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Accumulation and Transport of Cd, Pb, As, and Cr in Different Maize Varieties in Southwest China

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Abstract: The southwestern region of China is one of the major maize (*Zea mays* L.)-producing areas and a concentrated zone of farmland contaminated by heavy metals (HMs). Selection of maize varieties with low accumulation of HMs under complex HM pollution conditions is one the most feasible and effective ways for safe utilization of HM-polluted farmland. In this study, we conducted field experiments to investigate the differences in biological traits among 28 local maize varieties under combined soil pollution with Cd, Pb, As, Cr, and Hg. We analyzed the absorption, accumulation, and transport characteristics of Cd, Pb, As, and Cr in various parts of the maize plant (Hg was not detected in any part of maize plants) and explored the relationships of HM contents in different parts of maize with soil HM contents through cluster analysis, correlation analysis, and principal component analysis. The results indicated that among different biological traits of maize, root length, root dry weight, and plant height were the most significantly influenced by soil HM content, while stem dry weight was the least affected. The accumulation capacity of various maize parts for HMs followed the order of grains < stems < cobs < leaves < roots, while the transport capacity followed the order of root–grain < root–stem < cob–grain < stem–cob < stem–leaf. In addition, the accumulation capacity of maize grains for HMs followed the order of As < Cr < Pb < Cd. Different HMs exhibited synergistic effects in various maize parts, except for the stem, particularly in the grains. A synchronous transport mechanism was observed for As and other HMs in different parts. The accumulation of HMs in maize was primarily derived from human activities such as the extraction, storage, and smelting of non-ferrous metals, while the HMs in soil parent material and weathering products played a secondary role. The yield of the tested maize varieties ranged from 7377.6 to 11,037.0 kg·hm^{-2}, with M5 (Haoyu 1511) achieving the highest yield. M2, M4, M5, M9, M10, M21, and M25–28 were identified as suitable varieties with low Cd, Pb, As, and Cr accumulation for popularization in HM-contaminated soils in southwestern China due to their low accumulation of HMs.

Keywords: heavy metals; maize; phytoremediation; low accumulation; variety selection

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1. Introduction

With the development of society and improvement of living standards, industrialization and urbanization have been greatly accelerated, leading to further intensified and large-scale agricultural production and thereby causing increasingly severe soil pollution [1]. Soil pollutants include organic and inorganic pollutants. Organic pollutants can be decomposed by plant roots and soil microorganisms, whereas inorganic pollutants, primarily heavy metals (HMs), cannot be decomposed [2]. Any metallic or metalloid elements with a high density that remains toxic even at trace levels, such as cadmium (Cd), lead (Pb), chromium (Cr), mercury (Hg), and arsenic (As), are considered as HMs [3]. Due to their high toxicity, rapid accumulation, non-degradability, and persistence, HMs have become one of the most severe pollutions in global terrestrial and aquatic environments [3,4]. Statistics has shown that over 50% of the more than 10 million significant polluted sites worldwide are contaminated by HMs or metalloids [5]. In Europe, approximately 37.3% of the total soil pollution is attributed to HMs [6]. In the United States, there are over 100,000 sites related to HMs pollution [7]. A similar situation has been reported in China, where about 80% of contaminated soils are caused by HMs, affecting 20 million hectares of farmland and leading to the annual production of nearly 12 million tons of HM-contaminated grains [8]. There has been increasing evidence suggesting the association of HMs with various human diseases, such as cardiovascular diseases, cancer, cognitive impairments, chronic anemia, and damage to the kidneys, nervous system, brain, skin, and bones [9]. Liu et al. investigated HMs in agricultural soils and crops in a Pb/Zn-smelting city and analyzed the exposure risk of HMs through multiple pathways in a soil–crop system by Monte Carlo simulation. The results showed that the carcinogenic risk for both children and adults exceeded the risk limit (TCR = 0.0001), and adults had higher carcinogenic risk than children, while Cd had the highest carcinogenic risk and probability of exceeding the limiting risk [10]. In China's 2009 "Twelfth Five-Year Plan for Comprehensive Prevention and Control of HM Pollution", Cd, Pb, Cr, Hg, and metalloid As are listed as priority pollutants for control [11].

In recent years, there has been an obvious increase in public awareness of the impact of HM-contaminated soils on human health, leading to greater attention on the remediation of soil HM pollution and making it a key research area in agricultural environmental protection [12]. The common remediation methods include chemical, physical, and biological remediation [13], which have been typically applied in large-scale remediation practices, with each having certain effectiveness as well as some inherent limitations. For instance, the commonly used physicochemical remediation methods can effectively remove pollutants, but they are also costly and difficult to be implemented on a large scale in mildly contaminated farmlands [14]. Conversely, biological remediation methods are more cost-effective and environmentally friendly, but they involve longer remediation cycles and are faced with challenges in practical application [9]. Hence, there is a pressing need for environmentally sound, resource-efficient, and economically viable approaches. In this context, screening of low-accumulation varieties to reduce crop absorption and accumulation of HMs, thereby reducing their contents in agricultural products, has been widely recognized as a green and economically feasible solution for safe utilization of HM-polluted farmland [15,16]. Current research on low-accumulation crop variety selection has been mainly conducted on cereal crops such as rice [17–19], maize [18,20–22], wheat [23,24], and barley [25] as well as various vegetable crops such as leafy, cruciferous, root, solanaceous, and leguminous vegetables [19,26–29]. Samal et al. investigated the As content in rice grains from 44 rice varieties in the Nadia region of India, where 42 rice varieties exceeded the Codex Alimentarius Commission limit for polished rice (0.2 $mg \cdot kg^{-1}$), with high-yielding rice varieties being more prone to accumulation of As [17]. Zhang et al. conducted a two-year field trial, identifying two promising low-cadmium-accumulating rapeseed varieties from 225 varieties, with bioaccumulation factor (BCF) values of 0.07 and 0.08 [27].

Maize is the second largest food crop worldwide, with a wide cultivation area and high biomass and yield. In addition to direct human consumption, maize is also extensively used in animal feed, ethanol production, high-fructose syrup, sweeteners, and alcoholic beverages. Different maize varieties may differ in the absorption, transport, distribution, and accumulation of HMs due to their varying sensitivity to HM pollution and different accumulation capacities. For example, previous studies have shown significant differences in the absorption and accumulation capabilities of different maize varieties for Cd and Pb [21]. Early research has been primarily focused on the absorption and accumulation differences of single HMs (such as Cd, Pb, or As) among different varieties and their selection. In recent years, the focus of research has been gradually shifted from the selection of low-accumulation varieties under pollution of single HMs to combined pollution of multiple HMs [22]. Additionally, due to the limitations of pot experiments, the low-accumulation varieties selected through pot trials generally have poor reproducibility and stability under field conditions. Therefore, it is necessary to conduct field experiments under combined HM pollution in the soil to explore the interactions among multiple HMs and the mechanisms for low HM accumulation in different maize varieties for safe utilization of large-area HM-polluted farmland in specific regions.

Southwestern China suffers from severe Cd, Pb, As, and Cr pollution in farmland soils [1]. This study selected 28 maize varieties widely cultivated in the southwest as test subjects. Through field comparative experiments in the HM-polluted maize planting areas of eastern Yunnan Province, this study explored the variations in biological traits and yield of different maize varieties under combined pollution of various HMs as well as differences in the contents, BCF, and translocation factor (TF) of Cd, Pb, As, and Cr in different parts of the maize plant. Furthermore, the relationships of the Cd, Pb, As, and Cr contents in various maize parts with the HM contents in the soil were investigated through cluster analysis, correlation analysis, and principal component analysis, aiming to identify maize varieties with low-accumulation potential for HMs and promote their cultivation in regions with HM pollution, thereby providing technical support for the safe utilization of HM-contaminated farmland.

2. Materials and Methods

2.1. Overview of the Experimental Area

The field experiment was conducted in Geyi Town, Xuanwei City, Yunnan Province, China (26°20′41″ N, 104°21′48″ E), which is situated in the mountainous plateau region of southwestern China and characterized by karst topography and red soil. This area was historically one of the significant bases for non-ferrous metal mining and smelting in Yunnan, leading to severe HM contamination in the surrounding soils and the emergence of complex HM pollution issues. The soil at the experimental site has a pH value of 4.74 ± 0.28, organic matter content of 68.70 ± 4.17 g·kg^{-1}, alkaline nitrogen content of 253.58 ± 68.33 mg·kg^{-1}, available phosphorus content of 72.78 ± 20.91 mg·kg^{-1}, and available potassium content of 456.22 ± 107.29 mg·kg^{-1}. The total concentrations of Cd, Pb, As, Cr, and Hg are 6.99 ± 1.59, 59.61 ± 3.15, 44.10 ± 6.67, 336.51 ± 40.07, and 0.20 ± 0.03 mg·kg^{-1}, respectively. The available concentrations were found to be 1.74 ± 0.66 mg·kg^{-1} for Cd, 3.37 ± 1.45 mg·kg^{-1} for Pb, 0.50 ± 0.29 mg·kg^{-1} for As, 0.03 ± 0.02 mg·kg^{-1} for Cr, and 0.02 ± 0.01 mg·kg^{-1} for Hg.

2.2. Maize Varieties Used in the Experiment

This study selected 28 maize varieties widely cultivated in southwestern China, and the variety names and their main agronomic traits are shown in Table 1, with seeds purchased from the maize seed market in Kunming City.

Table 1. Tested Maize Varieties and their Main Agronomic Traits.

Number	Variety Name	Main Agronomic Feature of Maize
M1	Datian 183	Ear shape: conical to cylindrical, grain color: medium yellow
M2	Diwo 1	Ear shape: cylindrical, grain color: yellow
M3	Diwo 8	Ear shape: cylindrical, grain color: orange-yellow
M4	Dunyu 735	Ear shape: cylindrical, grain color: yellow
M5	Haoyu 1511	Ear shape: conical to cylindrical, grain color: medium yellow
M6	Hongdan 6	Ear shape: cylindrical, grain color: orange-red
M7	Huaxingdan 7	Ear shape: cylindrical, grain color: yellow
M8	Huaxingdan 88	Ear shape: conical, grain color: orange-yellow
M9	Huayu 17	Ear shape: cylindrical, grain color: yellow-red
M10	Huidan 888	Ear shape: cylindrical, grain color: orange-yellow
M11	Huidan 936	Ear shape: conical to cylindrical, grain color: orange
M12	Jiyuan 8	Ear shape: cylindrical, grain color: orange-yellow
M13	Jinboshi 917	Ear shape: cylindrical, grain color: yellow
M14	Jinyu 150	Ear shape: cylindrical, grain color: yellow
M15	Jinyu 932	Ear shape: conical, grain color: yellow
M16	Jingdan 16	Ear shape: conical to cylindrical, grain color: medium yellow
M17	Ludan 25	Ear shape: conical to cylindrical, grain color: orange-yellow
M18	Luodan 297	Ear shape: cylindrical, grain color: yellow
M19	Shengyu 16	Ear shape: conical to cylindrical, grain color: orange-yellow
M20	Shengyu 607	Ear shape: conical to cylindrical, grain color: orange-yellow
M21	Shengxing 199	Ear shape: conical to cylindrical, grain color: yellow
M22	Xikang 18	Ear shape: cylindrical, grain color: white
M23	Xianyu 1798	Ear shape: conical to cylindrical, grain color: yellow
M24	Xingdan 106	Ear shape: conical to cylindrical, grain color: medium yellow
M25	Yunhuang 7	Ear shape: conical to cylindrical, grain color: medium yellow
M26	Yunli 4	Ear shape: conical to cylindrical, grain color: orange-yellow
M27	Zuyu 606	Ear shape: conical to cylindrical, grain color: orange-yellow
M28	Zuyu 809	Ear shape: conical to cylindrical, grain color: orange-yellow

2.3. Experimental Design

The total area of the experimental site was approximately 9350 m^2, with a flat terrain. All plots were arranged in a randomized block design (see Table 1). Each maize variety was treated as a separate treatment with three replicates, resulting in a total of 84 plots. Each experimental plot measured approximately 110 m^2 and adopted a double-row planting system with a row spacing of 60 cm and a plant spacing of 40 cm. Each plot consisted of 24 rows, with 25 plants per row. The outermost four rows of each plot were designated as a buffer to prevent cross-pollination among different varieties to maintain variety stability. Three maize seeds were sown per hole at a depth of 2–3 cm. Thinning was conducted when the maize developed two leaves, leaving one plant per hole, with a target density of 600 plants per plot. Prior to sowing, a compound fertilizer ($N + P_2O_5 + K_2O = 45\%$, N: P_2O_5: K_2O = 15: 15: 15, produced by Yunnan Yuntianhua Co., Ltd., Kunming, China) was applied at a rate of 100 $kg \cdot km^{-2}$ and mixed uniformly into the top 0–20 cm layer of soil through rotary tillage, followed by mulching and seeding. During the crop growing period, irrigation was solely based on natural rainfall, and no chemical agents were used for weeding and pest control; all management tasks were carried out manually. At the booting stage, urea (total nitrogen $\geq$ 46%, produced by Yunnan Yuntianhua Co., Ltd.) was applied at a rate of 75 $kg \cdot km^{-2}$. The experiment was commenced with sowing on 10 April 2022, and sampling was conducted on 10 October 2022.

2.4. Sample Collection and Analysis

Soil (0–20 cm) and maize plant samples were collected from each plot using a five-point sampling method. Soil samples were air-dried in the dark at room temperature (25 $\pm$ 5 °C) and made free from stones and organic debris, ground in a mortar, passed through a 100-mesh nylon sieve, and stored in sealed plastic bags. Maize plant samples were divided into five parts, including the roots, stems, leaves, cobs, and grains. They were rinsed with deionized water and air-dried (25 ± 5 °C), and the dry weights were measured. The samples were then ground using a mill, passed through a 100-mesh nylon sieve, and stored in sealed plastic bags until analysis.

For soil sample analysis, the pH was measured using a PHS-3E pH meter (produced by Shanghai INESA Scientific Instrument Co., Ltd., Shanghai, China); organic matter content was determined by the potassium dichromate volumetric method with heating; alkaline nitrogen content was measured by the alkaline diffusion method; available phosphorus was extracted with sodium bicarbonate and determined by molybdenum–antimony spectrophotometry; available potassium was extracted with ammonium acetate and measured by flame photometry. The total Cd and Pb content were analyzed by inductively coupled plasma mass spectrometry (ICP-MS, produced by Thermo Fisher Scientific Inc., Waltham, MA, USA), according to the standards DZ/T 0279.5-2016 and DZ/T 0279.3-2016, respectively. The total Cr content and available Cd, Pb, and Cr content were measured by inductively coupled plasma atomic emission spectroscopy (ICP-AES, produced by Thermo Fisher Scientific Inc.), following the standards DZ/T 0279.2-2016 and HJ 804-2016, respectively. The total As and Hg content and available As and Hg content were analyzed using atomic fluorescence spectroscopy (AFS, produced by Beijing Haiguang Instrument Co., Ltd., Beijing, China), in accordance with the standards GB/T 22105.2-2008 and GB/T 22105.1-2008, and DB35/T 1459-2014, respectively.

For maize sample analysis, the Cd, Pb, and Cr contents were determined by graphite furnace atomic absorption spectroscopy (GFAAS, produced by Shimadzu Corporation, Kyoto, Japan), following the standards GB5009.15-2014, GB5009.12-2017, and GB 5009.123-2014, respectively. The As and Hg content were analyzed using atomic fluorescence spectroscopy (AFS, produced by Beijing Haiguang Instrument Co., Ltd.), based on the standards GB 5009.11-2014 and GB 5009.17-2021, respectively.

The chemicals and reagents used in this study were of analytical grade (produced by Sinopharm Chemical Reagent Co., Ltd., Shanghai, China), and deionized water was used in all experiments. All glassware and utensils were cleaned, soaked in nitric acid solution (10% v/v) overnight, rinsed with deionized water, and dried before use. National Standard Materials of Soil (GBW07405 (GSS-5)) and Maize (GBW10012 (GSB-3)), produced by Institute of Geophysical and Geochemical Exploration, Chinese Academy of Geological Sciences., Langfang, China, were used during the analysis for quality control. To ensure the accuracy and precision of the measurement results, repeated analysis with a repetition rate of 20% and standard sample analysis with spiked recovery rates between 90% and 110% were conducted, and the relative deviation of all test results was less than 10%.

2.5. Evaluation Methods

2.5.1. Single-Factor Pollution Index and Nemero Comprehensive Pollution Index

This study employed the single-factor pollution index (P_i) and the Nemero comprehensive pollution index (P_{N}) to evaluate the HM pollution status of the experimental area [30]. The evaluation criteria are presented in Table 2, and the calculation formulas are as follows:

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

$$P_{\mathrm{N}} = \sqrt{\frac{{P_{avg}}^2 + {P_{max}}^2}{2}} \tag{2}$$

where C_i represents the measured content of HM *i*, S_i is the evaluation standard value for HM *i* (using the Yunnan Provincial soil element background value [31]), P_{avg} is the average value of the single-factor pollution index, and P_{max} is the maximum value of the single-factor pollution index.

Table 2. Evaluation Criteria for Single-Factor Pollution Index and Nemero Comprehensive Pollution Index.

Single-Factor Pollution Index (P_i)	Pollution Level	Nemero Comprehensive Pollution Index (P_N)	Pollution Level
$P_i \leq 1$	No Pollution	$P_N \leq 0.7$	No Pollution (Safe)
$1 < P_i \leq 2$	Light Pollution	$0.7 < P_N \leq 1$	Slight Pollution (Warning)
$2 < P_i \leq 3$	Moderate Pollution	$1 < P_N \leq 2$	Light Pollution
$P_i > 3$	Severe Pollution	$2 < P_N \leq 3$	Moderate Pollution
		$P_N > 3$	Severe Pollution

2.5.2. Potential Ecological Risk Index Evaluation

The potential ecological risk index (PERI) was employed to analyze the potential risks of HMs in the soil of the study area [32]. The evaluation criteria are shown in Table 3, and the calculation formulas are as follows:

$$E_i = T_i \times \frac{C_i}{S_i} \tag{3}$$

$$RI = \sum_{i=1}^{n} E_i \tag{4}$$

where E_i represents the PERI of HM *i*, C_i is the measured concentration of HM *i*, S_i is the evaluation standard value for HM *i* (using the background values of soil elements in Yunnan Province [31]), T_i is the toxicity coefficient for HM *i* (referring to the HM toxicity coefficients proposed by Hakanson [32]: $T_{Cr} = 2$, $T_{Pb} = 5$, $T_{As} = 10$, $T_{Cd} = 30$, $T_{Hg} = 40$), and *RI* represents the integrated PERI of HMs.

Table 3. Evaluation Criteria for Potential Ecological Risk Index and Integrated Potential Ecological Risk Index.

Potential Ecological Risk Index (E_i)	Integrated Potential Ecological Risk Index (RI)	Risk Level
$E_i \leq 40$	$RI \leq 150$	Slight Risk
$40 < E_i \leq 80$	$150 < RI \leq 300$	Low Risk
$80 < E_i \leq 160$	$300 < RI \leq 600$	Moderate Risk
$160 < E_i \leq 320$	$600 < RI \leq 1200$	High Risk
$E_i > 320$	$RI > 1200$	Extremely High Risk

2.5.3. Bioaccumulation Factor and Translocation Factor

The bioaccumulation factor (BCF) indicates the capacity of crops to accumulate HMs from the soil, with a higher value reflecting a greater ability to accumulate HMs. The calculation formula is as follows:

$$\mathrm{BCF_i} = \frac{C_{ia}}{C_{is}} \tag{5}$$

where $\mathrm{BCF_i}$ represents the BCF for HM *i* in the part *a* of the test maize, C_{ia} is the concentration of HM *i* in part *a* of the test maize, and C_{is} is the concentration of HM *i* in the soil.

The translocation factor (TF) indicates the ability of crops to translocate and distribute HMs between different parts, with a higher TF value reflecting a greater ability to transport HMs. The calculation formula is as follows:

$$TF_i = \frac{C_{ib}}{C_{ia}} \quad (6)$$

where TFi represents the TF of HM i from part a to part b in the test maize, and C_{ia} and C_{ib} are the concentrations of HM i in a and b, respectively.

2.6. Data Statistics and Analysis

All data were processed using Microsoft Excel 2019. Redundancy analysis (RDA) was conducted using the GenesCloud Tools data analysis platform (https://www.genescloud.cn, accessed on 15 November 2024) for analysis and plotting. Variance analysis (ANOVA) and cluster analysis were performed using IBM SPSS 23.0 for analysis and plotting. Correlation analysis, principal component analysis, and figure construction were carried out using OriginPro 2021. Mean comparisons were conducted using the least significant difference (LSD) method, and data in the charts are presented as mean $\pm$ standard deviation (M $\pm$ SD), with a significance level set at $p < 0.05$.

3. Results

3.1. Pollution Status of the Experimental Area

Figure 1 shows the calculation results of pollution indices (P_i and P_N) for the soil in the study area. The P_{Cd}, P_{Pb}, P_{As}, P_{Cr}, P_{Hg}, and P_N for various HMs were 16.1–42.6, 1.3–1.7, 2.0–3.4, 3.5–6.0, 2.6–4.7, and 12.6–33.1, with average values of 31.8, 1.5, 2.5, 5.2, 3.4, and 24.7, respectively. Based on P_i, the average pollution levels of the five HMs in the soil followed the order of Pb < As < Hg < Cr < Cd. Notably, Pb was categorized as having light pollution ($1 < P_i \leq 2$), while As and Hg fell into moderate ($2 < P_i \leq 3$) to severe pollution ($P_i > 3$); Cr and Cd were classified as severe pollution ($P_i > 3$), with Cd exhibiting significantly higher pollution levels than other HMs. The overall soil pollution level in the study area was determined to be severe based on P_N (P_N = 24.7 > 3).

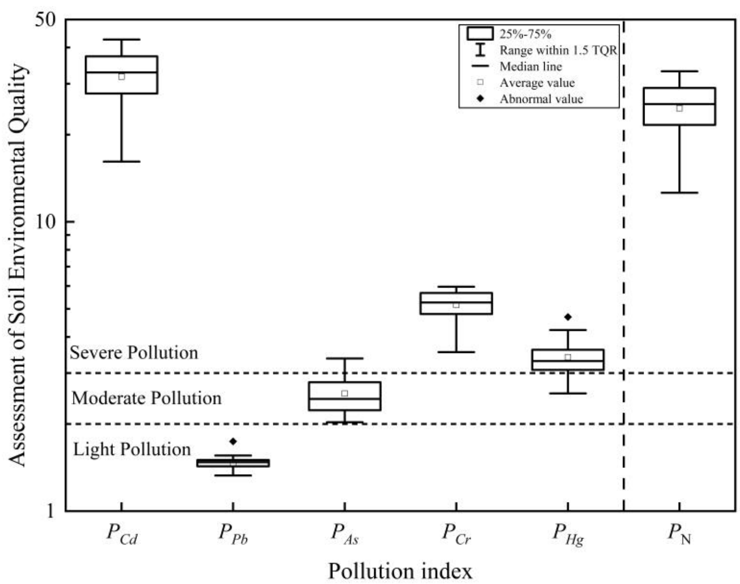

Figure 1. Box plots of soil single-factor pollution index (P_i) and Nemero comprehensive pollution index (P_N).

The evaluation results of PERI for soil in the study area are presented in Figure 2. The potential ecological risk indices of various HMs and the comprehensive PERI were E_{Cd} 484.1–1279.1, E_{Pb} 6.6–8.7, E_{As} 20.3–33.7, E_{Cr} 7.1–11.9, E_{Hg} 102.1–187.6, and RI 621.1–1458.8, with averages of 952.8, 7.3, 25.5, 10.3, 136.1, and 1132.1, respectively. According to E_i, the average potential ecological risk indices of the five HMs followed the order of Pb < Cr < As < Hg < Cd. Pb, As, and Cr were classified as having slight risks ($E_i \leq 40$); Hg fell into moderate risk ($80 < E_i \leq 160$) to high risk ($160 < E_i \leq 320$); while Cd was classified as extremely high risk ($E_i > 320$), contributing 84.2% to the RI. The overall ecological risk level of the soil in the study area was classified as high based on RI ($600 < RI \leq 1200$).

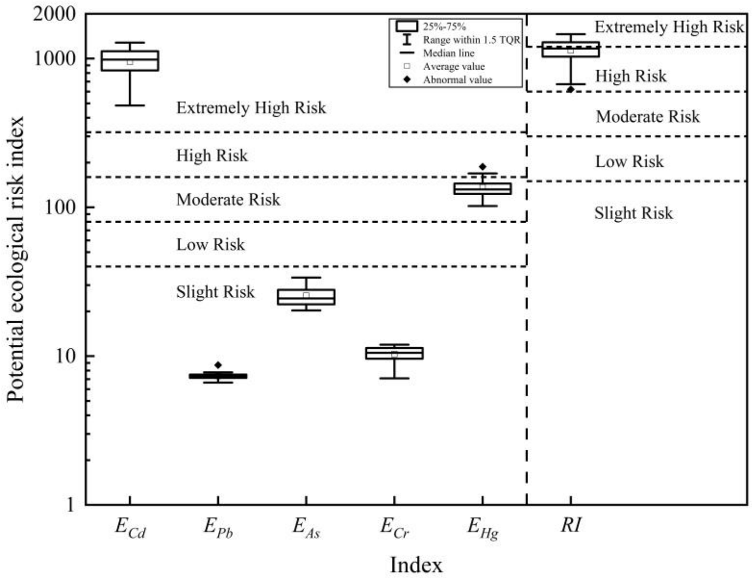

Figure 2. Box plots of potential ecological risk index (E_i) and comprehensive potential ecological risk index (RI) for soil.

3.2. Analysis of Biological Traits of Maize Plants and Soil Properties

3.2.1. Biological Traits of Maize Plants

Table 4 presents the biological traits of different maize varieties. The results indicated significant differences in biological traits among the tested maize varieties ($p < 0.05$). The dry biomass of the roots, stems, leaves, cobs, and grains was 16.1–36.5, 40.3–92.7, 64.9–124.9, 12.5–37.6, and 182.6–273.2 g·plant^{-1}, with average values of 22.2, 63.1, 93.5, 27.1, and 229.7 g·plant^{-1}, respectively. The yields of the tested maize varieties ranged from 7377.6 to 11,037.0 kg·hm^{-2}, with an average of 9280.8 kg·hm^{-2}. Furthermore, the plant height, stem diameter, and root length for the tested maize varieties were 184.7–311.0 cm, 14.8–25.8 mm, and 17.0–31.3 cm, with average values of 254.0 cm, 19.4 mm, and 23.7 cm, respectively.

Table 4. Biological Traits of Different Maize Varieties.

Variety Number	Root Dry Weight (g·plant^{-1})	Stem Dry Weight (g·plant^{-1})	Leaf Dry Weight (g·plant^{-1})	Cob Dry Weight (g·plant^{-1})	Grain Dry Weight (g·plant^{-1})	Yield (kg·hm^{-2})	Plant Height (cm)	Stem Diameter (mm)	Root Length (cm)
M1	21.4 ± 0.7 hi	78.4 ± 9.5 ab	98.2 ± 8.9 cde	19.5 ± 1.9 hi	230.3 ± 12.4 ghijk	9304.8 ± 499.5 ghijk	296.0 ± 5.1 ab	24.3 ± 0.2 ab	19.7 ± 1.7 lmno
M2	31.4 ± 1.0 b	75.5 ± 9.2 abc	104.4 ± 9.5 bcd	26.5 ± 2.4 cdefgh	242.8 ± 6.7 efgh	9808.4 ± 270.6 efgh	233.0 ± 5.0 hijk	25.8 ± 2.6 a	22.7 ± 1.2 hijk
M3	16.7 ± 0.5 no	48.1 ± 5.8 fghi	86.7 ± 7.9 cdefghi	22.1 ± 5.3 efghi	205.0 ± 8.3 lmno	8282.5 ± 336.5 lmno	254.3 ± 4.6 efg	19.3 ± 0.9 cdefgh	28.0 ± 0.8 bcde
M4	16.7 ± 0.5 no	60.0 ± 7.3 bcdefgh	72.7 ± 6.6 ghij	12.5 ± 4.7 j	182.6 ± 2.9 p	7377.6 ± 117.2 p	287.3 ± 2.5 bc	18.3 ± 1.1 defghi	28.7 ± 0.9 bc
M5	22.9 ± 0.7 g	74.8 ± 9.1 abc	119.2 ± 10.8 ab	37.6 ± 5.3 a	273.2 ± 3.7 a	11,037.0 ± 151.1 a	259.7 ± 3.3 ef	22.4 ± 0.4 abcd	25.7 ± 1.7 defg
M6	25.7 ± 0.8 de	90.4 ± 11.0 a	124.9 ± 11.4 a	32.8 ± 1.4 abc	216.0 ± 11.2 jklmn	8726.7 ± 454.4 jklmn	226.7 ± 5.7 jkl	17.0 ± 2.4 fghi	18.0 ± 0.8 no
M7	18.8 ± 0.6 lm	43.1 ± 5.2 hi	78.4 ± 7.1 efghij	30.2 ± 3.2 bcd	210.1 ± 5.7 klmno	8487.6 ± 228.4 klmno	218.7 ± 12.8 kl	15.1 ± 1.4 hi	21.3 ± 1.2 jklm
M8	21.0 ± 0.6 ij	50.0 ± 6.1 efghi	76.8 ± 7.0 fghij	31.0 ± 1.8 abcd	271.2 ± 3.2 ab	10,958.5 ± 128.3 ab	269.3 ± 8.5 de	18.8 ± 1.7 cdefghi	26.3 ± 0.5 cdefg
M9	24.9 ± 0.8 ef	65.4 ± 7.9 bcdef	93.1 ± 8.5 cdefg	27.2 ± 1.5 cdefg	253.9 ± 14.6 abcdef	10,259.8 ± 589.0 abcdef	276.0 ± 8.5 cd	20.0 ± 2.1 bcdefg	31.3 ± 1.7 a
M10	28.7 ± 0.9 c	61.9 ± 7.5 bcdefg	106.3 ± 9.7 abc	29.4 ± 1.3 bcde	258.3 ± 5.8 abcde	10,435.9 ± 234.1 abcde	261.3 ± 9.4 def	19.3 ± 2.3 cdefgh	24.7 ± 0.9 fghi
M11	30.1 ± 0.9 bc	77.5 ± 9.4 ab	123.6 ± 11.2 ab	31.3 ± 2.0 abcd	246.4 ± 10.0 defg	9955.5 ± 405.5 defg	304.7 ± 12.3 a	21.7 ± 1.2 bcde	20.3 ± 1.2 klmn
M12	19.3 ± 0.6 klm	63.0 ± 7.7 bcdefg	78.5 ± 7.1 efghij	24.0 ± 5.1 defgh	217.7 ± 8.4 jklmn	8794.7 ± 340.3 jklmn	245.7 ± 5.3 fgh	20.2 ± 2.0 bcdefg	19.0 ± 0.8 mno
M13	22.7 ± 0.7 gh	57.4 ± 7.0 cdefghi	96.3 ± 8.8 cdef	27.4 ± 3.4 cdefg	221.0 ± 15.7 ijklm	8929.1 ± 633.0 ijklm	239.0 ± 3.7 ghij	17.5 ± 0.5 efghi	20.3 ± 0.5 klmn
M14	29.8 ± 0.9 c	92.7 ± 11.3 a	121.7 ± 11.1 ab	36.5 ± 1.8 ab	264.4 ± 9.2 abcd	10,684.4 ± 370.3 abcd	246.0 ± 7.8 fgh	20.1 ± 2.9 bcdefg	24.0 ± 0.8 fghij
M15	18.0 ± 0.6 mn	60.2 ± 7.3 bcdefgh	90.7 ± 8.2 cdefgh	33.2 ± 6.0 abc	239.6 ± 6.3 efghi	9680.9 ± 254.4 efghi	266.0 ± 7.8 de	20.2 ± 2.7 bcdefg	25.7 ± 1.7 defg
M16	26.7 ± 0.8 d	57.8 ± 7.0 cdefghi	90.9 ± 8.3 cdefgh	20.7 ± 4.4 fghi	194.4 ± 5.9op	7855.1 ± 237.4 op	184.7 ± 7.8 m	21.6 ± 1.6 bcde	20.0 ± 0.8 klmn
M17	16.1 ± 0.5 o	40.3 ± 4.9 i	64.9 ± 5.9 j	28.1 ± 1.4 cde	208.4 ± 11.3 lmno	8418.3 ± 456.9 lmno	216.3 ± 4.0 l	18.0 ± 1.1 defghi	22.3 ± 1.2 ijkl
M18	23.5 ± 0.7 fg	63.3 ± 7.7 bcdefg	94.4 ± 8.6 cdef	27.8 ± 1.7 cdefg	250.8 ± 7.1 bcdefg	10,133.1 ± 287.4 bcdefg	222.0 ± 10.7 kl	14.8 ± 1.0 i	17.0 ± 0.8 o
M19	18.6 ± 0.6 lm	63.6 ± 7.7 bcdefg	105.2 ± 9.6 abcd	27.7 ± 4.7 cdefg	248.2 ± 13.8 cdefg	10,027.6 ± 558.9 cdefg	262.7 ± 1.7 de	20.4 ± 2.8 bcdefg	30.3 ± 1.2 ab
M20	17.9 ± 0.5 mn	51.9 ± 6.3 efghi	93.0 ± 8.5 cdefg	30.7 ± 2.0 abcd	233.7 ± 10.3 fghij	9442.5 ± 414.5 fghij	228.0 ± 5.9 ijkl	16.9 ± 0.9 fghi	25.3 ± 2.1 efgh
M21	16.3 ± 0.5 o	68.3 ± 8.3 bcde	86.8 ± 7.9 cdefghi	29.9 ± 1.8 bcd	225.6 ± 11.7 hijkl	9115.5 ± 472.6 hijkl	262.7 ± 8.2 de	19.5 ± 1.0 cdefgh	26.7 ± 1.2 cdef
M22	20.8 ± 0.6 ijk	71.9 ± 8.7 bcd	84.8 ± 7.7 defghij	28.0 ± 1.6 cdef	202.8 ± 5.3 mnop	8194.2 ± 213.8 mnop	298.0 ± 4.5 ab	20.4 ± 1.4 bcdef	28.3 ± 1.2 bcd
M23	20.7 ± 0.6 ijk	53.5 ± 6.5 defghi	77.8 ± 7.1 efghij	20.5 ± 1.9 ghi	200.7 ± 8.3 mnop	8109.6 ± 335.5 mnop	311.0 ± 1.4 a	15.5 ± 3.2 hi	25.7 ± 1.7 defg
M24	16.5 ± 0.5 no	54.3 ± 6.6 defghi	68.1 ± 6.2 ij	16.5 ± 2.8 ij	199.6 ± 12.1 mnop	8064.0 ± 490.6 mnop	217.7 ± 6.5 kl	18.2 ± 1.8 defghi	20.0 ± 0.8 klmn
M25	16.7 ± 0.5 no	44.9 ± 5.5 ghi	72.2 ± 6.6 hij	20.5 ± 0.4 ghi	196.9 ± 2.0 nop	7956.2 ± 79.2 nop	242.3 ± 4.5 ghi	15.9 ± 1.3 ghi	26.0 ± 1.6 cdefg
M26	19.7 ± 0.6 jkl	58.4 ± 7.1 cdefghi	118.6 ± 10.8 ab	36.3 ± 1.4 ab	268.6 ± 9.9 abc	10,852.9 ± 398.3 abc	254.0 ± 2.9 efg	19.4 ± 2.9 cdefgh	23.5 ± 0.4 ghij
M27	23.8 ± 0.7 fg	61.1 ± 7.4 bcdefgh	93.3 ± 8.5 cdefg	25.2 ± 0.6 defgh	256.6 ± 7.7 abcde	10,367.4 ± 309.6 abcde	261.3 ± 6.9 def	18.9 ± 1.8 cdefghi	24.7 ± 1.2 fghi
M28	36.5 ± 1.1 a	78.3±9.5ab	97.5 ± 8.9 cdef	25.7 ± 3.2 cdefgh	212.9 ± 6.5 jklmno	8601.3 ± 260.8 jklmno	267.0 ± 8.3 de	23.0 ± 0.6 abc	18.3 ± 1.2 no
Average	22.2	63.1	93.5	27.1	229.7	9280.8	254.0	19.4	23.7
Coefficient of Variation	23.88%	24.07%	20.25%	24.57%	12.01%	12.01%	11.87%	16.40%	16.90%

Note: Different lowercase letters in the same column indicate significant differences in the biological traits among different maize varieties ($p < 0.05$).

3.2.2. Redundancy Analysis of Soil HM Contents and Maize Biological Traits

Redundancy analysis (RDA) was conducted to identify the relationship between variations in soil HM contents and changes in maize biological traits, as depicted in Figure 3. The first two axes of the RDA explained 28.15% and 0.73% of the variation in maize biological traits, respectively, accounting for a total of 28.88% of the differences, indicating that soil HM content drives the variation in maize biological traits. Among all biological traits, root length (R^2 = 0.2552, p = 0.001), root dry weight (R^2 = 0.2100, p = 0.001), and plant height (R^2 = 0.1538, p = 0.002) were the most significantly influenced by soil HM content, followed by stem diameter (R^2 = 0.0799, p = 0.040), grain dry weight (R^2 = 0.0779, p = 0.024), yield (R^2 = 0.0778, p = 0.024), leaf dry weight (R^2 = 0.0653, p = 0.072), and cob dry weight (R^2 = 0.0588, p = 0.084). In contrast, stem dry weight (R^2 = 0.0311, p = 0.269) was the least affected by soil HM content. Among various biological traits of the tested maize varieties, root length was positively correlated with plant height while negatively correlated with other biological traits. Root dry weight, stem dry weight, and leaf dry weight were positively correlated with all other biological traits except for root length. Cob dry weight had a positive correlation with stem diameter but negative correlations with grain dry weight, yield, and plant height. Grain dry weight was positively correlated with yield, plant height, and stem diameter, while yield was also positively correlated with plant height and stem diameter. Plant height was positively correlated with stem diameter and root length.

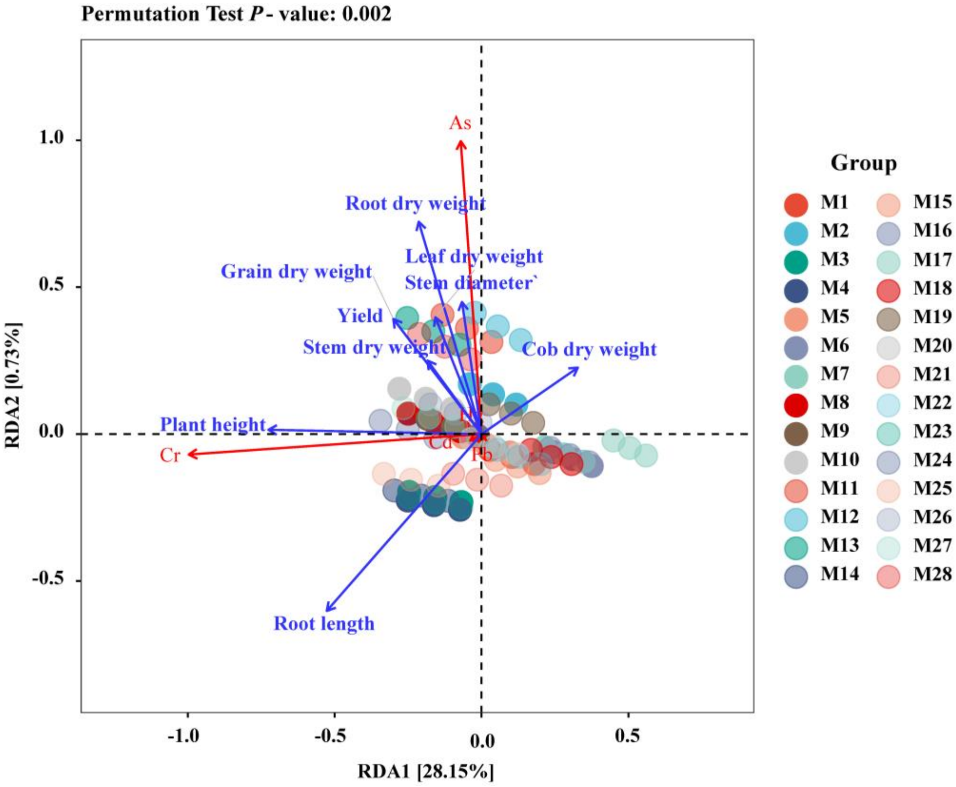

Figure 3. Redundancy analysis between biological traits of different maize varieties and soil HM contents. Each point in the figure represents a sample, with different colors indicating different maize varieties. The closer the points, the higher the similarity between samples. The red arrows represent different background factors, while the blue arrows indicate various influencing factors. The angle between the factors indicates the degree of correlation; acute angles represent positive correlations, right angles indicate no correlation, and obtuse angles signify negative correlations. The longer the arrow, the greater the influence. The p-values displayed above the ordination diagram are derived from random permutation non-parametric tests, with smaller p-values indicating more significant effects of the influencing factors on the samples. The percentages in parentheses on the axes represent the proportion of variance in the original data explained by the corresponding axes.

3.3. Analysis of Cd, Pb, As, and Cr Contents in Different Parts of Maize Plants

Figure 4 illustrates the contents of Cd, Pb, As, and Cr in various parts of maize plants across different varieties. The results indicated significant differences in the concentrations of these HMs among different maize varieties ($p < 0.05$). As shown in Figure 4a, the Cd content in the tested maize parts was 2.720–6.200, 0.116–0.488, 0.900–3.500, 0.071–0.530, and 0.017–0.220 mg·kg^{-1} in the roots, stems, leaves, cobs, and grains, with averages of 4.350, 0.229, 1.932, 0.242, and 0.067 mg·kg^{-1}, respectively. Figure 4b shows that the Pb content was 0.640–4.000, 0.112–0.538, 0.109–0.690, 0.101–0.416, and 0.058–0.280 mg·kg^{-1} in the roots, stems, leaves, cobs, and grains, with average values of 1.365, 0.207, 0.322, 0.236, and 0.140 mg·kg^{-1}, respectively. Figure 4c indicates that the As was 1.100–3.900, 0.041–0.200, 0.290–0.820, 0.041–0.525, and 0.041–0.101 mg·kg^{-1} in the roots, stems, leaves, cobs, and grains, with average values of 1.964, 0.087, 0.546, 0.160, and 0.058 mg·kg^{-1}, respectively. Figure 4d shows that the Cr was 4.850–16.100, 0.360–1.210, 1.350–6.310, 0.325–3.360, and 0.071–1.350 mg·kg^{-1} in the roots, stems, leaves, cobs, and grains, with average values of 8.843, 0.778, 3.728, 1.563, and 0.483 mg·kg^{-1}, respectively. The content of Cd, Pb, As, and Cr in various parts followed the order of grains < stems < cobs < leaves < roots, where the grains exhibited the lowest content and the roots the highest.

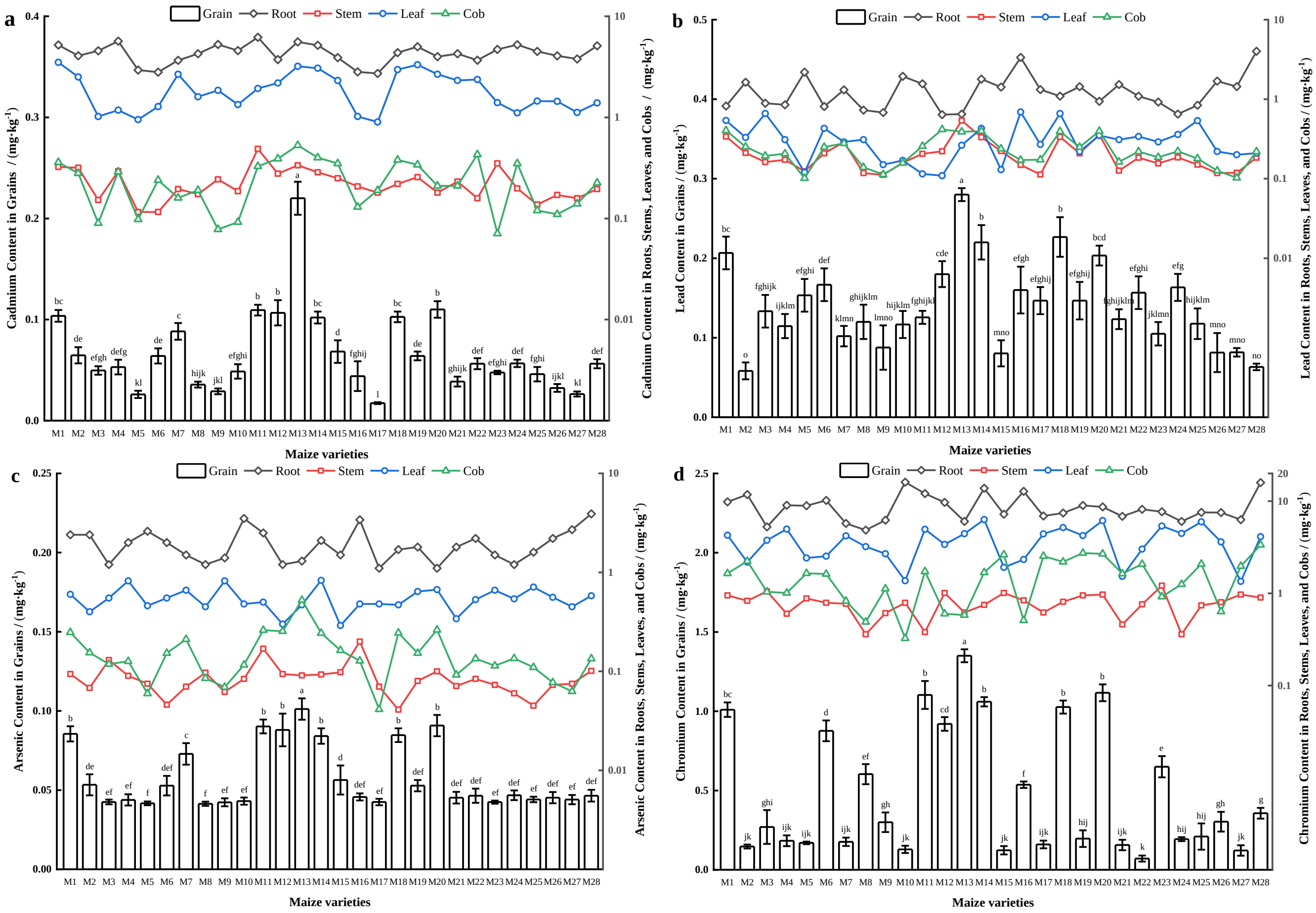

Figure 4. Cd, Pb, As, and Cr contents in various parts of maize plants of different varieties. (**a**) Cd content; (**b**) Pb content; (**c**) As content; (**d**) Cr content. Different lowercase letters indicate significant differences in HM content in the grains of different maize varieties ($p < 0.05$).

Given that the Hg content in different parts of all tested maize varieties was below the detection limit of 0.01 mg·kg^{-1}, this study focused on the analysis of Cd, Pb, As, and Cr in maize plants. The concentrations of Cd, Pb, As, Cr, and Hg in all maize grains met the limits set by the Chinese Feed Hygiene Standard (GB13078-2017) for feed materials (Cd $\leq$ 1.0 mg·kg^{-1}, Pb $\leq$ 10.0 mg·kg^{-1}, As $\leq$ 2.0 mg·kg^{-1}, Cr $\leq$ 5.0 mg·kg^{-1}, Hg $\leq$ 0.1 mg·kg^{-1}). Therefore, all parts of the maize cultivated in this experiment could be utilized for feed production, indicating the possibility of "production during remediation" and safe utilization of HM-contaminated farmland. However, the Cd content in the grains of M1, M11, M12, M13, M14, M18, and M20 as well as the Pb content in the grains of M1, M13, M14, M18, and M20 exceeded the limits specified in the National Food Safety Standard for Contaminants in Food (GB2762-2022) for grains (Cd $\leq$ 0.1 mg·kg^{-1}, Pb $\leq$ 0.2 mg·kg^{-1}, As $\leq$ 0.5 mg·kg^{-1}, Cr $\leq$ 1.0 mg·kg^{-1}, and Hg $\leq$ 0.02 mg·kg^{-1}), indicating that these maize varieties are unsuitable for food use, while the remaining varieties comply with the standards and can be utilized as food.

3.4. Analysis of BCF_{Cd}, BCF_{Pb}, BCF_{As}, and BCF_{Cr} in Different Parts of Maize Plants

Figure 5 presents the BCF_{Cd}, BCF_{Pb}, BCF_{As}, and BCF_{Cr} in various parts of maize plants across different varieties. The results indicated significant differences in the BCFs of Cd, Pb, As, and Cr among different maize varieties ($p < 0.05$). Figure 5a shows that the BCF_{Cd} in the tested maize parts was 0.432–0.828, 0.015–0.056, 0.124–0.566, 0.008–0.068, and 0.003–0.028 in the roots, stems, leaves, cobs, and grains, with averages of 0.638, 0.034, 0.288, 0.036, and 0.010, respectively. Figure 5b indicates that the BCF_{Pb} was 0.101–0.707, 0.0018–0.0088, 0.0017–0.0128, 0.0014–0.0071, and 0.0010–0.0046 in the roots, stems, leaves, cobs, and grains, with average values of 0.0231, 0.0035, 0.0055, 0.0040, and 0.0024, respectively. Figure 5c shows that the BCF_{As} was 0.0215–0.0916, 0.0011–0.0054, 0.0054–0.0214, 0.0012–0.0090, and 0.0008–0.0022 in the roots, stems, leaves, cobs, and grains, with average values of 0.0450, 0.0020, 0.0127, 0.0036, and 0.0013, respectively. Figure 5d indicates that the BCF_{Cr} was 0.0131–0.0467, 0.0009–0.0033, 0.0036–0.0191, 0.0009–0.0110, and 0.0002–0.0036 in the roots, stems, leaves, cobs, and grains, with average values of 0.0267, 0.0024, 0.0112, 0.0048, and 0.0015, respectively. The accumulation capacity of the tested maize parts for Cd, Pb, As, and Cr followed an order of grains < stems < cobs < leaves < roots, with the grains exhibiting the lowest enrichment capacity and the roots the highest.

The BCF_{Cd}, BCF_{Pb}, BCF_{As}, and BCF_{Cr} in the non-edible parts of the tested maize varieties were all below 1, while those in the edible parts were all below 0.1, indicating a weak absorption capacity of the tested maize varieties for Cd, Pb, As, and Cr. Among them, the grains of M13 (JinBoShi 917) exhibited the highest BCF_{Cd}, BCF_{Pb}, and BCF_{Cr}, which were 1.5–8.4, 1.2–4.8, and 1.0–15.9 times higher than those of other varieties, respectively, while the grains of M18 (Luodan 297) exhibited the highest BCF_{As}, which was 1.0–2.7 times higher than those of other varieties.

3.5. Cluster Analysis of BCF_{Cd}, BCF_{Pb}, BCF_{As}, and BCF_{Cr} in Maize Grains

By using the BCF_{Cd}, BCF_{Pb}, BCF_{As}, and BCF_{Cr} of the tested maize grains as parameters, we performed a hierarchical cluster analysis to classify the 28 maize varieties into a low-accumulation group (I), medium-accumulation group (II), and high-accumulation group (III), as shown in Figure 6. The low- (I), medium- (II), and high-accumulation (III) groups had BCF_{Cd} of 0.003–0.010, 0.012–0.019, and 0.028; BCF_{Pb} of 0.0010–0.0022, 0.0023–0.0031, and 0.0035–0.0046; BCF_{As} of 0.0008–0.0012, 0.0014–0.0017, and 0.0019–0.0022; and BCF_{Cr} of 0.0003–0.0010, 0.0016–0.0020, and 0.0028–0.0036, respectively. Among them, M2, M4–M5, M9–M10, M21, and M25–M28 belonged to the low-accumulation group for Cd, Pb, As, and Cr, indicating their potential for low accumulation of these HMs.

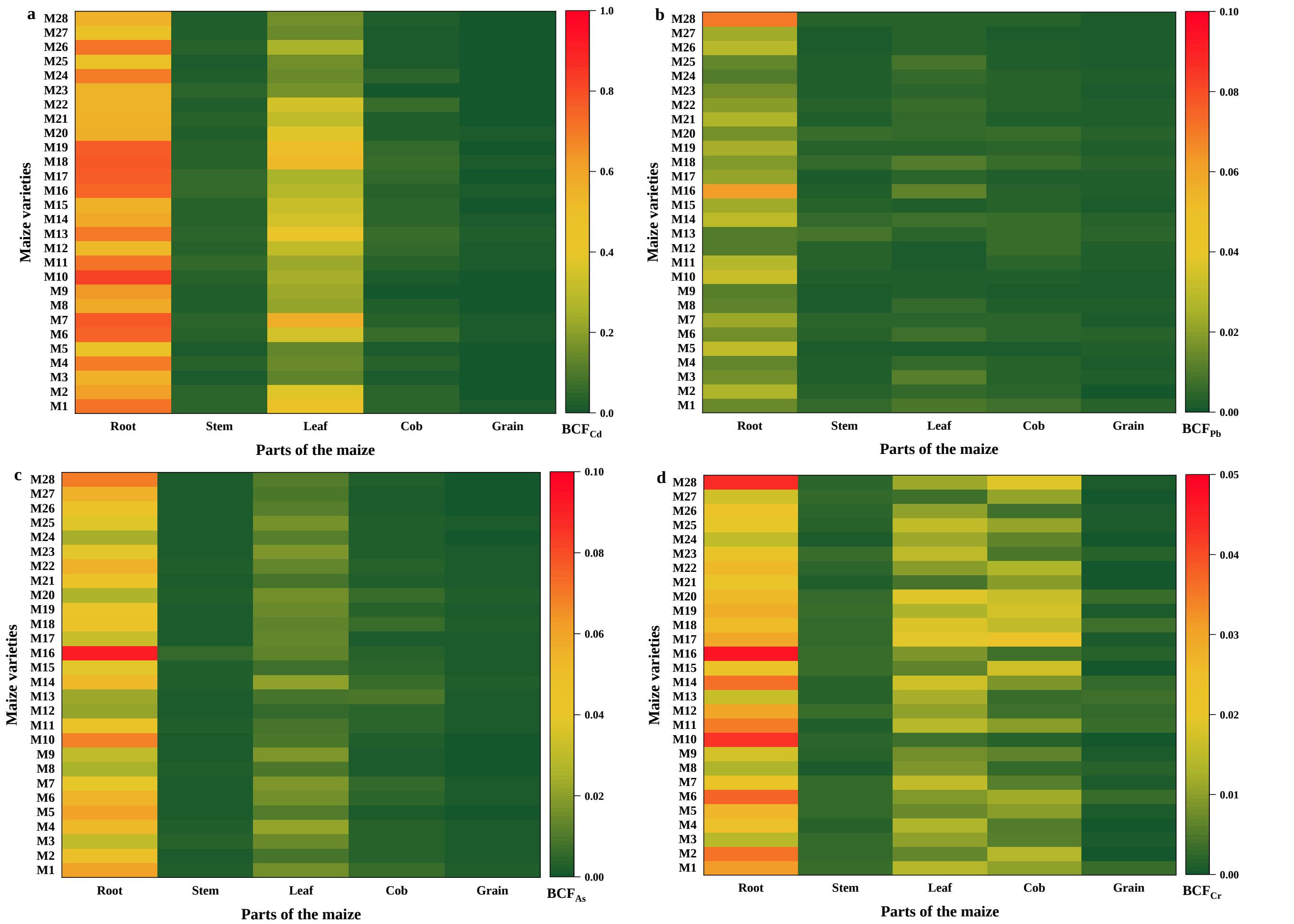

Figure 5. BCF$_{Cd}$, BCF$_{Pb}$, BCF$_{As}$, and BCF$_{Cr}$ in various parts of maize plants of different varieties. (**a**) BCF$_{Cd}$; (**b**) BCF$_{Pb}$; (**c**) BCF$_{As}$; (**d**) BCF$_{Cr}$.

3.6. Analysis of TF$_{Cd}$, TF$_{Pb}$, TF$_{As}$, and TF$_{Cr}$ in Different Parts of Maize Plants

Figure 7 presents the TF$_{Cd}$, TF$_{Pb}$, TF$_{As}$, and TF$_{Cr}$ in various parts of different maize varieties. The results indicated significant differences in TFs among various parts of maize ($p < 0.05$). As illustrated in Figure 7a, the TF$_{Cd}$ was 0.031–0.079, 3.968–14.981, 0.203–2.720, 0.091–0.672, and 0.006–0.039 for root–stem, stem–leaf, stem–cob, cob–grain, and root–grain, with average values of 0.053, 8.839, 1.101, 0.307, and 0.015, respectively. Figure 7b shows that the TF$_{Pb}$ was 0.045–0.828, 0.492–5.004, 0.726–1.875, 0.230–1.562, and 0.016–0.431 for root–stem, stem–leaf, stem–cob, cob–grain, and root–grain, with average values of 0.199, 1.774, 1.160, 0.655, and 0.136, respectively. Figure 7c indicates that the TF$_{As}$ was 0.023–0.109, 2.408–15.831, 0.593–5.975, 0.194–1.028, and 0.012–0.083 for root–stem, stem–leaf, stem–cob, cob–grain, and root–grain, with averages of 0.049, 7.154, 2.007, 0.425, and 0.034, respectively. Figure 7d displays that the TF$_{Cr}$ was 0.032–0.200, 1.396–13.070, 0.413–4.555, 0.035–2.333, and 0.008–0.224 for root–stem, stem–leaf, stem–cob, and cob–grain, with average values of 0.096, 5.345, 2.135, 0.460, and 0.058, respectively. The translocation abilities of Cd, Pb, As, and Cr between different parts of the maize plants followed the order of root–grain < root–stem < cob–grain < stem–cob < stem–leaf. Among these, the translocation ability of Cd, Pb, As, and Cr from roots to grains followed the order of Cd < As < Cr < Pb.

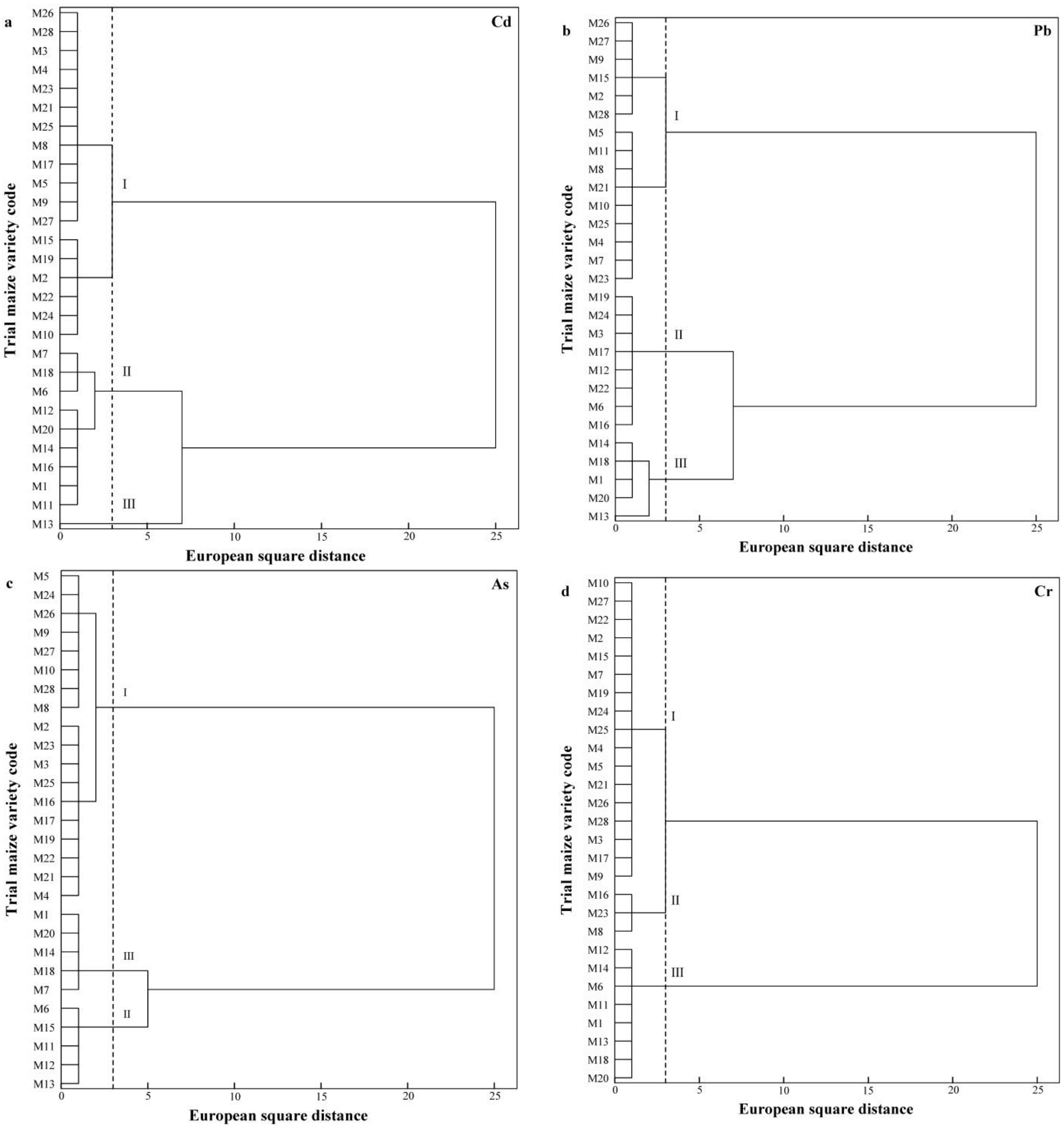

Figure 6. Cluster analysis of BCF_{Cd}, BCF_{Pb}, BCF_{As}, and BCF_{Cr} in maize grains of different varieties. Cluster analysis of (**a**) BCF_{Cd}; (**b**) BCF_{Pb}; (**c**) BCF_{As}; (**d**) BCF_{Cr}. The dashed line indicates the values of Euclidean squared distance, while I, II, and III indicate the hierarchical clustering categories.

3.7. Correlation Analysis of Cd, Pb, As, and Cr Contents in Different Parts of Maize Plants

HM contamination in agricultural soils is often associated with complex interactions, which may be manifested as synergistic or antagonistic effects. To explore the interactions among Cd, Pb, As, and Cr in different parts of maize and their impacts on plant growth as well as the absorption and translocation of HMs within the plant, we conducted a Pearson correlation analysis on the HM contents in various parts of the tested maize, as shown in Figure 8. Highly significant positive correlations ($p < 0.001$) were observed among the contents of Pb, As, and Cr in maize roots, while there were no significant correlations among the contents of Cd, Pb, As, and Cr in maize stems ($p > 0.05$). In maize leaves, a highly significant positive correlation ($p < 0.001$) was observed between As and Cr. In maize cobs, highly significant positive correlations ($p < 0.001$) were observed among the contents of Cd, Pb, and As. In maize grains, all four HMs exhibited highly significant positive correlation ($p < 0.001$) with each other. Overall, there were differences in HM contents among various parts of the tested maize. Except for the stems, other parts showed evident correlation trends in HM contents, particularly in the grains, where higher positive correlations among HMs were observed than in other parts. These results indicated that under complex HM contamination in the soil, there are certain synergistic effects among different HMs in various maize parts (except for the stems), especially in the maize grains. Furthermore, As showed highly significant positive correlations ($p < 0.001$) with other HMs in all maize parts, suggesting that it has a synchronized transport mechanism in different parts with other HMs, potentially involving co-precipitation or accompanying transport mechanisms.

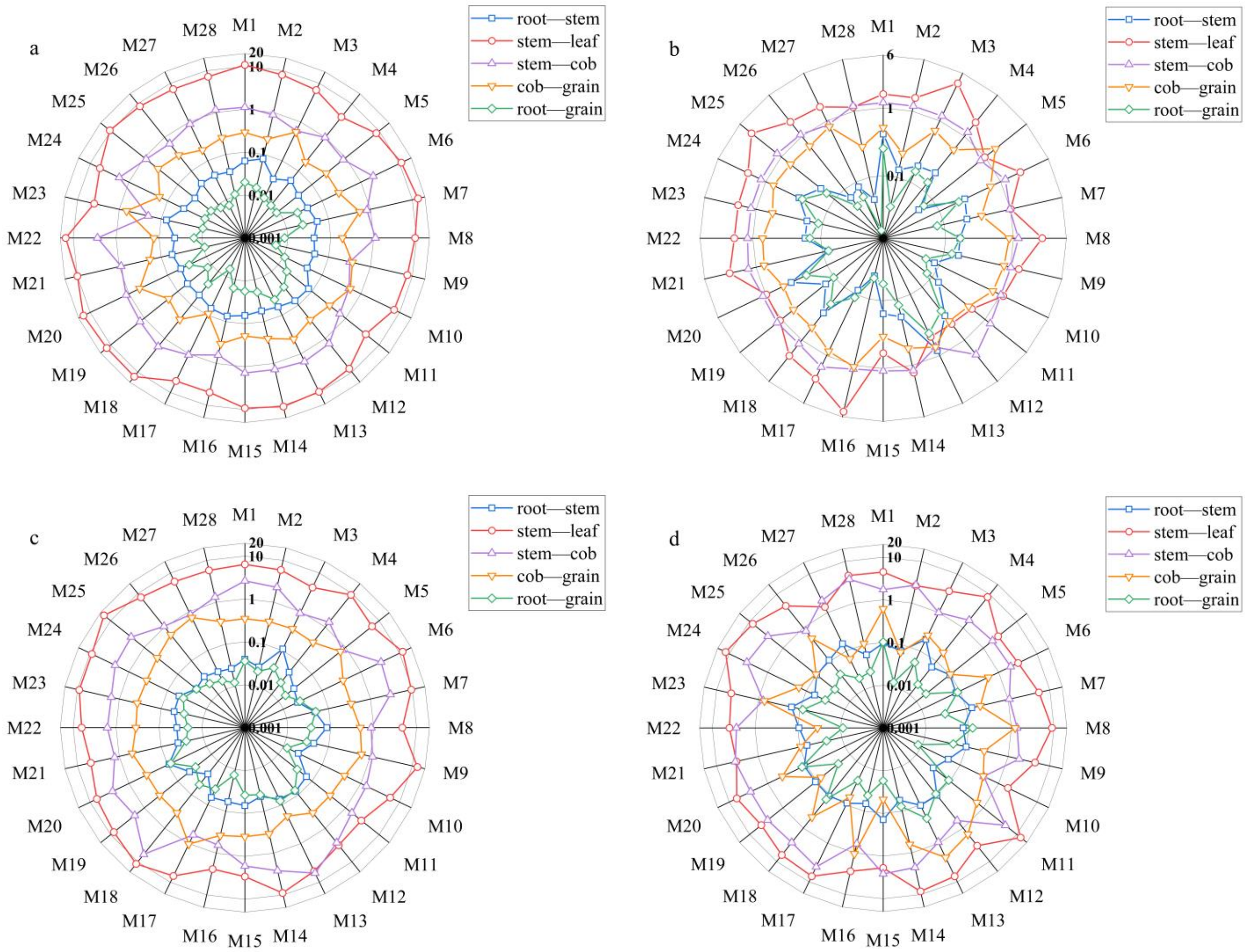

Figure 7. TF_{Cd}, TF_{Pb}, TF_{As}, and TF_{Cr} in various parts of maize plants of different varieties. (**a**) TF_{Cd}; (**b**) TF_{Pb}; (**c**) TF_{As}; (**d**) TF_{Cr}.

3.8. Principal Component Analysis of Cd, Pb, As, and Cr Contents in Different Parts of Maize Plants

To further analyze the sources of HMs in different parts of maize plants, the KMO (Kaiser–Meyer–Olkin) and Bartlett's test of sphericity were employed to evaluate the HM contents from the roots, stems, leaves, cobs, and grains of maize. The results indicated that the KMO statistic was 0.778, which is greater than 0.7, and the significance of Bartlett's test was 0.000, which is less than 0.05, suggesting that the data of HM contents are suitable for principal component analysis (PCA).

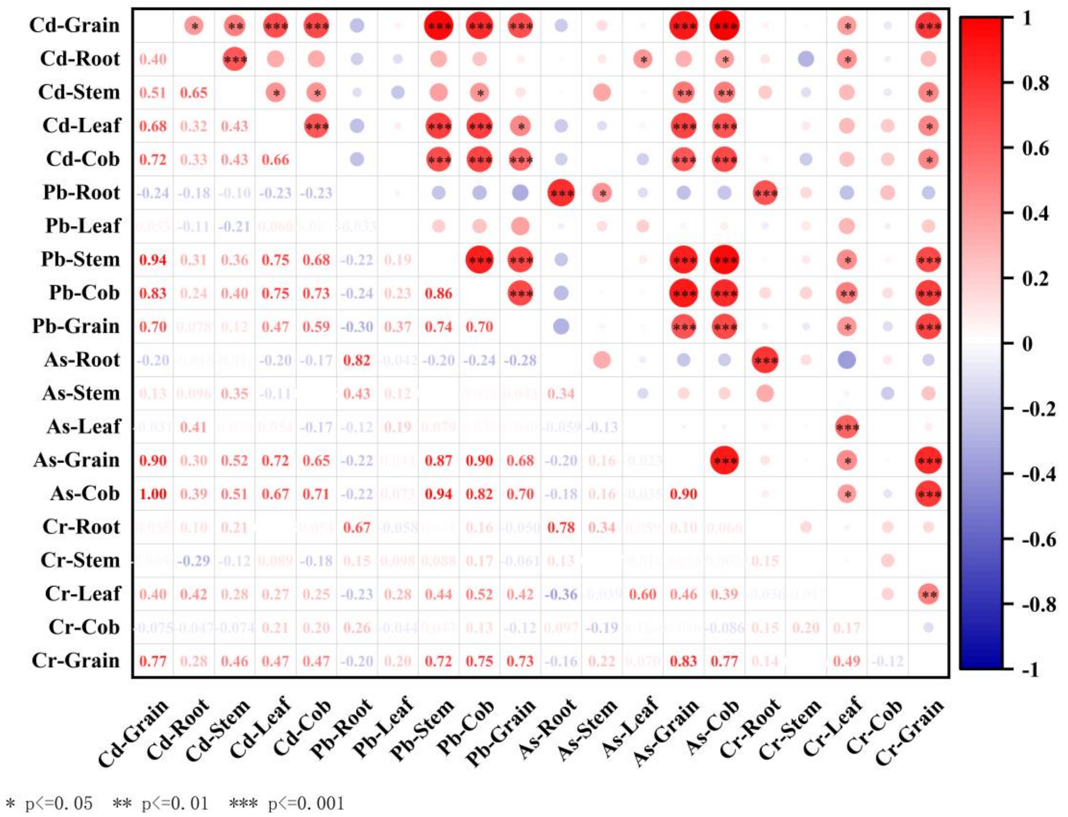

Figure 8. Correlation analysis of Cd, Pb, As, and Cr contents in various parts of different maize varieties. The numbers and circles in the figure represent correlation coefficients. (The size and color intensity correspond to the magnitude of the coefficients.) * Significance levels (* $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$).

The results of PCA in Table 5 reveal that three principal components were extracted from the HMs in various parts of the tested maize, which cumulatively explain 98.92% of the total variance, indicating that these three principal components can reflect the primary information of the four HMs. The first principal component had a contribution of 88.82% and was characterized by high loadings of Cd, Pb, As, and Cr; the second principal component had a contribution of 7.94%, with a higher loading of Cd; and the third principal component contributed 2.16% to the total variance and was characterized by higher loadings of Cd and Pb.

Figure 9 illustrates the three-dimensional plot for the loadings of the first three principal components, which shows the degree of dispersion among the HMs, visually reflecting the sources of HMs in the tested maize. The sources of Cd primarily included industrial activities and emissions from mining enterprises. The developed mining and industrial sectors in this study area inevitably discharge large amounts of Cd. Additionally, the application of chemical fertilizers in agricultural production can also lead to the accumulation of Cd in the soil [33]. Pb contamination arises from various anthropogenic factors, including leaded gasoline, lead-based paints, pesticides, coal combustion, and smelting, resulting in significant Pb accumulation in the soil due to the long half-life of Pb [34]. The As in the soil originates from both natural backgrounds and human activities, particularly mining, smelting, fertilization, and pesticide use, all of which contribute to substantial As input into the soil [35]. Cr is an important industrial metal, and Cr ore-processing residue (COPR) is a significant source of Cr pollution in the environment, primarily those released through anthropogenic activities such as metal mining, smelting, and processing, making it one of the most common HMs in industrial wastewater byproducts [36].

Table 5. Principal component analysis results of Cd, Pb, As, and Cr contents in different parts of the tested maize varieties.

Item	Principal Component 1	Principal Component 2	Principal Component 3
Cd	7.39	2.92	0.71
Pb	7.50	−2.67	0.62
As	8.04	−0.56	−0.07
Cr	7.94	0.38	−1.17
Eigenvalue	3.55	0.32	0.09
Contribution Rate (%)	88.82	7.94	2.16
Cumulative Contribution Rate (%)	88.82	96.76	98.92

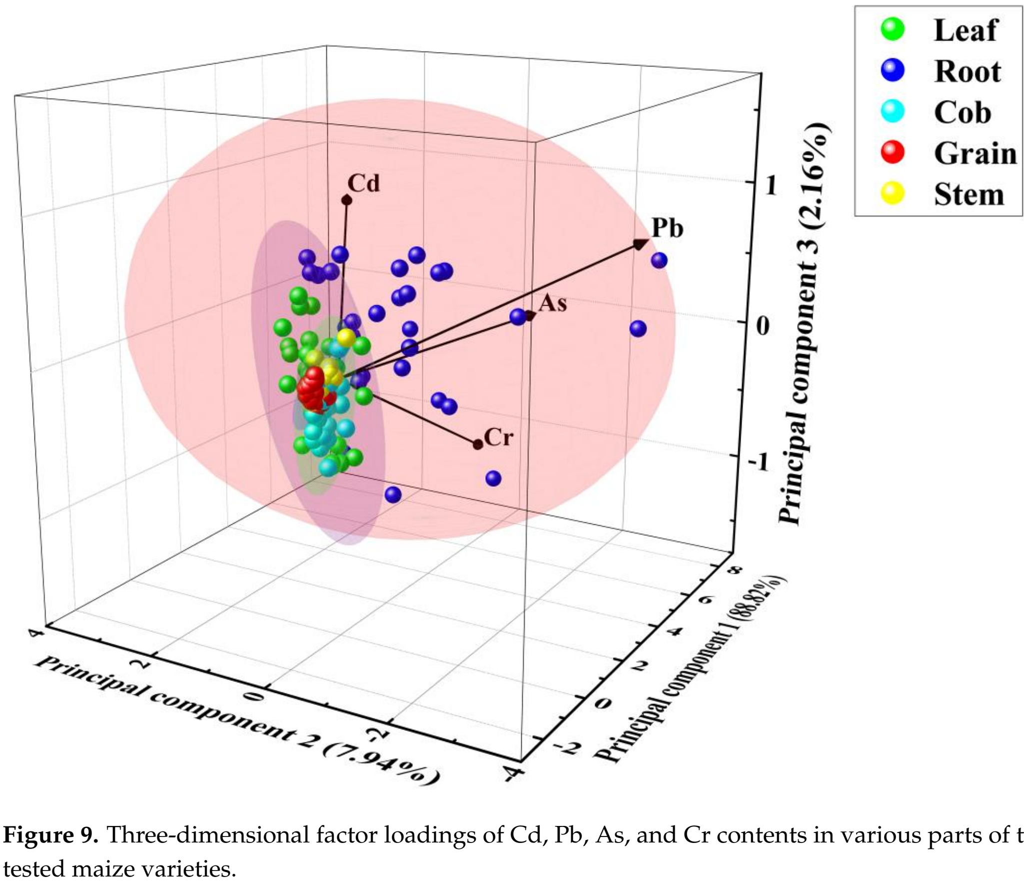

Figure 9. Three-dimensional factor loadings of Cd, Pb, As, and Cr contents in various parts of the tested maize varieties.

In summary, the first principal component primarily reflects the sources of Cd, Pb, As, and Cr in maize plants, indicating strong correlations among these four HMs and demonstrating a high degree of homogeneity, which is mainly influenced by the excessive pollution of these HMs in the soil, particularly the anthropogenic sources resulting from the mining, storage, and smelting of non-ferrous metals. The second and third principal components are less influenced by external pollution and primarily derived from the accumulation of HMs in the soil parent material and weathered products. Karst soils are developed from carbonate rocks and are predominantly composed of sedimentary dolomite and limestone, which typically exhibit high geological background concentrations of HMs [37].

4. Discussion

The accumulation of HMs in the soil–crop system is not a simple linear relationship. The capacity of crops to absorb HMs is primarily influenced by both the genetic factors of the crops and the external environmental conditions. Factors such as the concentration and form of HMs in the soil, physicochemical properties of the soil, status of nutrient elements, as well as the prevailing climatic and geographical conditions are all closely related to the ability of crops to absorb and accumulate HMs [38]. RDA revealed that the concentration of HMs in the soil significantly affects the biological traits of maize plants, particularly root length, root dry weight, and plant height, indicating that the state of HMs in the soil has a direct impact on maize growth.

There were significant differences in the accumulation of Cd, Pb, As, and Cr among different maize varieties in the root, stem, leaf, cob, and grain, which can be attributed to the differences in genetic background among the 28 maize varieties selected for the experiment. The regulation processes and mechanisms of HM absorption and translocation vary among different maize varieties, leading to different contents and distribution of HMs [39]. The BCF_{Cd}, BCF_{Pb}, BCF_{As}, and BCF_{Cr} of maize grains of the 28 varieties tested were 0.003–0.028, 0.0010–0.0046, 0.0008–0.0022, and 0.0003–0.0036, respectively. The BCF_{Cd} of maize grains of all varieties was significantly higher than that of BCF_{Pb}, BCF_{As}, and BCF_{Cr}. A smaller enrichment coefficient represents the weaker enrichment capacity of heavy metals, indicating that the varieties are more tolerant to heavy metals. These results were consistent with the fact that the contamination level and risk of Cd in the soil of the test site were significantly higher than those of other heavy metals. From 24 varieties, Du et al. screened out 3 varieties for low accumulation of Cd, Pb, and As in the mining area of Gejiu City, Yunnan Province, China [40]. M8 was one of the three varieties with low accumulation of Cd, Pb, and As. In the present study, M8 was also one of the 12 varieties with low accumulation of Cd, Pb, and As from the 28 varieties, further validating the regional environmental stability of the low-accumulation characteristics of certain tested varieties in suitable ecological zones.

The mechanisms for reducing the HM accumulation in plants typically include two aspects: reducing the absorption of HMs by the roots and sequestering HMs in the roots through compartmentalization, thereby restricting their translocation to the aerial parts [41]. The distribution patterns of Cd, Pb, As, and Cr vary in different parts of maize plants, and the disparities in translocation and compartmentalization capability among different parts are also an important reason for the different accumulation capacity in the grains [42]. Generally, the accumulation capacity of maize for HMs follows the order of aerial organs < underground organs, conductive organs < absorptive organs and reproductive organs < assimilative organs. This is because the root system, as the primary interface for ion exchange between the plant and the environmental medium, is the most sensitive to HM stress. Once HM ions are absorbed by the roots, they are typically translocated to other parts through the transport pathways of essential nutrient elements or ion channels, resulting in a lower accumulation of ions with poor translocation capacity in the aerial parts [43]. In low-accumulation maize, only a small amount of Cd, Pb, As, and Cr absorbed from the soil are translocated to the grains, while the majority of HMs are retained in the roots and leaves, with a smaller portion being retained in the stems and cobs. Maize reduces the translocation of HMs to the grains through detoxification by plant cells and metabolic antagonism against toxic HMs, thereby protecting the nutritional and reproductive organs [44]. In this study, the Cd content and BCF_{Cd} in the roots of the tested maize were higher than those in the leaves, cobs, and stems and significantly higher than those in the grains, which is consistent with previous research findings [38,45]. In addition, since there were some differences in the cell structure and transpiration between different varieties of maize, the cell wall and vesicles of different varieties of maize had different binding capacities for heavy metals, and the long-distance transport of heavy metals in the body of the plant, especially in the above-ground parts, is closely related to transpiration, thus affecting the mobility of heavy metals in the body of different varieties, which also leads to differences in the accumulation of heavy metals between different varieties [46,47].

Currently, there is no unified standard for the screening and identification of low-accumulation varieties of HMs. However, related studies have adhered to a common principle: under high-pollution background conditions, the accumulation level of specific pollutants in the edible parts of a variety should be relatively low, and under medium- to low-pollution backgrounds, the accumulation level of specific pollutants in the edible parts of a variety should be below the food safety standards. Some studies have suggested that the criteria for screening low-accumulation varieties of HMs should include the following four aspects. Firstly, the content of specific pollutants in the edible parts should be below national or international food safety standards; secondly, the BCF (such as BCF_{grain}) of the edible parts should be <1; thirdly, the TF from roots to edible parts ($TF_{root–grain}$) should be <1; and finally, the variety should tolerate the toxicity of pollutants on contaminated farmland and its yield not be significantly affected [45,48]. Furthermore, some studies proposed that low-accumulation crops should also possess local adaptability and resistance to multiple HMs, and the low-accumulation characteristics in the edible parts should be reproducible [48]. However, the criteria that BCF and TF should be less than 1 for edible parts in the aforementioned standards are overly broad. In this study, the BCF_{Cd} in grains and TF_{Cd} from roots to grains were both less than 1 for some maize varieties, but the Cd content in the grains still exceeded the standard. Additionally, the BCF and TF values for Cd in the tested maize varieties were significantly higher than those for Pb, As, and Cr. Therefore, it is imperative to establish a standardized evaluation system for the comparative selection of low-accumulation crop varieties so as to ensure that the low-accumulation characteristics can be sustained over time and kept stable across different regional environments to safeguard food safety.

5. Conclusions

Among the biological traits of the tested maize varieties, the root length, root dry weight, and plant height were the most significantly influenced by the concentrations of Cd, Pb, As, Cr, and Hg in the soil, whereas the stem weight was the least affected. The accumulation capacities of different parts in maize for Cd, Pb, As, and Cr follow the order of grain < stem < cob < leaf < root, while the translocation capacity follows the order of root–grain < root–stem < cob–grain < stem–cob < stem–leaf. The accumulation capacity of maize grains for Cd, Pb, As, and Cr follows the order of As < Cr < Pb < Cd. Different HMs exhibit synergistic effects in various parts of maize (except for the stem), which is particularly pronounced in the grains. Notably, As demonstrates a synchronous transport mechanism with other HMs across different parts. The accumulation of Cd, Pb, As, and Cr in maize plants is primarily derived from human activities such as the mining, storage, and smelting of non-ferrous metals in the experimental area, while the HMs in the soil parent material and weathered products play a secondary role. The yields of the 28 tested maize varieties range from 7377.6 to 11,037.0 $kg \cdot hm^{-2}$, with M5 (Haoyu 1511) showing the highest yield. M2, M4, M5, M9, M10, M21, and M25–M28 are recommended for cultivation in the HM-contaminated farmlands of southwestern China, as they exhibit low-accumulation characteristics for Cd, Pb, As, and Cr.

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