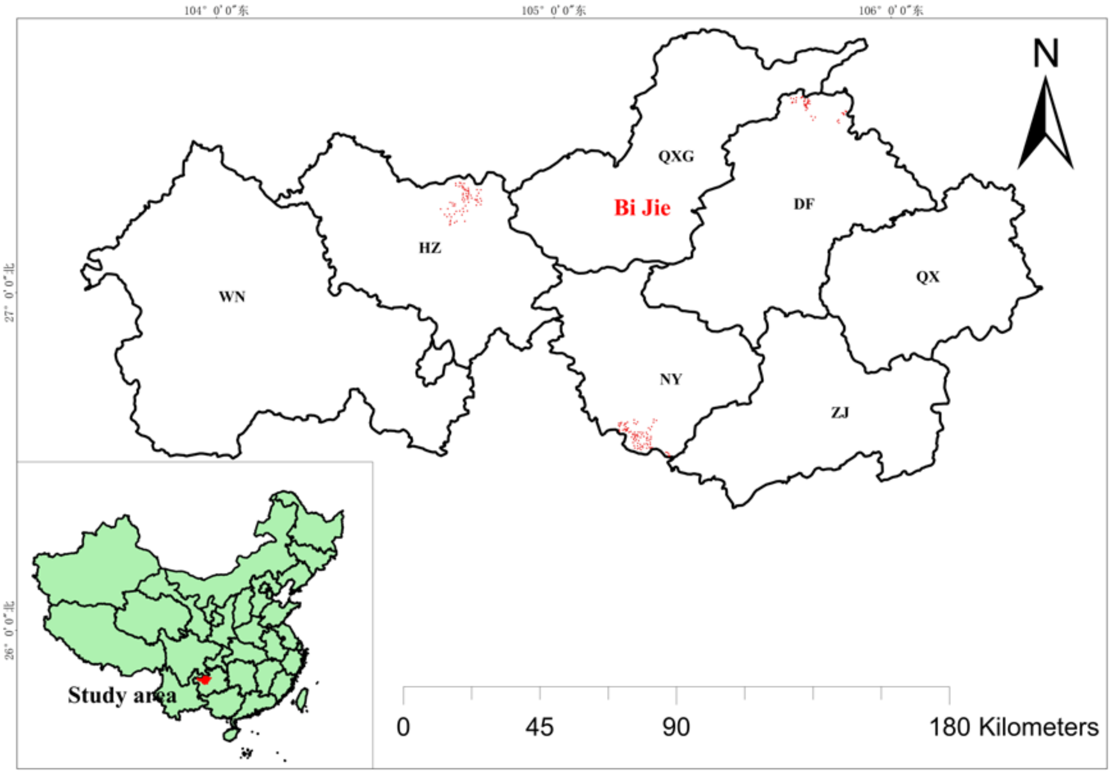

Fig. 1. Location map of the study area and distribution of sampling points.

and 88 sampling points in HZ, DF, and NY counties, respectively. A five-point sampling method was used for cooperative sampling. Mature wheat samples (grains) and surface soil samples (0-20 cm) were uniformly mixed and placed in bags. The specific geographic coordinates of each sampling point were recorded using GPS. The distribution map of the sampling points is shown in Fig. 1.

Wheat grains were deactivated at 105°C for 30 min to remove enzyme activity, followed by oven-drying at 60°C until a constant weight was achieved. The samples were subsequently ground into fine powder for risk elements analysis. Soil samples were air-dried and passed through sieves to eliminate plant residues, plastics, roots, and stones. A portion of each sample was finely ground and sieved through a 2 mm nylon mesh for pH measurement. A subsample was further sieved to 0.149 mm for risk elements analysis. Soil pH was determined using a pH meter (PHS-3C) at a soil-to-water ratio of 1:2.5. Exactly 10 g of soil (sieved to 2 mm) was weighed into a 100 mL beaker, mixed with 25 mL of deionized water, and stirred vigorously for 5 min using a magnetic stirrer. After settling for 15 min, pH was measured. For the determination of Cd, Hg, As, Pb, and Cr, 0.5 g of wheat flour was digested in a microwave digestion system with 5 mL of concentrated HNO_3, 3 mL of deionized water, and 2-3 drops of H_2O_2. Following digestion, the solution was diluted to 50 mL and analyzed using inductively coupled plasma mass spectrometry (ICP-MS). For the determination of Cd, Pb, and Cr content in soil, 0.1 g of soil was digested with 3 mL of HNO_3 and 1 mL of HF, followed by heating at 185°C for 24 h. After evaporating the solution to near dryness, the remaining residue was dissolved in 2% HNO_3 and diluted to a final volume of 50 mL for ICP-MS analysis. Total Hg was measured directly on solid samples using an atomic mercury analyzer (AMA 254) to account for its volatility. A 0.15 g soil sample was placed into a nickel boat, loaded into the autosampler in sequence, and subsequently introduced into the instrument for analysis. Soil As was determined using atomic fluorescence spectrometry (AFS; AFS-8230, Beijing Titan Instruments, China). A 0.3 g soil sample was placed in a 50 mL stoppered colorimetric tube, moistened, and digested with 10 mL of diluted aqua regia (HNO_3:HCl = 1:3, then diluted 1:1) in a boiling-water bath for 2 h with intermittent shaking. After cooling, the digest was diluted to volume and mixed. A 10 mL aliquot of the digest was transferred to a 50 mL colorimetric tube, followed by 3 mL HCl, 5 mL thiourea solution (10 g in 200 mL water), and 5 mL ascorbic acid solution (10 g in 200 mL water). The mixture was diluted to volume, mixed, allowed to stand, and the supernatant was used for analysis. A reagent blank was prepared simultaneously. Certified reference materials for soil (GBW07385, GSS-29) and wheat (GBW(E)100913) were employed to verify analytical accuracy, with each reference material analyzed in triplicate. Recovery rates for soil and wheat samples ranged from 80% to 120% and 70% to 130%, respectively, confirming acceptable analytical performance.

Research Methods

Risk Elements Pollution Assessment

The Potential Ecological Risk Index method, developed by Swedish researcher Hakanson in 1980 [25], is widely used to evaluate the extent of soil risk elements contamination and its associated ecological risks. The calculation formula is as follows:

$$E_r^i = T_r^i \times \left(\frac{C_i}{C_n^i}\right) \tag{1}$$

$$RI\sum E_r^i \tag{2}$$

In the formula, E_r^i denotes the potential ecological risk factor associated with risk element *i*; C_i represents the measured concentration of risk element *i* in the soil; C_n^i refers to the background concentration of risk element *i*; and T_r^i denotes the toxicity response coefficient of risk element *i*. The toxicity coefficients for Cd, Hg, As, Pb, and Cr are 30, 40, 10, 5, and 2, respectively. *RI* represents the overall potential ecological risk index for risk elements in the soil, and the classification criteria for this index are presented in Table 1.

Soil Threshold Derivation Method

This study employs the Species Sensitivity Distribution (SSD) approach [26]. The safe threshold of soil Cd content is investigated using the cumulative

Table 1. Potential ecological risk factor E_r^i, risk index (RI), and risk levels for risk elements.

E_r^i	Ecological Risk Level	RI	Ecological Risk Level
$E_r^i<40$	Slight	$RI<150$	Slight
$40\leq E_r^i<80$	Moderate	$150\leq RI<300$	Moderate
$80\leq E_r^i<160$	Strong	$300\leq RI<600$	Strong
$160\leq E_r^i<320$	Very Strong	$RI\geq 600$	Very Strong
$E_r^i\geq 320$	Extremely Strong		

probability distribution curve. A nonlinear fitting of the data is performed using a log-logistic distribution to establish the functional relationship between exposure concentration and the cumulative probability of affected species. Based on this, the potential proportion of species affected under specific exposure scenarios is extrapolated. The maximum allowable environmental concentration, which ensures 95% of species are protected from significant adverse effects, is calculated as the Hazard Concentration for 5% of species (HC_5), enabling quantitative characterization of the ecological risk of pollutants.

The detailed procedure is outlined as follows:

1. Using the Cd concentrations measured in crop samples and their corresponding soils, the bioaccumulation factor (BCF) for the edible parts of the crops was calculated and expressed as a probabilistic distribution indicator.
2. The log-logistic distribution is used to fit the SSD curve.
3. According to the Cd limits for different crops specified in the "National Food Safety Standard for Contaminant Limits in Food" (GB 2762-2025), the HC_5 value is derived, which ensures the safety of 95% of crop species. This HC_5 value is defined as the threshold for soil safe production. The BCF for the edible portion of a crop is defined as the ratio between the pollutant concentration in the crop and the total pollutant concentration in its surrounding ecological environment. The calculation formula is presented in Equation (3).

$$\mathrm{BCF} = \frac{c_{crop}}{c_{soil}} \tag{3}$$

Determining the fitting function. In this study, the commonly used logistic fitting function was selected to construct the SSD curve. The corresponding formula is as follows:

$$y = \frac{a}{1 + \left(\frac{x}{x_0}\right)^b} \tag{4}$$

The safe production threshold for soil risk elements in wheat is derived by back-calculating from the above equation. The calculation formula is shown in Equation (5).

$$\frac{1}{\mathrm{BCF}} = 10^{\frac{\lg\left(\frac{a}{y}-1\right)}{b}} + \lg x_0 \tag{5}$$

The safe production threshold of soil risk elements for wheat, denoted as C_{soil}, is estimated using the formula presented in Equation (6).

$$C_{\mathrm{soil}} = \frac{1}{\mathrm{BCF}} \times C_{\mathrm{crop}} \tag{6}$$

According to the "National Food Safety Standard for Contaminant Limits in Food" (GB 2762-2025), the standard limit for Cd in wheat grains is 0.10 mg·kg^{-1}.

Data Analysis

Microsoft Excel 2019 was utilized for data organization. Statistical differences among experimental treatments were analyzed using analysis of variance (ANOVA), and treatment means were compared with the Tukey test in SPSS Statistics 23.0 (IBM, Armonk, NY). Graphical visualizations were created using Origin 2021.

Results

Risk Elements Concentrations in Soils and Pollution Assessment across Different Study Areas

Soil risk element contamination poses a direct threat to food safety. Thus, accurately evaluating the potential ecological risks of risk elements-polluted soils is crucial for ensuring regional environmental security and promoting sustainable agricultural development. The results of the calculation of the E_r^i for risk elements in each study area are shown in Fig. 2. In the HZ area, the average E_r^ivalues for the five risk elements, ranked from highest to lowest, are as follows: Cd (64.20) > Hg (48.56) > As (5.85) > Pb (4.89) > Cr (2.82). The E_r^i values for As, Pb, and Cr are all below 40, suggesting a low level of ecological risk. The overall soil risk associated with Cd and Hg is classified as a moderate ecological hazard; in the DF area, the average E_r^i values for the five risk elements, arranged in descending order, are as follows: Hg (61.16) > Cd (49.96) > As (6.11) > Pb (5.15) > Cr (2.68). The E_r^i values for As, Pb, and Cr are all below 40, indicating a slight ecological risk, while the overall soil risk associated with Cd and Hg falls within the category of moderate ecological risk; In the NY area, the average E_r^i values for the five risk elements, ranked from highest to lowest, are as follows: Hg (44.23) > Cd (37.63) > As (8.41) > Pb (4.88) > Cr (2.58). The E_r^i values for Cd, As, Pb, and Cr are all less than 40, indicating a slight ecological risk. Hg overall presents a moderate ecological risk. The *RI* for HZ, DF, and NY areas are all below 150 (Fig. 2b)), indicating a slight ecological risk in all three regions.

As presented in Table 2, the pH of surface soils across the study region varied from 4.27 to 8.17, with an average value of 5.79±0.92. The average concentrations of Cd, Hg, As, Pb, and Cr in soils were 1.15, 0.25, 14.91, 48.09, and 125.61 mg·kg^{-1}, respectively. When compared with the corresponding local background values, these concentrations were 1.74, 2.27, 1.37, and 1.32 times higher for Cd, Hg, Pb, and Cr, respectively. Notably, 74.38% of sampling points exceeded background values for Cd, and 79.80% exceeded background values for Cr, indicating substantial enrichment. The coefficients of

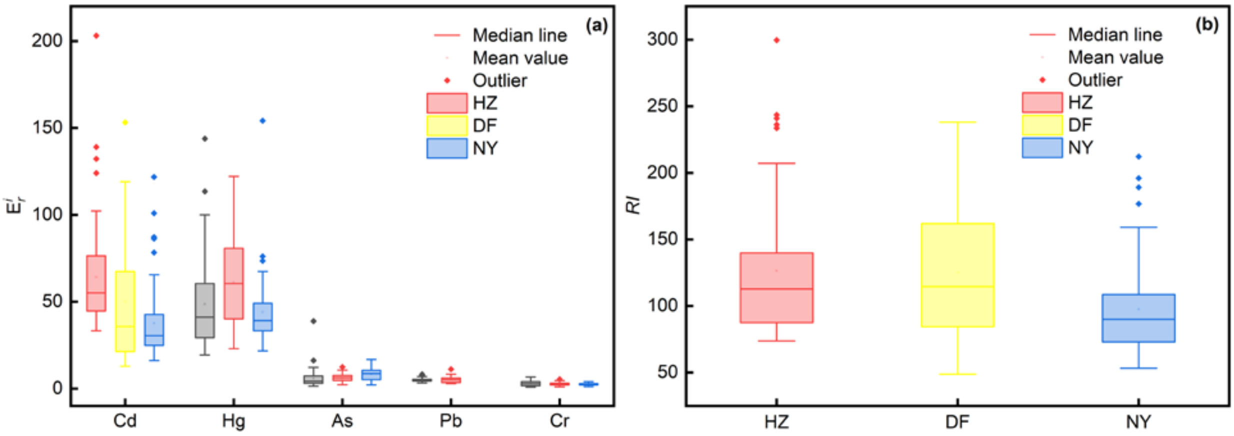

Fig. 2. Potential ecological risk assessment of soil risk elements in different study areas.

variation (CVs) for the five risk elements, in descending order, were: Hg (275.81%) > Pb (168.47%) > Cd (61.62%) > As (59.64%) > Cr (36.33%), with Hg and Pb showing substantial variability, and Cd, As, and Cr showing moderate variability.

Among the three counties, HZ County showed the highest mean soil Cd concentration (1.46 mg·kg^{-1}) and the lowest average pH (5.55±0.82). Cd concentrations in HZ exceeded background values at all sampling points (100%). DF County had an average soil Cd content of 1.22 mg·kg^{-1}, in contrast, NY County had the lowest mean Cd concentration (0.87 mg·kg^{-1}), yet it still exceeded the background level at 57.95% of the sampling sites. The soil As concentration in NY was markedly higher than that in HZ and DF. Moreover, NY exhibited the highest mean pH value (6.10±0.92), substantially exceeding those observed in the other two counties.

Compared with the national agricultural land pollution risk control standards, the proportion of samples in HZ County exceeding screening values for Cd, As, and Cr were 100%, 1.43%, and 71.43%, respectively, with 22.86% of samples exceeding the Cd control value. In DF County, 95.56% and 15.56% of samples exceeded screening values for Cd and Cr, respectively, with 28.89% exceeding the Cd control value. Although NY County is considered a high-background and non-polluted area, 97.73% of its samples still exceeded the Cd screening value. These findings indicate that all three counties experience varying degrees of Cd and Cr enrichment; the most severe contamination was observed in HZ County, attributed to its history of artisanal mining and smelting activities.

Analysis of the Differences in Wheat Cd Accumulation across Different Study Areas

The statistical summary of risk elements concentrations in wheat grains from each study area is provided in Table 3. It is noteworthy that Hg was not detected in any of the samples; therefore, Hg-related data are not included in the tables or figures. Across all regions, Cd concentrations in wheat grains varied from 0.002 to 0.475 mg·kg^{-1}, with an average of 0.142±0.106 mg·kg^{-1}. About 54.19% of the samples exceeded the national maximum permissible Cd limit in food (0.1 mg·kg^{-1}), suggesting a potential dietary exposure risk in the study area. The Cd content in wheat grains exhibited clear spatial variability, with the highest mean concentration found in HZ County (0.210 mg·kg^{-1}), followed by DF County (0.158 mg·kg^{-1}), and the lowest in NY County (0.079 mg·kg^{-1}). The corresponding exceedance rates were 84.29%, 64.44%, and 26.14%, respectively. In contrast, only a single sample from NY County surpassed the national limit for Pb (0.2 mg·kg^{-1}).

The Cd content in different wheat varieties is shown in Fig. 3. The ω(Cd) values for Fengyou 5, ApoGaomai, Qianmai 20, Qianmai 22, Yaanzao, and Yuanmai are 0.079, 0.217, 0.136, 0.196, 0.202, and 0.169 mg·kg^{-1}, respectively. The ω(Cd) content of Fengyou 5 is significantly lower than the other five varieties. Except for Fengyou 5, the ω(Cd) content of the other five wheat varieties exceeds the national food safety limit (0.1 mg·kg^{-1}). The exceedance rates for Fengyou 5, ApoGaomai, Qianmai 20, Qianmai 22, Yaanzao, and Yuanmai are 27.27%, 91.30%, 63.64%, 83.33%, 75.00%, and 61.54%, respectively. The average BCF for Fengyou 5, ApoGaomai, Qianmai 20, Qianmai 22, Yaanzao, and Yuanmai are 0.105, 0.206, 0.102, 0.208, 0.219, and 0.107, respectively. The BCF of Fengyou 5 is significantly lower than that of ApoGaomai, Yaanzao, and Qianmai 22, indicating it has a low accumulation characteristic.

The Cd content and BCF of wheat from different pollution areas are shown in Fig. 4. In HZ County, the average ω(Cd) content for ApoGaomai, Yaanzao, and Qianmai 20 are 0.217, 0.222, and 0.158 mg·kg^{-1}, respectively. Among these, Qianmai 20 has a significantly lower average ω(Cd) content and BCF compared to ApoGaomai and Yaanzao, but the ω(Cd) content for all three varieties exceeds 0.1 mg·kg^{-1}. In DF County, the average ω(Cd) content for Yuanmai, Yaanzao, Qianmai 22, and Qianmai 20 are 0.170, 0.154, 0.196, and 0.128 mg·kg^{-1}, respectively. The ω(Cd) content of Qianmai 20 is significantly lower than that of

Table 2. Risk elements content and pollution assessment of soil in different study areas.

Study area	Project	Risk elements					
		Cd	Hg	As	Pb	Cr	pH
Total(n=203)	Range	0.28~4.47	0.05~4.49	2.82~77.60	18.10~553.00	39.60~318.00	4.27~8.17
	The mean ± standard deviation	1.15±0.71	0.25±0.68	14.91±8.89	48.09±81.02	125.61±45.63	5.79±0.92
	Coefficient of variation/%	61.62%	275.81%	59.64%	168.47%	36.33%	15.93%
	Super-filtered values /%	98.03%	2.46%	2.46%	2.46%	18.72%	-
	The control value is exceeded /%	14.29%	2.46%	-	2.46%	-	-
	Point exceedance rate /%	74.38%	56.16%	20.20%	39.41%	79.80%	-
HZ (70)	Range	0.73~4.47	0.05~0.40	2.82~77.60	22.90~57.10	39.60~318.00	4.30~7.82
	The mean ± standard deviation	1.46±0.73a	0.14±0.07a	12.14±9.95b	34.68±7.63a	133.63±62.26a	5.55±0.82b
	Super-filtered values /%	100.00%	-	1.43%	-	71.43%	-
	The control value is exceeded /%	22.86%	-	-	-	-	-
	Point exceedance rate /%	100.00%	57.14%	10.00%	34.29%	74.29%	-
DF (45)	Range	0.28~3.37	0.06~0.34	4.30~24.70	19.60~77.80	48.3~256.00	4.27~7.80
	The mean ± standard deviation	1.22±0.81b	0.18±0.07a	12.48±4.36b	37.69±14.36a	126.48±39.21a	5.66±0.95b
	Super-filtered values /%	95.56%	-	-	-	15.56%	-
	The control value is exceeded /%	28.89%	-	-	-	-	-
	Point exceedance rate /%	66.67%	77.78%	4.44%	55.56%	80.00%	-
NY (88)	Range	0.35~2.68	0.06~4.49	4.06~38.10	18.10~553.00	55.20~191.00	4.55~8.17
	The mean ± standard deviation	0.87±0.49c	0.36±1.01a	18.36±8.48a	64.08±120.26a	118.78±28.46a	6.10±0.92a
	Super-filtered values /%	97.73%	5.68%	4.55%	5.68%	12.50%	-
	The control value is exceeded /%	-	5.68%	-	5.68%	-	-
	Point exceedance rate /%	57.95%	44.32%	36.36%	35.23%	84.09%	-
	Local soil background value	0.66	0.11	20.00	35.20	95.50	-

Note: Different lowercase letters within a column indicate significant differences among study areas at $p \leq 0.05$ (LSD test). The unit of risk elements is mg·kg-1. A "-" indicates no relevant data.

Table 3. Risk elements content and safety risk assessment of wheat in different study areas.

Study area	Project	Risk elements			
		Cd	As	Pb	Cr
Total(n=203)	Range	0.002~0.475	0.001~0.133	0.000~0.237	0.052~0.324
	The mean ± standard deviation	0.142±0.106	0.014±0.017	0.050±0.034	0.127±0.044
	Coefficient of variation/%	74.8%	127.0%	68.7%	34.6%
	Out-of-limit values/%	54.19%	-	0.49%	-
HZ (n=70)	Range	0.063~0.475	0.004~0.133	0.031~0.155	0.070~0.246
	The mean ± standard deviation	0.210±0.103a	0.012±0.017c	0.070±0.024a	0.143±0.035b
	Coefficient of variation/%	0.49	1.34	0.35	0.24
	Out-of-limit values/%	84.29%	-	-	-
DF (n=45)	Range	0.002~0.472	0.006~0.121	0.016~0.062	0.052~0.324
	The mean ± standard deviation	0.158±0.117b	0.031±0.020a	0.031±0.009c	0.147±0.060a
	Coefficient of variation/%	0.74	0.66	0.71	0.41
	Out-of-limit values/%	64.44%	-	0.49%	-
NY (n=88)	Range	0.015~0.315	0.000~0.056	0.000~0.237	0.070~0.203
	The mean ± standard deviation	0.079±0.053c	0.014±0.018b	0.044±0.044b	0.104±0.026a
	Coefficient of variation/%	0.66	1.42	1.00	0.25
	Out-of-limit values/%	26.14%	-	1.14%	-
	Limited value	0.10	0.50	0.20	1.00

Note: Different lowercase letters within the same column denote statistically significant differences among study areas at $p \leq 0.05$, as determined by the LSD test. The unit of risk elements is mg·kg-1. A "-" indicates no relevant data.

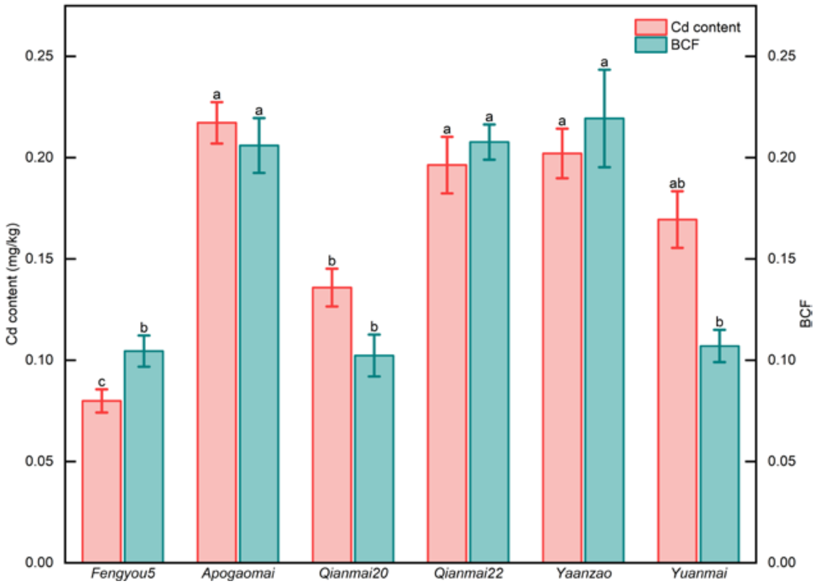

Fig. 3. Cd content and BCF of different wheat varieties.

Note: Different lowercase letters within the same column denote statistically significant differences among study areas at $p \leq 0.05$, as determined by the LSD test.

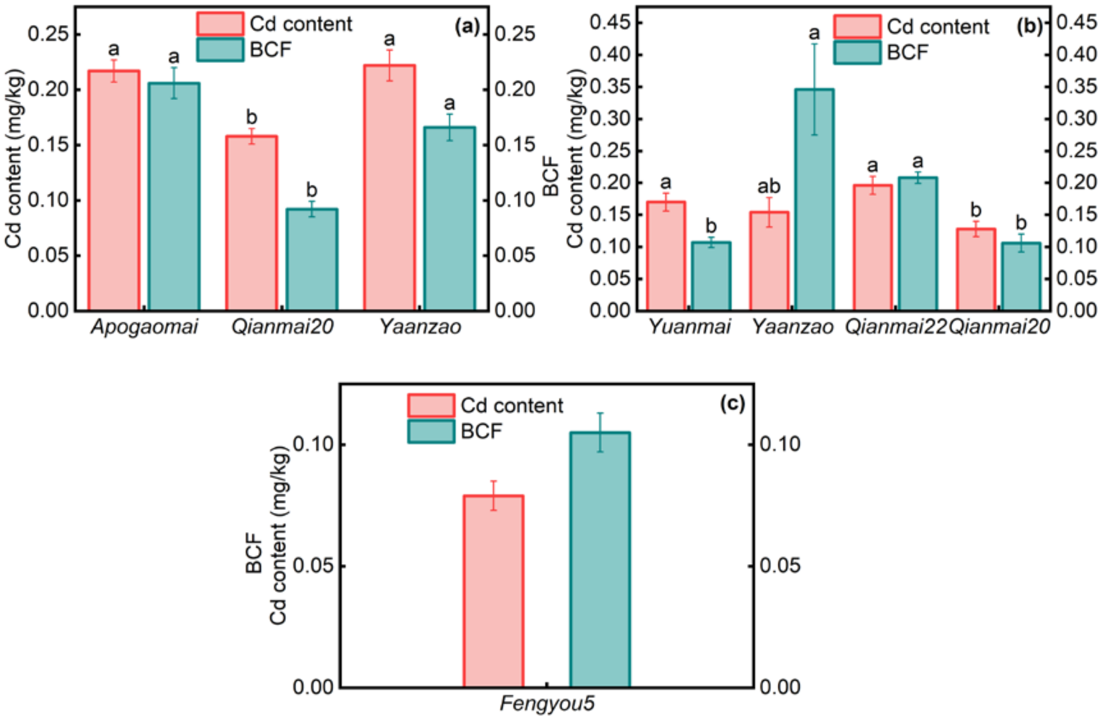

Fig. 4. Cd content and BCF of wheat in different study areas.
Note: Different lowercase letters within the same column denote statistically significant differences among study areas at p≤0.05, as determined by the LSD test.

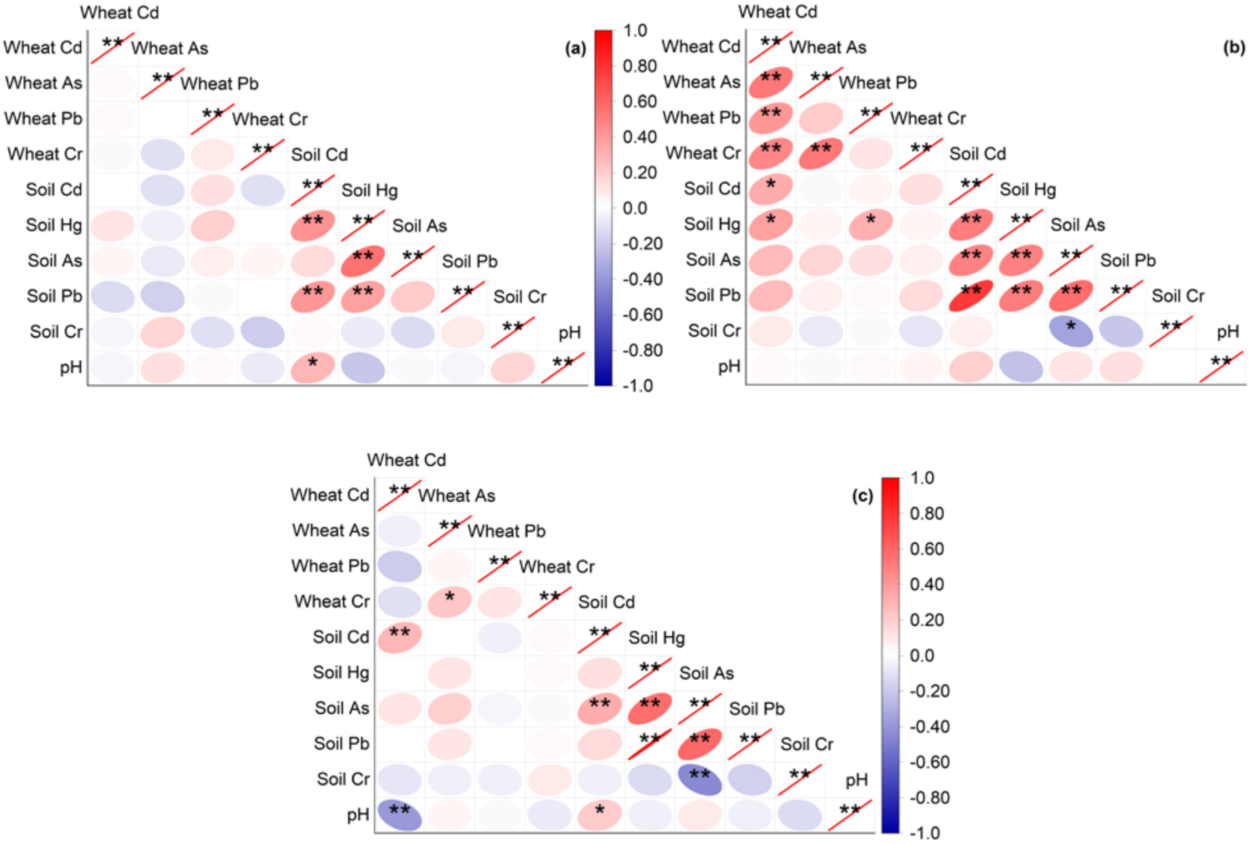

Fig. 5. Correlation analysis between factors in different study areas (*p≤0.05, **p≤0.01).

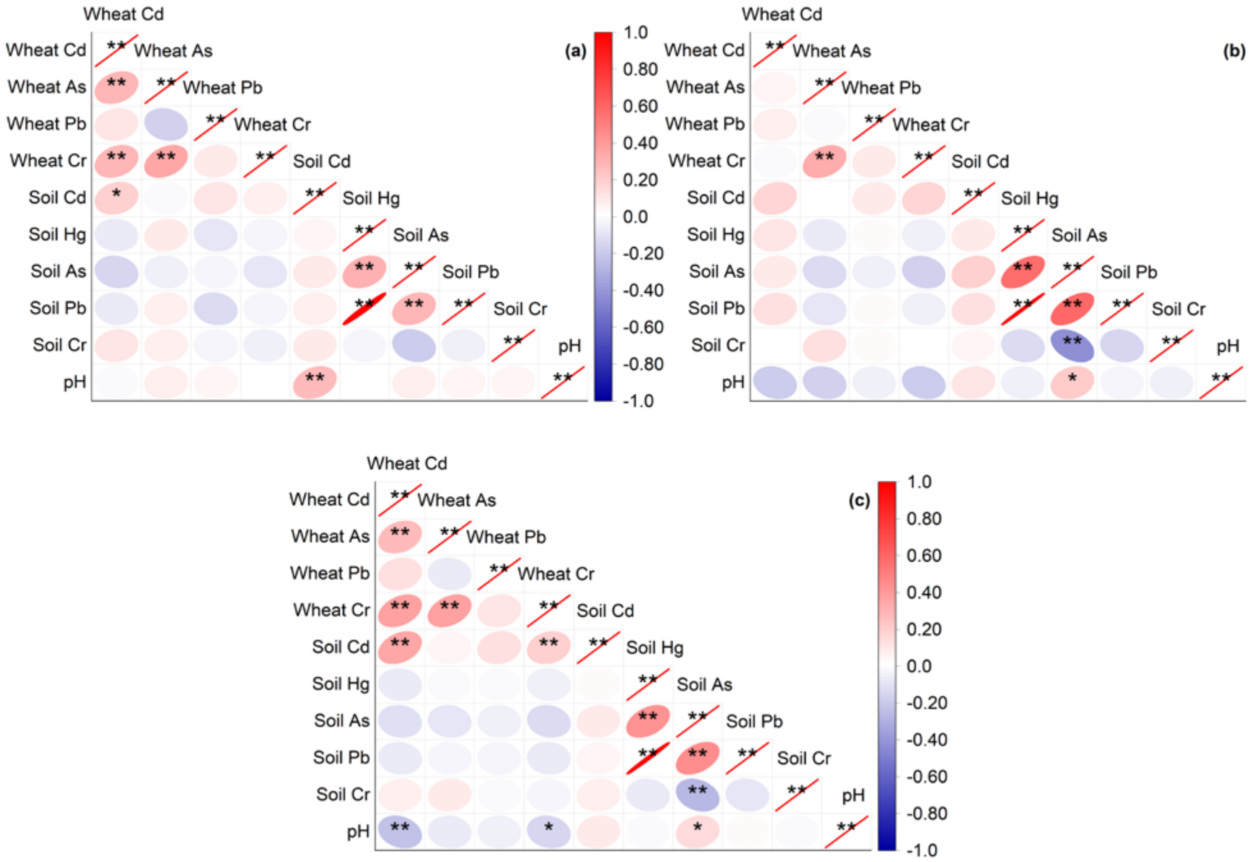

Fig. 6. Correlation analysis between wheat risk elements, soil risk elements, and pH (*p≤0.05, **p≤0.01).

Yuanmai and Qianmai 22, and its BCF is significantly lower than that of Yaanzao and Qianmai 22. However, the ω(Cd) content for all varieties is higher than 0.1 mg·kg^{-1}. Compared to HZ County, the average ω(Cd) for Yaanzao and Qianmai 20 in DF County is lower. In NY County, the average ω(Cd) for Fengyou 5 is 0.079 mg·kg^{-1}, which is lower than the national food safety limit (0.1 mg·kg^{-1}), meeting the national food safety standard.

Analysis of Factors Influencing Cd Accumulation in Wheat

As illustrated in Fig. 5, the relationship between wheat Cd content and soil variables varied across regions. In HZ County, wheat Cd did not correlate significantly with soil pH or risk elements concentrations. Soil Cd was positively correlated with soil Hg (r = 0.44, $p<0.01$), Pb (r = 0.42, $p<0.01$), and pH (r = 0.28, $p<0.05$). Soil Hg was also positively associated with As and Pb. In DF County, wheat Cd showed significant positive correlations with wheat As, Pb, and Cr, as well as with soil Cd and Hg. The correlation coefficients were 0.54, 0.40, 0.48, 0.33, and 0.39, respectively ($p<0.01$ or $p<0.05$). Soil Cd also correlated positively with Hg, As, and Pb, and soil Hg was positively associated with As and Pb, indicating similar sources or mobility pathways. In NY County, wheat Cd content was significantly positively correlated with soil Cd (r = 0.29, $p<0.01$) and negatively correlated with pH (r = -0.39, $p<0.01$). Soil Cd was also significantly correlated to soil As and pH. These results suggest that in non-polluted areas with high geogenic Cd, soil pH and total Cd are the primary drivers of accumulation.

Table 4 further confirms this pH dependence. When pH≤5.5, wheat Cd averaged 0.170 mg·kg^{-1}, decreasing progressively as pH increased, reaching 0.079 mg·kg^{-1} when pH>7.5. This trend confirms that acidic conditions promote Cd availability and uptake.

The correlation between wheat risk elements, soil risk elements, and pH is shown in Fig. 6. For the wheat Cd non-exceedance group (Fig. 6b)), there is no significant correlation between wheat Cd and soil risk elements or pH. For the wheat Cd exceedance group (Fig. 6a)), wheat Cd is extremely positively correlated with wheat As and wheat Cr, and significantly positively correlated with soil Cd, with correlation coefficients of 0.29 (p<0.01), 0.28 (p<0.01), and 0.19 (p<0.05), respectively. In summary, for the wheat Cd exceedance group, wheat Cd is co-absorbed with wheat As and wheat Cr, and its Cd content is mainly influenced by soil Cd levels.

The correlation between wheat risk elements, soil risk elements, and pH across the entire region is shown in Fig. 6c). Wheat Cd is extremely positively correlated with wheat As, wheat Cr, and soil Cd, with correlation

Table 4. Statistical analysis of soil and wheat risk elements content in different pH ranges.

pH range	Project	Risk elements					
		Cd	Hg	As	Pb	Cr	pH
pH≤5.5	Soil	1.052±0.524	0.155±0.073	13.141±9.205	33.878±8.554	126.480±48.435	4.95±0.315
	Wheat	0.170±0.108	-	0.015±0.018	0.055±0.036	0.133±0.047	
5.5<pH≤6.5	Soil	1.114±0.677	0.444±1.141	15.941±9.357	73.712±135.401	126.730±46.013	5.96±0.29
	Wheat	0.123±0.103	-	0.015±0.020	0.043±0.029	0.125±0.043	
6.5<pH≤7.5	Soil	1.557±1.016	0.134±0.072	17.219±6.292	38.583±9.633	120.203±40.791	6.93±0.28
	Wheat	0.128±0.096	-	0.008±0.010	0.048±0.033	0.121±0.039	
pH>	Soil	0.922±0.667	0.095±0.028	15.266±8.770	31.391±7.273	128.773±38.322	7.80±0.238
	Wheat	0.079±0.089	-	0.013±0.014	0.066±0.052	0.115±0.036	

Note: The unit of risk elements is mg·kg-1. A "-" indicates no relevant data.

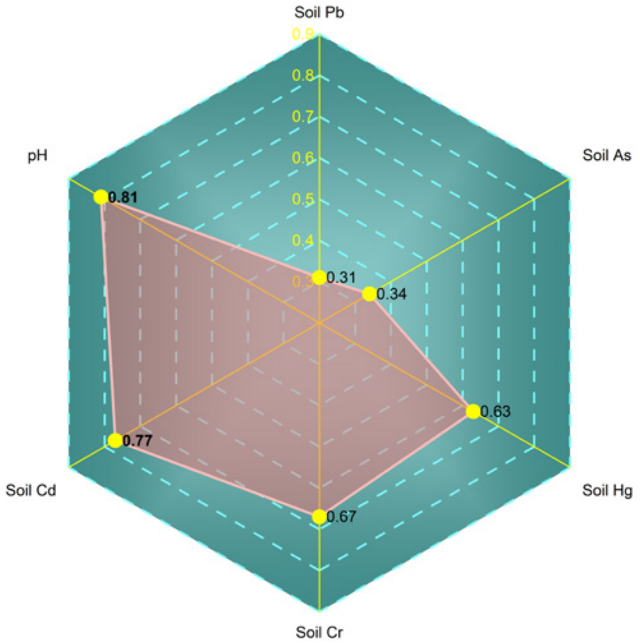

Fig. 7. Random forest feature importance analysis.

coefficients of 0.28 ($p<0.01$), 0.38 ($p<0.01$), and 0.35 ($p<0.01$), respectively. Wheat Cd is extremely negatively correlated with pH, with a correlation coefficient of -0.24 ($p<0.01$). This indicates that wheat Cd is co-absorbed with wheat As and Cr, and the accumulation of wheat Cd is mainly influenced by soil Cd and pH.

Six indicators, including soil pH, soil Cd, soil Cr, soil Hg, soil As, and soil Pb, were selected as feature variables to construct a Random Forest (RF) model using MATLAB R2022a. The 203 mixed samples in this study were used as the dataset for subsequent analysis. The RF model was built through random sampling, with 70% of the dataset used as the model test set, and the remaining 30% as the training set. The model underwent continuous training, and the optimal training result was retained. The RF model yielded $R^2 = 0.673$, MAE = 0.042, and RMSE = 0.061. Additionally, the importance of feature variables was ranked based on the RF interpreter. Soil Cd and pH had importance values of 0.773 and 0.813, respectively (Fig. 7), making them the primary feature variables affecting the prediction accuracy of wheat Cd.

Derivation of Soil Risk Elements Safety Thresholds for Wheat Production Using the SSD Method

This study adopts an SSD approach built on a logistic distribution model. Using the standard limit of wheat Cd from the "National Food Safety Standard for Contaminant Limits in Food" (GB 2762-2025), the soil

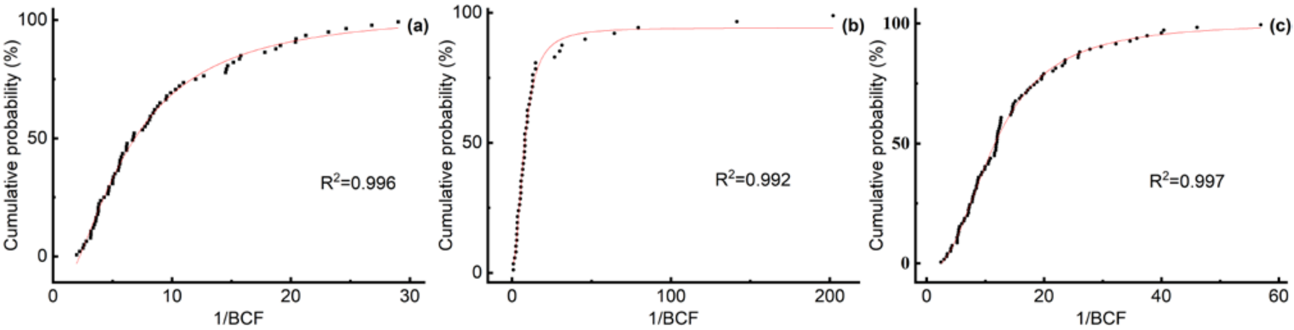

Fig. 8. SSD curve based on wheat Cd content.

total Cd content limit is inversely estimated. The SSD curve, derived from total soil Cd concentrations, was fitted using a logistic distribution model, with 1/BCF plotted along the x-axis and cumulative probability on the y-axis (Fig. 8). The R^2 values of the SSD curves based on wheat Cd content for the three study areas are 0.996 (HZ), 0.992 (DF), and 0.997 (NY), indicating high precision and statistical significance of the fitting results.

Based on the acceptable risk level, the derived fitting equation, and the national food safety standard limits, the safe threshold values (HC_5) for total soil Cd content were estimated to be 0.28 mg·kg⁻¹ in HZ, 0.13 mg·kg⁻¹ in DF, and 0.45 mg·kg⁻¹ in NY. The root mean square errors (RMSE) are 0.027432, 0.041953, and 0.023024, respectively. The K-S test results show that $p>0.05$. The difference between the observed distribution and the theoretical distribution confirms that the model fitting is satisfactory, with no significant deviation detected. This verifies that the predicted values align well with the theoretical calculations, indicating a good model fitting effect.

Discussion

Total soil Cd content is widely regarded as a primary factor governing Cd accumulation in wheat grains [27, 28]. However, our study revealed significant variations among areas with different pollution gradients (Fig. 5). In HZ County (heavily polluted), wheat Cd showed no significant correlations with total soil Cd, soil pH, or other risk elements ($p>0.05$). In DF County (moderately polluted), wheat Cd was significantly and positively correlated with total soil Cd ($p<0.05$). In NY County (unpolluted), wheat Cd was strongly positively correlated with total soil Cd ($p<0.01$) and strongly negatively correlated with soil pH ($p<0.01$). Notably, although soil Cd content in HZ County was significantly higher than that in the other regions, its regulatory effect on wheat Cd accumulation had largely disappeared. This suggests mechanistic differences arising from the combined influence of "geological background-exogenous pollution".

In NY County, soil Cd exerts a direct and strong regulatory effect on wheat Cd accumulation, consistent with the findings of Carabulea et al. [29] in regions with similar geological backgrounds. The mechanism can be described as a chain reaction of "content-bioavailability-uptake": the total soil Cd determines the size of the Cd pool available to root systems, thereby influencing Cd bioavailability and uptake-translocation efficiency, which ultimately leads to a significant increase in grain Cd levels [30, 31]. In contrast, the "high Cd but no crop response" pattern observed in HZ County corresponds to the weakened "soil-crop transfer relationship" commonly reported in complexly polluted regions, as described by Lu et al. [32]. This phenomenon may result from variations in the chemical speciation of exogenous versus geogenic Cd, combined with the influence of environmental factors that weaken the linear relationship between soil Cd levels and crop accumulation [33-35]. Furthermore, wheat Cd shows a significant positive correlation with As and Cr ($p<0.01$, Fig. 6c)), suggesting that multiple metals may exhibit synergistic effects during the processes of "common pollution sources-soil acidification and mobilization-co-transport-grain redistribution" [36-39]. This finding highlights the synchronous response of crops to combined heavy-metal pollution.

Soil pH, as a key physicochemical property, indirectly regulates wheat Cd accumulation by influencing Cd speciation and bioavailability [40, 41]. In this study, grain Cd significantly increased with decreasing pH, which is consistent with the findings of Yang et al. [42]. Regional differences indicated that in NY County, soil pH had a highly significant negative regulatory effect on wheat Cd accumulation ($p<0.01$), in agreement with the conclusions of Deng et al. [43]. In contrast, in HZ County, soil pH had no significant effect on wheat Cd accumulation ($p>0.05$), consistent with the observations of Xu et al. [44] in areas with complex pollution. The mechanistic differences can be explained as follows: in HZ County, Cd derived from exogenous pollution mainly exists in highly active forms, leaving little scope for pH-driven speciation changes; whereas in NY County, Cd is dominated by geogenic background forms, making its activity more sensitive to pH variation [45]. Further analysis indicates that soil pH regulates Cd bioavailability through multiple pathways [46]. Moreover, under acidic conditions, organic acids secreted by wheat roots can mobilize Cd through complexation, forming a positive feedback loop of "pH decrease – increased organic acid secretion – enhanced Cd activation", which significantly increases the efficiency of Cd uptake by wheat [47, 48].

Fig. 6c) and the interpretability analysis of the Random Forest model (Fig. 7) further confirm that total soil Cd and pH are the two dominant factors influencing Cd accumulation in wheat, with importance values of 0.773 and 0.813, respectively. This finding is consistent with the results of Lin et al. [49], highlighting the leading roles of these two variables in regulating Cd accumulation in wheat. The synergistic mechanism between them can be summarized as follows: soil Cd provides the material basis, whereas pH determines Cd activation and competitive adsorption [45, 48]. Under acidic conditions, desorption and activation effects are enhanced, and a larger Cd pool further amplifies these effects, resulting in markedly higher Cd accumulation in wheat. This conclusion aligns with the widely recognized understanding that pH and total Cd content are the dominant factors controlling Cd uptake in wheat [50], and provides a quantitative foundation for region-specific Cd risk management.

Beyond soil factors, varietal differences in wheat also play a significant role in Cd accumulation, as genotypic variations in Cd uptake and translocation capacities have been widely documented [51]. In this study, highly significant differences were observed among the tested varieties ($p<0.01$). Notably, the Fengyou 5 had an average grain Cd concentration of only 0.079 mg·kg^{-1}, significantly lower than that of other varieties and below the national limit (0.1 mg·kg^{-1}, GB 2762-2022). Its BCF value was just 0.105, highlighting its potential for application in karst regions with high Cd backgrounds. The low-Cd trait of Fengyou 5 may be associated with its plant architecture and physiological mechanisms [52]. For example, a greater number of tillers, thicker stems, and broader leaves may sequester more Cd in vegetative tissues, thereby reducing grain accumulation. Mechanistically, genotypic variation primarily manifests in: (i) root morphology and transporter differences that influence Cd uptake efficiency; (ii) vascular system regulation, whereby low-Cd varieties restrict long-distance Cd transport; and (iii) enhanced chelation and compartmentalization capacities that fix Cd in roots or cell walls [51-54]. Previous studies have confirmed that screening and promoting low-Cd varieties represent an effective strategy for the sustainable utilization of contaminated farmland [55]. This study further validates the effectiveness of this approach in karst areas, demonstrating that Fengyou 5 can ensure grain safety even in soils with high geogenic background Cd levels. Looking ahead, breeding programs in karst regions should focus on selecting varieties that combine "acid tolerance-low Cd accumulation" traits. Molecular marker-assisted breeding could further enhance adaptability and stability, ensuring safer and more resilient wheat production under complex soil Cd conditions.

With respect to soil Cd risk thresholds for safe wheat production, China's current soil quality management framework is primarily guided by two key standards: the "Soil environmental quality – Risk control standard for soil pollution in agricultural land" (GB 15618-2018) and the "Safety thresholds of Cd, Pb, Cr, Hg, As in soil for wheat production" (GB/T 41685-2022). However, these thresholds are largely derived from national average soil conditions and do not adequately account for regional soil characteristics. In karst regions characterized by elevated geogenic heavy-metal backgrounds, the applicability of these standards is greatly constrained [49], often resulting in inconsistent outcomes such as "over-regulation" or "under-regulation". Our study, by deriving soil Cd thresholds using the SSD method, further confirms these regional adaptability issues. For NY County, the calculated soil Cd threshold was 0.45 mg·kg^{-1}, about twice the value (0.23 mg·kg^{-1}) specified in GB/T 41685-2022 for soils with pH 5.5-6.5. This result is consistent with the findings of Yang et al. [56] in areas with similar geological backgrounds. The main reason lies in the geogenic origin of Cd in karst soils, where Cd predominantly exists in low-activity forms such as residual and Fe-Mn oxide-bound fractions. Although the total Cd content is relatively high, its bioavailability is much lower than that in anthropogenically polluted soils [57]. Direct application of the current standard would therefore misclassify soils as unsafe (exceeding Cd threshold but with safe wheat grains), resulting in excessive designation of risk control areas and unnecessary loss of high-quality farmland. In contrast, for DF County, the derived soil Cd threshold was 0.13 mg·kg^{-1}, much lower than the 0.23 mg·kg^{-1} in the standard. This difference can be attributed to exogenous Cd inputs dominated by exchangeable and acid-soluble forms, which substantially increase the proportion of bioavailable Cd [58]. Applying a uniform threshold in such areas would underestimate Cd bio-mobility and risk, potentially leading to food-safety hazards where soil Cd does not exceed the standard but wheat-grain Cd does. Xu et al. [18] emphasized that the accuracy of environmental thresholds depends on coupled models linking soil physicochemical properties with crop-accumulation characteristics. Uniform standards that neglect regional differences substantially reduce the precision of risk management. A case study from Anhui also demonstrated that region-specific benchmarks based on soil-crop systems were 0.13 times higher than the national screening values, further supporting the necessity of differentiated thresholds [59]. Based on these findings, it is evident that two distinct types of Cd occurrence exist in karst regions: pure geogenic background and geogenic background combined with exogenous pollution. Accordingly, separate soil-Cd threshold systems for safe wheat production should be established: relaxed thresholds for pure geogenic-background areas to avoid over-regulation, and stricter thresholds for pollution-overlapped areas to prevent food-safety risks.

Conclusions

Wheat Cd levels were significantly correlated with soil Cd and pH in karst regions with high geogenic background. However, under pollution-affected conditions, these correlations weakened. The variety Fengyou 5 demonstrated a characteristic of low Cd accumulation. The estimated soil Cd risk thresholds for wheat were 0.28 mg·kg^{-1} for HZ (heavily polluted), 0.13 mg·kg^{-1} for DF (moderately polluted), and 0.45 mg·kg^{-1} for NY (unpolluted). Compared with the national standard (0.23 mg·kg^{-1}), increased attention should be directed toward controlling Cd accumulation in polluted areas. Additionally, in unpolluted regions, further research is essential to establish differentiated thresholds, thereby enhancing the scientific foundation and precision of farmland classification and management.

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Conflict of Interest

The authors declare no conflict of interest.

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