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Screening for Low-Cadmium Accumulation in Maize Varieties Based on Species Sensitivity Distribution and Research on Soil Environmental Thresholds

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Abstract: Screening for low-accumulation varieties is an effective way to reduce the cadmium (Cd) content in crops and decrease human Cd intake. In this study, a field experiment was conducted to analyze the characteristics of Cd absorption and accumulation in 24 maize varieties at maturity in farmland with different levels of Cd pollution. Cluster analysis and Pareto analysis methods were used to screen for maize varieties with low Cd absorption. In addition, the environmental threshold of Cd in farmland in the study area was estimated based on the Species Sensitivity Distribution (SSD) characteristics of different maize Cd enrichment coefficients (1/BCF). The results showed that maize in the study area was subject to varying degrees of Cd pollution, with total soil Cd content ranging from 1.81 to 2.71 mg·kg^{-1} at test site 1 and from 0.95 to 1.76 mg·kg^{-1} at test site 2. Only the Cd content of heavy metals in maize kernels at test site 2 did not exceed China's national food safety standard (GB 2762-2022, 0.1 mg·kg^{-1}), with the Cd content of different maize varieties at test site 2 ranging from 0.008 to 0.073 mg·kg^{-1} and the bioconcentration factor (BCF) of maize kernels for Cd ranging from 0.004 to 0.054. According to cluster analysis and Pareto analysis, the low-Cd accumulation maize varieties suitable for local planting were identified as Yufeng 303, Nongda 372, Jingnongke 728, MC121 (Fengda Seed Industry), and Jinyu 1233. In addition, the soil Cd environmental threshold for ensuring that 95% of maize would not be polluted by Cd in soil was derived as 1.39 mg·kg^{-1}.

Keywords: cadmium; maize; variety selection; species-sensitive distribution; environmental thresholds

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1. Introduction

The rapid development of industrial and agricultural production has led to an increase in the content of toxic and harmful heavy metals in farmland soil worldwide [1]. Approximately 23.5 million hectares of cultivated land are polluted by heavy metals [2], including 280,000 hectares of agricultural soil in China that are polluted by cadmium (Cd) [3]. Cd is considered one of the most dangerous substances globally due to its strong migration and transformation characteristics in the environment and its high hazard to human health. In China, 7.0% of soil exceeds the Cd standard, with 0.5% of sites heavily polluted by Cd [4]. Unreasonable discharge of mine and factory sewage, sedimentation from industrial waste gas and automobile exhaust, and unscientific application of pesticides and fertilizers have all contributed to China's soil heavy metal pollution problem, posing a serious threat to agricultural product safety and human health [5,6].

Soil is the direct carrier of agricultural production, and when it is polluted by heavy metals, the edible parts of crops can have high heavy metal content. These heavy metals can enter the human or animal body through the food chain and accumulate, causing chronic heavy metal poisoning and endangering human health [7,8]. To reduce the transfer of heavy metals to the food chain, two main approaches are currently used: passivating heavy metals in soil through chemical methods or screening for crop varieties that are

tolerant to heavy metals and have low accumulation [4]. The latter approach has the advantages of being simple, low-risk, and easy to implement, making it a popular measure for safely using polluted cultivated land [9]. By exploring the characteristics of heavy metal enrichment in bulk grain crops and screening for low-accumulation varieties, it is possible to reduce the absorption and accumulation of heavy metals in crops and lower their heavy metal content [10].

Studies have shown that different plants exhibit significant variations in their Cd accumulation characteristics, with genetic factors playing a fundamental role [11]. Arthur et al. classified plants into high-, medium-, and low-accumulation types based on their Cd accumulation capacity [12]. Maize (*Zea mays* L.), a widely cultivated economic grain crop in China, has been shown to be a low-accumulation crop for Cd compared to wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.) [13]. Its large biomass and high economic efficiency make it suitable for use in the "production while remediation" of polluted farmland. Advances in technology have also enabled the use of maize for the production of biofuels, aligning with China's sustainable development goals [14,15]. However, different varieties of maize have varying abilities to absorb and accumulate Cd [10], and variations in soil physicochemical properties and Cd pollution levels can alter the total amount and bioavailability of Cd in the soil. This presents challenges for the screening of low-accumulation maize varieties [16,17]. To address this issue, researchers are working to screen for maize varieties with low Cd accumulation characteristics in their edible parts and test their adaptability to different soil environments [18,19].

China's current "Soil Environmental Quality Standard" (GB 15618-2018) has encountered situations where soil heavy metals exceed the standard while agricultural products do not, or vice versa [20,21]. This is because the standard does not fully account for differences in soil type and crop variety when setting soil thresholds for agricultural land [22,23]. As a result, there is a need for research on the environmental baseline values of Cd in soil to effectively control cadmium pollution in different soil types and crop species. Compared to developed countries, China's ecological risk assessment research is still in its initial stage [24], with most current work focusing on environmental quality evaluation and grading of polluted soils using different index evaluation methods [25]. Conducting research on the ecological risk threshold values of crops under different soil Cd pollution levels is crucial for preventing and controlling Cd pollution in China's major agricultural products and evaluating the suitability of Cd-polluted soils.

The Species Sensitivity Distribution (SSD) curve method is a commonly used extrapolation method in ecological risk assessment. It is used to determine the maximum environmental permissible concentration threshold (HC_x, usually HC_5), where HC_5 represents the concentration at which no more than 5% of species are affected or 95% of species are protected [26]. From this value, the predicted no-effect concentration (PNEC) can be derived for use in ecological risk assessment and environmental quality standards [23]. The SSD method has been adopted by many countries and organizations as a means of formulating environmental quality standards and has become a focus of international risk assessment research.

This study aims to identify low cadmium (Cd) accumulation maize varieties in a Cd-polluted agricultural area in eastern Anhui Province, China. Through field experiments, we will screen for maize varieties with low Cd accumulation and use the bioconcentration factor (BCF) of Cd in maize kernels as an evaluation index for species sensitivity. Using the species sensitivity distribution (SSD) model, we will derive the safe threshold (HC_5) of total soil Cd based on protecting 95% of maize varieties. Our findings will provide an important reference for the safe production of maize and the safety evaluation of agricultural product origins in the region.

2. Materials and Methods

2.1. Study Area Overview

As shown in Figure 1, the test site is located in Tongling City (30°57′ N, 117°49′ E), Anhui Province, China. The test site was established on two adjacent Cd-contaminated farmlands around a large pyrite mining area. The soil from the experimental field was characterized as sandy loam, with a composition of 25.8% clay, 11.5% silt, and 62.7% sand. The basic physical and chemical properties of the soil and the mass fraction of heavy metal Cd in the two test sites are shown in Table 1.

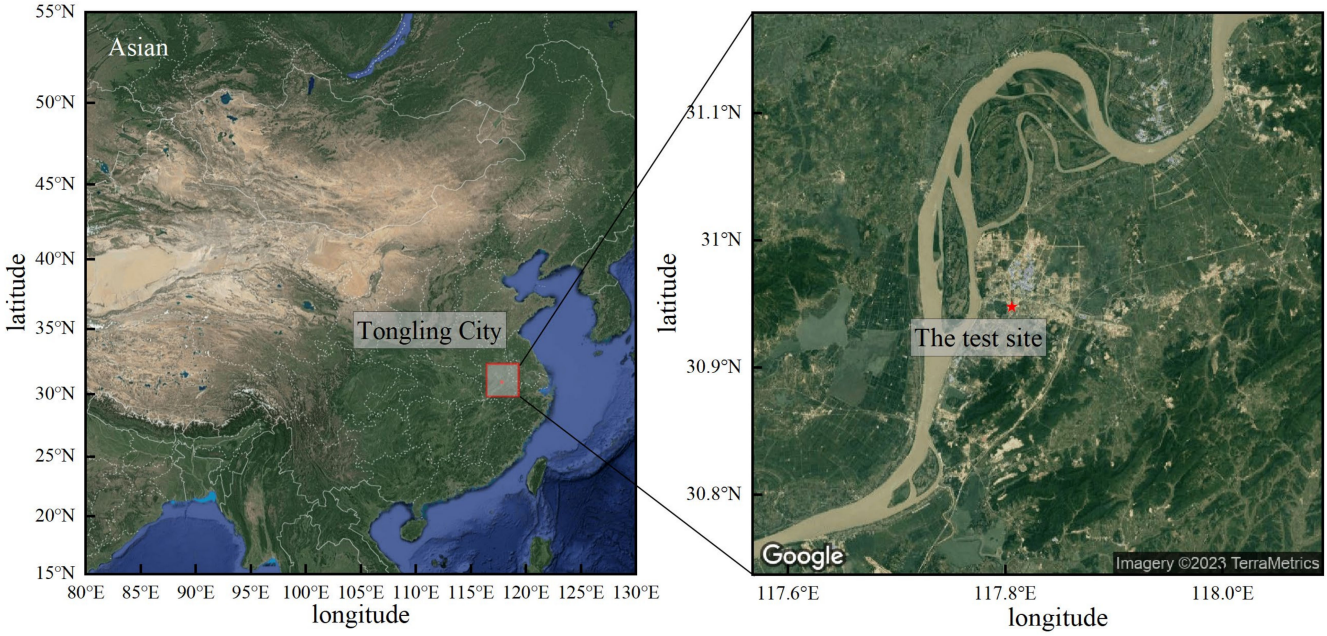


Figure 1. Map of the test site.

Table 1. Property traits of the test soil.

Test Site	pH	Cd (mg·kg^{-1})	Organic Matter (g·kg^{-1})	Total Nitrogen (g·kg^{-1})	Alkali-Hydrolyzable Nitrogen (mg·kg^{-1})	Available Phosphorus (mg·kg^{-1})	Available Potassium (mg·kg^{-1})
1	5.27	2.35	34.22	1.39	138.01	20.75	87.5
2	4.74	1.41	37.44	1.46	148.01	31.74	112.4

According to China's "Soil Environmental Quality Standards" (GB15618-2018), the Cd content in the soil of test site No. 1 is 1.56 times the risk intervention values for soil contamination of agricultural land; the Cd content in the soil of test site No. 2 is between the risk screening values and risk intervention values for soil contamination of agricultural land, at 0.94 times the risk intervention value.

2.2. Test Materials and Design

In this study, 24 maize varieties (Table 2) were evaluated, all of which were approved by the Anhui Provincial Crop Variety Approval Committee and purchased from local seed markets. No Cd was detected in the seeds.

Each variety was cultivated in a 7.2 m^2 (1.2 m × 6 m) plot, arranged in a randomized block design with three replicates. The maize was planted in double rows with a row spacing of 65 cm and a plant spacing of 30 cm, with protective rows around the perimeter. One week before sowing, a base fertilizer of NPK compound fertilizer (15:15:15) was applied at a rate of 750 kg·hm^{-2}, and the seeds were sunned before sowing. The soil moisture

content was maintained at 60–70% of the maximum field water holding capacity. During this period, field management was carried out in accordance with local cultivation practices.

Table 2. Tested maize varieties.

Varieties	Serial Number	Varieties	Serial Number
Yufeng303	S1	Yudan9953	S13
Huaiyu23	S2	Meijia303	S14
Nongda372	S3	Fanyu298	S15
Jiaxi100	S4	Xianda601	S16
Jingnongke728	S5	Longping206	S17
MC121	S6	Dedan123	S18
Jinyu1233	S7	Zhongkeyu505	S19
Jinqiu119	S8	Suyu29	S20
Aoyu503	S9	Hemao808	S21
Shaodan8	S10	Dedan5	S22
Xuntian1102	S11	Fengdu191	S23
Deli666	S12	Wanyu708	S24

2.3. Sample Collection and Processing

Prior to maize planting, soil samples (0–20 cm) were collected from each experimental site using the "X" shaped 5-point sampling method. At maturity, maize plants were removed, dried, and threshed to determine actual yield. Five plants from each maize variety were sampled using the plum blossom sampling method, and corresponding rhizosphere soil samples (0–20 cm) were collected to form composite soil samples. Soil samples were air-dried and sieved through 10, 60, and 100 mesh sieves. Plant samples were divided into roots, stems and leaves, and grains. The roots were treated with a 10 mmol·L^{-1} EDTA-Na_2 solution to remove Cd ions, and the plant samples were finally rinsed with deionized water. The samples were wilted for 30 min in a 105 °C oven and dried at 70 °C until constant weight was achieved. After measuring the dry mass, the samples were ground and sieved through a 100-mesh sieve.

2.4. Sample Analysis Methods and Quality Control

2.4.1. Analysis of Soil Sample Indices

In this study, the analysis of basic physicochemical properties of soil samples was mainly conducted following the methods described in Bao's "Soil and Agricultural Chemistry Analysis" [27]. Soil pH was measured using a precision pH meter (PHS-3G) after extraction with CO_2-free distilled water at a soil-to-water ratio of 1:2.5. Alkali-hydrolyzable nitrogen was determined using an alkali diffusion method. Total nitrogen was quantified using the semi-micro Kjeldahl method (KN620, Jinan HePu Instrument Equipment Co., Ltd., Jinan, China). Available potassium was extracted with ammonium acetate and measured using flame photometry (Sherwood410, Sherwood Scientific Ltd., Cambridge, UK). Organic matter was determined using the potassium dichromate oxidation volumetric method with external heating. Available phosphorus was extracted with sodium bicarbonate and quantified colorimetrically using a molybdenum-antimony method (UV-1800, Shimadzu Corporation, Kyoto, Japan). Soil particle size composition was measured using the pipette method, and texture was classified according to the international soil texture triangle. Total Cd content in soil samples was determined according to the Chinese national standard (GB/T17141-1997). A 0.2 g sample (accurate to 0.001 g) was placed in a mixture of HCl, HF, $HClO_4$, and HNO_3 and digested at high temperature in a graphite digestion box (GD40, Nanjing Kejie Analytical Instrument Co., Ltd., Nanjing, China). After cooling, the Cd content was measured using flame atomic absorption spectrophotometry with an atomic absorption spectrophotometer (ZEEnit700p, Analytik Jena AG, Jena, Germany).

2.4.2. Analysis of Plant Sample Indices

The Cd content in different parts of maize plants was determined according to the Chinese national standard (GB5009.268-2016). A 0.3 g sample (accurate to 0.001 g) was placed in a microwave digestion tank, and 5 mL of HNO_3 was added. The tank was covered and left for 1 h before being digested using a CEM MARS6 (CEM Corporation, Matthews, NC, USA) microwave. After cooling, the tank was removed, the lid was slowly opened to release gas, and the inner lid was rinsed with a small amount of ultrapure water. The digestion tank was placed on a temperature-controlled electric heating plate and heated at 100 °C for 30 min before being diluted to 25 mL with ultrapure water. The Cd content was measured using inductively coupled plasma emission spectroscopy (iCAP 7400, Thermo Fisher Scientific, Waltham, MA, USA).

2.4.3. Quality Control Methods in Experimentation

The certified reference materials (CRM) GBW07427 and GBW10012 for soil and maize (Institute of Geophysical and Geochemical Exploration, Chinese Academy of Geological Sciences), respectively, were used as quality control for Cd analysis. Analyses were performed after every ten samples and at the end of each experiment. Throughout the sample analysis period, all CRMs achieved good recovery rates. The average recovery rates for Cd in soil and maize were 95.3% ± 2.8% and 91.7% ± 5.1%, respectively.

2.5. Data Analysis

2.5.1. Maize Bioconcentration Factor Analysis

The accumulation capacity of crops for heavy metals was analyzed using the bioconcentration factor (BCF), Calculated using the formula:

$$BCF = \frac{C_p}{C_s} \quad (1)$$

where C_p and C_s represent the corresponding heavy metal content in maize and soil samples, respectively.

2.5.2. SSD Curve Fitting and Derivation of HC_5 Value

SSD is a method for evaluating the ecological risk of pollutants to certain species based on acute or chronic toxicological data, taking into account the differences in sensitivity of different species to pollutants by constructing statistical distribution models. The basic assumption of SSD is that the sensitivity of a group of organisms can be described by a distribution, such as a normal distribution or logistic distribution, and the toxicological data measured by experiments are considered to come from this distribution. The Logistic distribution model is a flexible distribution function with good fitting characteristics for species sensitivity data. In this study, the bioconcentration data of maize kernels were taken in reverse order (1/BCF) and arranged in ascending order, and then the SSD curve was fitted using the Logistic model distribution function. Based on China's national food safety standard (GB 2762-2022, 0.1 $mg \cdot kg^{-1}$), the safe threshold (HC_5) of soil Cd for rice was derived by backtracking [10].

$$y = a + \frac{b}{1 + (x/x_0)^c} \quad (2)$$

In the equation, x represents 1/BCF, y represents the cumulative probability of the corresponding crop sample, and a, b, c, and x_0 are constants.

$$C_S = \frac{C_P}{BCF} \quad (3)$$

In this study, data in figures or tables are presented as the mean ± standard deviation (M ± SD) of three replicates. Data obtained from experiments were analyzed using Microsoft

Excel 2016 (Microsoft, Redmond, DC, USA) and SPSS 22.0 (IBM, Chicago, IL, USA). One-way analysis of variance (ANOVA) was used to evaluate differences between treatments, and the least significant difference (LSD) was applied to test the significance between means. Duncan's test was used to test for significant differences ($p < 0.05$). Graphs were plotted using Origin 2021 (Origin Lab, Northampton, MA, USA).

3. Results

3.1. Soil pH and Cd Content

As shown in Figure 2, the total Cd content in the soil of test site 1 ranged from 1.81 to 2.71 mg·kg^{-1}, with soil pH values ranging from 4.52 to 6.36. The total Cd content in the soil of test site 2 ranged from 0.95 to 1.76 mg·kg^{-1}, with soil pH values ranging from 4.36 to 5.33. Analysis of variance (ANOVA) of the total Cd content and pH values of the soil at maturity revealed that there were highly significant differences ($p < 0.001$) between the total Cd content in the soil of different test sites, as the coefficient of variation was very low, around 0.05. Similarly, there were also highly significant differences ($p < 0.001$) between soil pH values between test sites. The box plot of the total Cd content and pH values of the soil at maturity also confirmed the results of the ANOVA, showing that there were certain differences in both mean and extreme values between the two test sites for both soil Cd content and soil pH.

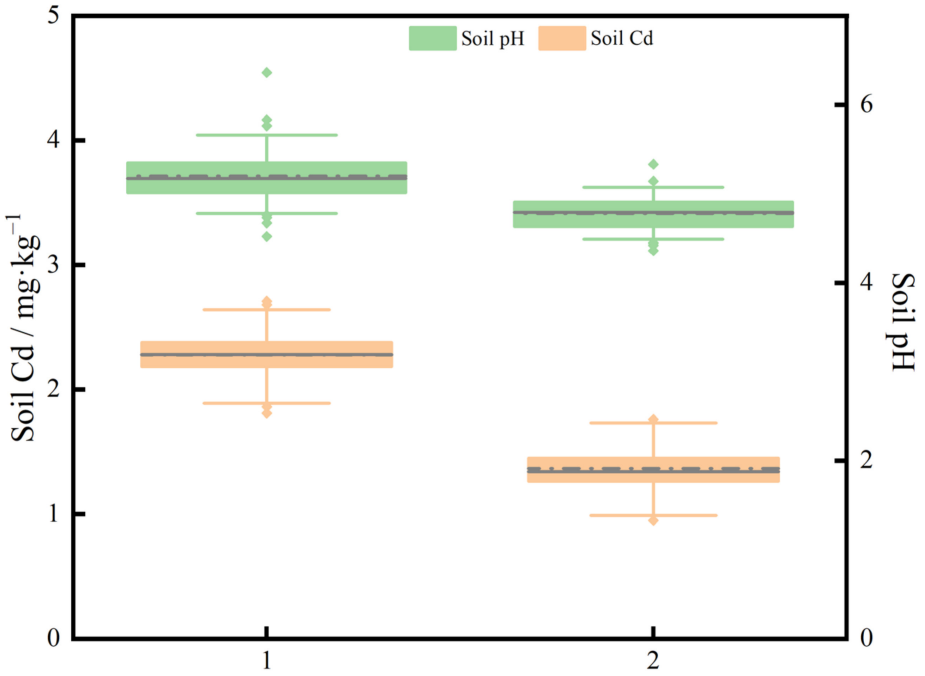


Figure 2. Comparison of pH value and Cd content of soil samples at the maturity stage of test site (**1**) and test site (**2**). Note: The bottom, middle line, middle dashed line, and top of the box in the box plot represent the lower quartile, median, mean, and upper quartile, respectively. The upper and lower edges (short horizontal lines) represent the maximum and minimum values within the 1.5 IQR range. Solid dots represent outliers beyond the 1.5 IQR range.

3.2. Cd Content and Enrichment Characteristics of Maize

3.2.1. Cd Content in Maize Kernel

The total Cd content of maize grains from different varieties in test sites 1 and 2 is shown in Figure 3. The mean total Cd content of maize grains in test site 1 was 0.150 ± 0.021 mg kg^{-1}, with a range from 0.087 to 0.196 mg kg^{-1}. Compared to the Cd contamination limit for maize crops set by the United Nations Food and Agriculture Organization (FAO) (0.1 mg kg^{-1}), the Cd content of crops in test site 1 almost all exceeded the limit. However, compared to the requirements of China's national standard, "Feed Hygiene Standard"

(GB 13078-2017) (Cd $\leq$ 1.0 mgkg^{-1}), the Cd content of all varieties of grains met the requirements for plant-based feed ingredients.

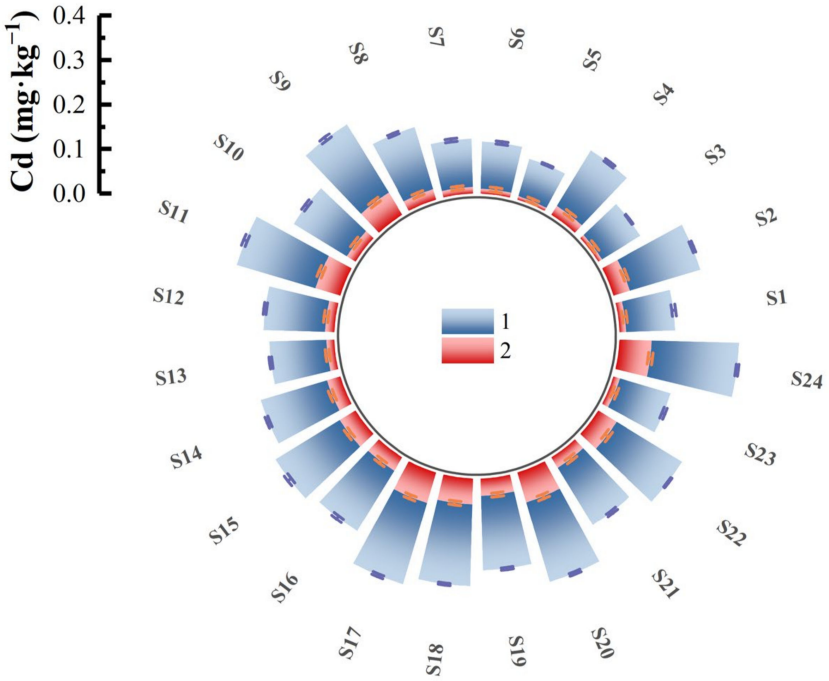


Figure 3. Comparison of Cd content in maize kernels of different varieties in test site (**1**) and test site (**2**).

The mean total Cd content of maize grains in test site 2 was 0.035 $\pm$ 0.032 mg kg^{-1}, with a range from 0.008 to 0.073 mg·kg^{-1} for grain Cd content. Compared to the FAOs Cd contamination limit, the Cd content of all varieties of grains met the requirements, with a compliance rate of 100%. Compared to test site 1, the Cd content of grains from different maize varieties decreased by 0.079 to 0.123 mg·kg^{-1}, which is related to the lower soil Cd content in test site 2 compared to test site 1, indicating that the Cd content in maize grains is directly related to the Cd content in soil.

3.2.2. Maize Root and Kernel Enrichment Factor

Maize roots absorb Cd from the soil and transfer it to the kernels, which is then transmitted to humans through the food chain, posing a serious threat to human health. The BCF is used to evaluate the enrichment of heavy metals in soil by plants. In this study, the enrichment coefficients of roots and kernels of different maize varieties are shown in Figure 4. It can be seen from the figure that there are significant differences in the absorption and accumulation of Cd by roots and kernels of different maize varieties.

In test site 1, the range of enrichment coefficients for roots and kernels of different maize varieties was 0.506 to 1.556 and 0.053 to 0.080, respectively. The coefficients of variation were 0.305 and 0.116, respectively, indicating a low degree of variation.

In test site 2, the range of enrichment coefficients for roots and kernels of different maize varieties was 0.890 to 3.110 and 0.004 to 0.054, respectively. The coefficients of variation were 0.284 and 0.651, respectively, with a high degree of variation in the enrichment coefficient of kernels. Compared to test site 1, the enrichment coefficient of maize roots increased in test site 2, while the enrichment coefficient of kernels decreased. This indicates that the heavy metal content in soil significantly affects the enrichment of Cd by above- and below-ground parts of maize and that the higher the Cd content in the soil, the smaller the enrichment coefficient of roots for Cd, while the opposite is true for kernels. This may be due to an increase in pollution levels, which reduces maize biomass and thereby increases the relative concentration of Cd in plants.

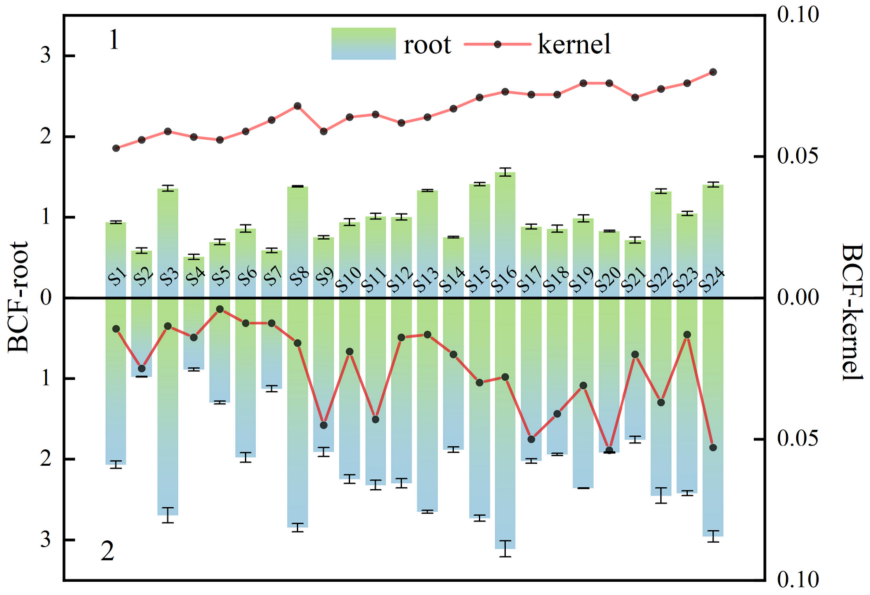


Figure 4. Comparison of Cd accumulation coefficient in root and grain of different maize varieties in test site (**1**) and test site (**2**).

3.3. Selection of Maize Varieties with Low Cd Accumulation

Although the Cd mass fraction of kernels from the 24 maize varieties planted in both test sites met the requirements of China's national standard "Feed Hygiene Standard" (GB 13078-2017) (Figure 3), according to the screening criteria for low-accumulation crops, the Cd content in edible parts must not exceed international or national food safety and hygiene standards. To screen maize varieties with low accumulation capacity in soils with different levels of Cd pollution, the authors used a systematic cluster analysis method—intergroup linkage—Euclidean distance analysis method, and Pareto analysis method to analyze the Cd enrichment coefficients of kernels from 24 maize varieties planted in two test sites, to identify low-Cd accumulation maize varieties. The analysis results divided different maize varieties into three categories: high enrichment, medium enrichment, and low enrichment of kernels, as shown in Table 3 and Figures 5 and 6.

Table 3. Systematic cluster analysis of Cd enrichment coefficients in seeds of different maize varieties.

Test Site	Low Accumulation Taxa Cluster I	Intermediate Accumulation Taxa Cluster II	High Accumulation Taxa Cluster III
1	S1, S4, S5, S3, S6, S9, S2,	S7, S12, S10, S11, S13, S8, S14	S15, S21, S18, S17, S16, S22, S19, S23, S20, S24
2	S1, S3, S6, S7, S4, S12, S13, S23, S8, S10, S14, S21, S5	S2, S15, S19, S16, S22	S9, S11, S18, S17, S20, S24

In test site 1, Category I included 7 low-enrichment varieties with a range of kernel enrichment coefficients (Cd) from 0.053 to 0.059. Category II was a medium-enrichment group consisting of 7 varieties, with a range of kernel enrichment coefficients (Cd) from 0.063 to 0.067. Category III was a high-enrichment group, with 10 varieties and an average kernel enrichment coefficient (Cd) of 0.074.

In test site 2, Category I included 13 low-enrichment varieties with a range of kernel enrichment coefficients (Cd) from 0.004 to 0.020. Category II was a medium-enrichment group consisting of 5 varieties with a range of kernel enrichment coefficients (Cd) from 0.025 to 0.037. Category III was a high-enrichment group, with 6 varieties and an average kernel enrichment coefficient (Cd) of 0.048. Compared to the results of test site 1, the number of Category I low-enrichment varieties increased, while the number of medium

and high-enrichment varieties decreased. In test sites with different levels of Cd pollution, maize varieties S1, S3, S5, and S6 consistently showed low enrichment of heavy metal Cd.

According to the results of the Pareto analysis method (Figure 5), there were significant differences in the Cd enrichment coefficients of kernels from different varieties in test site 1, with a value of 0.074. Of these, 18 maize varieties were low-Cd accumulation varieties, and 6 were high-Cd accumulation varieties. In test site 2, there were also significant differences in the Cd enrichment coefficients of kernels from different varieties, with a value of 0.029. Of these, 15 maize varieties were low-Cd accumulation varieties, and 9 were high-Cd accumulation varieties. The results indicate that maize varieties S1, S3, S5, S6, and S7 had relatively low accumulation levels.

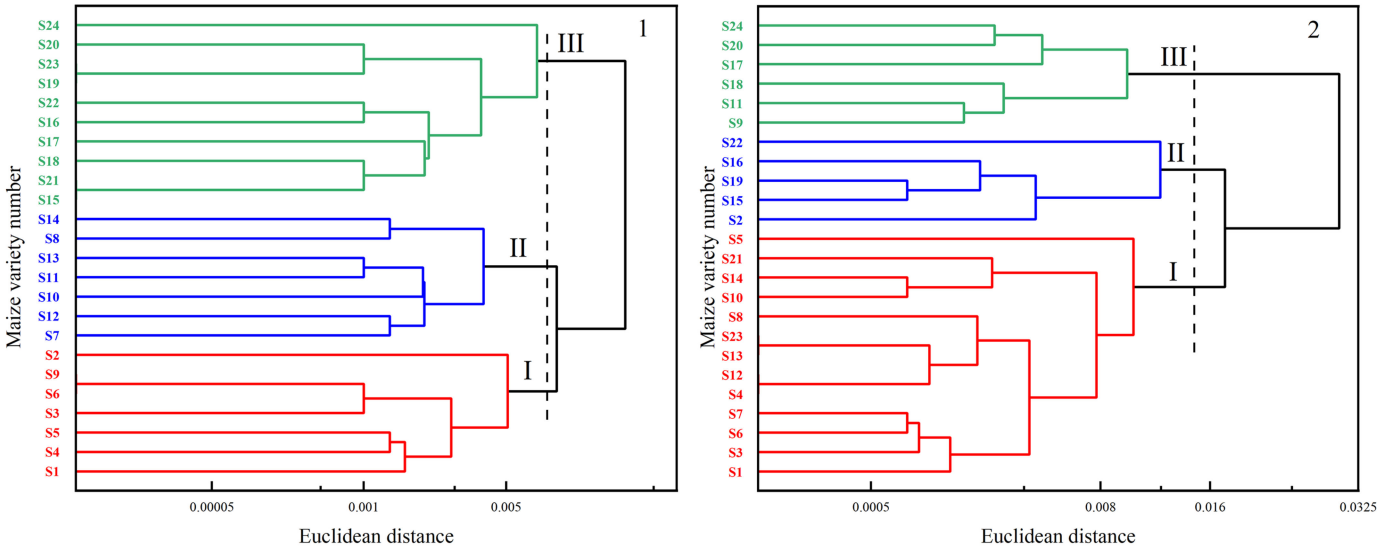


Figure 5. Systematic cluster analysis of Cd enrichment coefficients of different maize varieties in test site (**1**) and test site (**2**). The Roman numerals I, II, III indicate the ranking of maize kernels' absorption capacity for Cd from low to high.

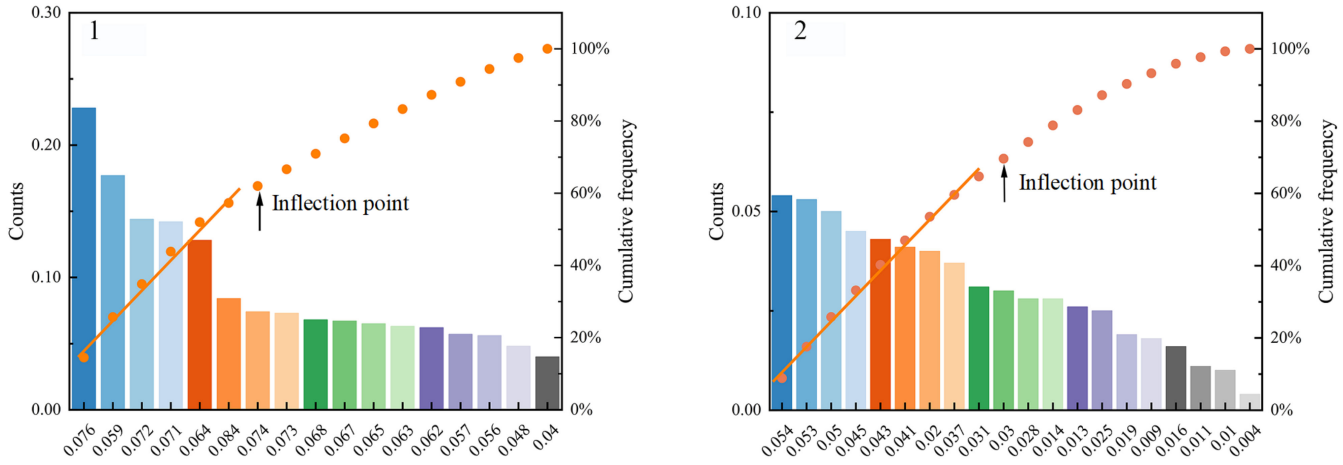


Figure 6. Pareto analysis of Cd enrichment coefficients of different maize varieties in test site (**1**) and test site (**2**). Note: The orange circle represents the cumulative frequency, and the inflection point indicates the boundary between high and low Cd accumulation varieties; the leftmost 20% of bars represent varieties responsible for 80% of total Cd accumulation.

3.4. Establishing Environmental Thresholds for Soil

Based on the differences in the migration capacity of heavy metals in different types of maize, the accuracy of determining soil environmental thresholds can be improved. In this

study, a Logistic model was used to fit the bioconcentration factor of Cd in maize kernels and construct an SSD curve (Figure 7), and the risk based on maize Cd absorption was evaluated; in other words, the concentration value (HC_5) for protecting 95% of species (maize) was determined. The R-squared values of the maize SSD curve in test sites 1 and 2 were 0.984 and 0.987, respectively, indicating good data fit. As shown in the figure, there are differences in the sensitivity of maize varieties to soil Cd. As can be seen from the figure, S20, S24, and S17 are below the safety threshold for protecting 95% of species (maize) derived from the Logistic model and are maize species with a risk of Cd enrichment. The enrichment coefficients (1/BCF) of the remaining maize varieties are all above the safety value. The cumulative frequencies (%) of different maize enrichment coefficients (1/BCF) in the frequency distribution based on species sensitivity were calculated as follows: test site 1: 2.91% to 85.41%; test site 2: 1.58 to 125.63. Also, maize varieties are generally distributed near the curve, indicating that both crops have strong transport and accumulation capacity for Cd and high sensitivity. From the analysis of crop varieties, maize varieties S1 and S5 are located at the top of the SSD curve; in other words, they are least sensitive to soil Cd accumulation and belong to low-accumulation varieties.

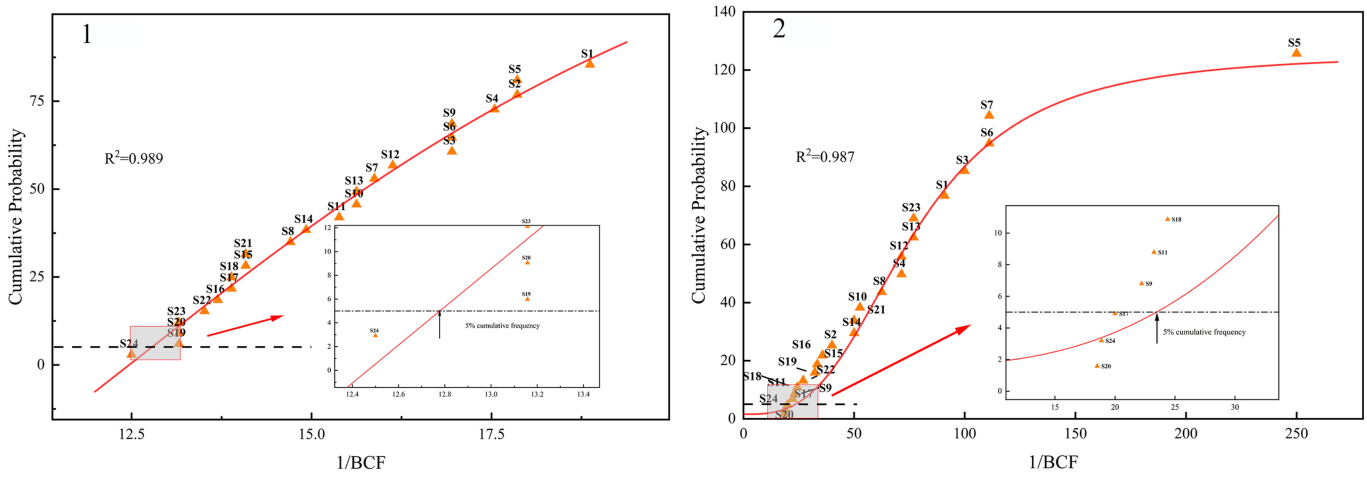


Figure 7. The SSD curves of Cd in different Maize varieties in test site (**1**) and test site (**2**).

In order to calculate the environmental threshold for Cd, an environmental threshold based on local soil scenarios was derived from the limit values set by the FAO to protect 95% of crop varieties from pollution (Table 4). Based on the derived threshold for protecting 95% of species (maize) safely (HC_5), HC_5 = 12.778 in test site 1 and HC_5 = 13.864 in test site 2. Also, when total soil Cd content $\leq$ 1.39 mg kg^{-1} in maize-producing areas, it is suitable for planting 95% of maize varieties and can be designated as a pollution-free maize-producing area. When soil Cd content is outside this range, planting of crops with high enrichment capacity should be prohibited. The planting process should use production techniques based on agronomic regulation, supplemented by soil remediation and strengthened coordinated monitoring of Cd in soil and crop products.

Table 4. Classification threshold of cadmium environmental quality in different crop areas.

Test Site	FAO Limit of Food /mg kg^{-1}	Y /%	Soil Environmental Classification Threshold /mg kg^{-1}	Soil Quality Category
1	0.10	5	1.28	Non-serious pollution
2			1.39	

4. Discussion

The absorption and transport of elements in maize are influenced by both environmental conditions and the plant's genetic characteristics [28]. Our study found significant

differences in Cd absorption, transport, and accumulation among different maize varieties, likely due to genotypic differences. Previous research has shown that maize varieties differ in their response to Cd stress, with some varieties exhibiting higher antioxidant system activity and transcription levels of oxidative stress response genes [29]. Our study also found significant differences in Cd absorption among different maize organs, with the highest levels found in roots, followed by stems and leaves, ear axis, and kernels [30]. These differences may be due to variations in Cd accumulation ability, distribution ratio, and transfer coefficient among maize varieties at different growth stages. For example, one study found that the Cd content in roots, stems, and leaves of different maize varieties followed a consistent trend across growth stages [31]. Our experiment investigated the differences among maize varieties grown in soil with varying levels of Cd contamination. We found that both the interaction among different maize varieties and between maize varieties and the experimental environment significantly affected kernel Cd content. Previous research has also shown that soil Cd environment can significantly affect the Cd accumulation risk of different maize inbred lines [32]. According to China's "Soil Pollution Prevention Action Plan," strict control measures are in place to prevent the planting of edible agricultural products on contaminated land without a safety assessment.

Some studies have reported that maize can tolerate certain levels of Cd without showing toxic symptoms and can be grown on contaminated soils as a replacement for other major crops such as wheat and rice [9,33].

In our study, we found that the soil Cd content at test site 2 exceeded China's risk screening value for Cd pollution in farmland soil. However, the Cd concentration in maize kernels at this site did not exceed the standard limit set by the FAO. Previous research has shown that maize has a low accumulation capacity for Cd, even in heavily polluted farmland [34,35]. This is because the plant's ability to absorb Cd depends on its bioavailability, which is influenced by soil pH [36,37]. As a result, even if the total concentration of Cd in the soil is high, the risk of crop Cd pollution will only increase significantly when soil acidification occurs. In this study, we screened several maize varieties with low Cd accumulation that are suitable for planting in Anhui Province, China. These varieties consistently showed low Cd accumulation in soils with different levels of Cd pollution. However, due to the fact that seed Cd accumulation capacity can vary under different soil Cd content conditions, further verification and study of these low-accumulation varieties through additional field experiments is needed.

Our study provides a comprehensive analysis of Cd concentration levels in different maize varieties and has important implications for crop selection and breeding strategies, as well as food safety policies. The results highlight the importance of China's "Soil Environmental Quality Risk Control Standard for Agricultural Land" (GB 15618-2018) [10] but also suggest that this standard may not be entirely applicable to places with high soil heavy metal background values due to insufficient basic toxicological data and lack of effective data [25]. In addition, biological and non-biological factors can affect the scientificity and rationality of soil environmental quality standards (SEQSs) during the derivation process of soil pollutant thresholds [38,39]. Therefore, when establishing soil environmental thresholds, consideration should be given to the ability of maize varieties to accumulate heavy metals [40]. For example, researchers have derived the safe threshold for Cd transfer in two rice varieties with high and low Cd accumulation, showing that there is a significant difference in soil thresholds between the two varieties [41]. Safari et al. used an efficiency threshold reflecting Cd risk to soil pollution to evaluate Cd transfer characteristics from polluted soil to crops [42]. This approach has been confirmed by other studies on the sensitivity of rice varieties to heavy metal accumulation [43]. The Species Sensitivity Distribution (SSD) model has been shown to be an effective means of deriving environmental safety thresholds for Cd in regional farmland soils [44,45]. Determining soil heavy metal environmental thresholds can provide a basis for assessing the harm of heavy metal pollution in agricultural products to human health and for regulating the management of heavy metal-polluted soil [46]. In our study, we derived the soil Cd

pollution threshold near a pyrite mine in Tongling. The extrapolated threshold for the Cd enrichment coefficient of maize kernels was higher than China's soil environmental threshold, indicating that China's threshold is generally strict [10,47]. However, our results are only applicable to maize soil in the study area and do not consider factors that affect the toxicity of pollutants in soil. It should be noted that our experiment was conducted under field conditions, where the factors affecting heavy metal Cd accumulation in crops are complex and diverse. As a result, there may be some differences between our results and those obtained from pot experiments [48]. Our finding that the soil Cd HC_5 value changes significantly with the degree of soil pollution highlights the need for more enforceable ecological thresholds. Further research is needed to understand the relationship between different soil properties and HC_5 values and to improve the scientific validity and rationality of the derived results.

5. Conclusions

In this study, we analyzed the Cd content in soil and maize kernels at maturity in two research areas with different levels of Cd pollution. We found that the average Cd content in the soil was 1.56 and 0.94 times higher than the risk control value specified in China's "Soil Environmental Quality Risk Control Standard for Agricultural Land" in test site 1 and test site 2, respectively. The Cd content of maize kernels ranged from 0.087 to 0.196 $mg \cdot kg^{-1}$ in test site 1 and from 0.008 to 0.073 $mg \cdot kg^{-1}$ in test site 2, with only the latter meeting China's national food safety standard (GB 2762-2022, 0.1 $mg \cdot kg^{-1}$). The BCF of maize roots and kernels for Cd in test site 2 ranged from 0.890 to 3.110 and from 0.004 to 0.054, respectively.

We used cluster analysis and Pareto analysis methods to screen for maize varieties with low Cd accumulation and identified five suitable varieties for planting in areas with high soil Cd content in Anhui Province, China: Yufeng 303, Nongda 372, Jingnongke 728, MC121, and Jinyu 1233. Additionally, based on the SSD curve of different maize Cd enrichment coefficients (1/BCF), we estimated that the soil Cd threshold for ensuring that 95% of maize would not be polluted by Cd was 1.39 $mg \cdot kg^{-1}$.

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