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Effect of Phosphorus Chemical Solid Waste Modified Landforming Soil on Corn Quality and Safety Evaluation

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Abstract

This study investigated the effect of phosphorus chemical solid wastes (phosphogypsum and phosphorus tailings) modified land-making soil on corn quality and its safety evaluation. The artificial soil was constructed by layered reconfiguration process (A process) and integrated land-making process (B process), and the effects of different processes on corn growth, yield, nutritional quality and heavy metal content were studied. The results showed that the phosphogypsum geo-constructed soil significantly increased the plant height, stem thickness, biomass and yield of corn, in which the A process and B process increased the yield by 19.34% and 12.71%, respectively. Phosphate tailings landforming soils, on the other hand, resulted in a decrease in corn yield by 5.84% to 6.47%. Phosphogypsum treatment also significantly enhanced total soluble sugar, protein and vitamin C content of corn. The safety evaluation showed that the heavy metal content in all treated corn kernels complied with the national food safety standards, and the enrichment capacity of heavy metals in the non-edible parts was higher than that in the edible parts. The study showed that phosphogypsum land-forming soil has high potential for agricultural utilization while ensuring the quality of guest soil, and that process A is superior to process B.

Keywords

Phosphorus Chemical Solid Waste, Resource Utilization, Landforming Soil, Corn, Safety Evaluation

1. Introduction

China's phosphorus chemical industry is on a huge scale and is a pillar industry of China's national economic development. Every year, the phosphorus chemical production process generates tens of millions of tons of industrial solid wastes, including phosphorus tailings and phosphogypsum (Zhong et al., 2019; Zhang et al., 2019). These wastes are basically in a state of saturation or overloaded stockpiling, which not only occupies a large amount of land resources but also increases the cost of business operations, affecting the economic efficiency of enterprises (Zhang et al., 2021). These solid wastes also contain a variety of harmful impurities, and stockpiling them can easily cause pollution of the atmosphere, water systems, and soil. This has seriously constrained the sustainable and healthy development of China's economy (Ji, 2018). Accelerating the research and development of the core technology for the utilization of phosphorus chemical solid wastes, and making full use of the P, Mg, and other elements and their special physical and chemical properties to turn waste into treasure and achieve resource recycling, has gradually attracted widespread public attention. At present, the main uses of phosphorus tailings and phosphogypsum are to fill mine voids, produce construction materials, and manufacture fertilizers for agricultural production (Sun et al., 2012). Many reports show that the components of these phosphorus chemical solid wastes contain many elements required for crop growth, which can promote crop quality and yield. However, they also contain some polluting elements that can enter crops and the human body through the food chain, ultimately endangering human health (Qian et al., 2020). Yunnan Province, as a typical province for the production and discharge of phosphorus chemical solid wastes in China, has an urgent need to explore more ways to utilize these solid wastes. Selecting the main typical phosphorus chemical solid wastes—phosphogypsum and phosphorus tailings in Yunnan—for soil utilization, and researching the effects of this solid waste on crop production, quality, and safety, is conducive to promoting the resourceful utilization of phosphorus chemical solid wastes and ensuring the safety of crop production.

Corn as an important grain, economic and feeding crop in Yunnan Province, is widely planted in 16 cities and towns in the province, and is an important part of the agricultural economy of Yunnan Province. 2022 statistics show that the area of corn planted in Yunnan Province amounted to 28,762,000 acre, with an average yield of 356.8 kg/mu, and the total output reached 10,260,000 tons, which accounted for the province's total grain output of 52.41% (Yu et al., 2024). This data fully reflects the core position of corn in Yunnan Province's grain production. It is worth noting that fresh corn, because of its high nutritional value, unique flavor, and significant health functions, has seen a continuous increase in market demand and economic benefits in recent years. At present, the planting area of fresh corn in Yunnan Province has reached 200,000 hm^2, which has become one of the important main producing areas of fresh corn in China (Guo et al., 2024). The development of fresh corn industry not only enriches the agricultural industrial structure of Yunnan Province, but also provides a new way for farmers to increase their income. In view of the important position of corn in Yunnan's agricultural production, it is of great theoretical and practical significance to carry out related planting research. Especially in the current context of sustainable agricultural development, how to efficiently utilize agricultural resources, reduce environmental pollution, and improve crop yield and quality has become an important direction of agricultural scientific research (Zhang, 2024a). This study is based on the agricultural utilization of phosphorus chemical solid waste, combined with the characteristics of essential plant nutrients contained in phosphorus chemical solid waste, attempted to use phosphorus gypsum and phosphorus tailings for modified land formation, studied the impact of land formation soil on the growth and development of corn and the quality of the soil, evaluated the safety of phosphorus gypsum land formation soil and agricultural products, and further explored the potential of phosphorus chemical solid waste used in artificial land formation with a view to further explore the potential of phosphorus chemical solid wastes for artificial land formation, with a view to providing reference for the safe utilization of phosphorus chemical solid wastes in the field of agriculture.

2. Materials and Methods

2.1. Test Raw Materials and Processing Methods

The raw materials used in the test are mainly phosphogypsum, phosphorus tailings and local unutilized soil, etc. Before leaving the factory, the phosphogypsum raw materials used in the land-making process are washed 2 - 3 times with the water washing equipment of the factory to reduce the concentration of harmful elements, and then the washed phosphogypsum is modified, and 0.4% - 0.6% of the lime is added to adjust the phosphogypsum pH to the range of 6 - 8, and then mixed and stacked for 3 - 5 days to obtain the modified phosphogypsum after its complete reaction. After mixing, it was piled up for 3 - 5 days, and the modified phosphogypsum was obtained after its complete reaction. Two land-making processes were used in the experiment, i.e., layered reconstruction process (A process construction) and integrated land-making process (B process construction):

1) A process construction: the construction process of layered reconstruction of soil is adopted, with reference to the natural soil occurrence layer law, divided into three layers, including the thickness of the impermeable water retention layer of 20 cm, the thickness of the transitional soil layer of 20 cm, and the thickness of the cultivation layer of 20cm; the overall thickness is 60 cm.

The bottom layer is the impermeable water retention layer thickness 20 cm, using laying 100% modified solid waste materials, which need to be compacted.

In the middle of the transition layer soil thickness of 20 cm, the material for modified solid waste materials and guest soil red soil, in accordance with the quality ratio of 7:3 mixed homogeneously made, the transition layer is laid on the top of the bottom layer.

The upper part of the cultivation layer thickness of 20 cm, the material is modified solid waste materials and red soil, according to the quality ratio of 5:5 mixed homogeneously made, laid on top of the transition layer.

2) B process construction: 60 cm integrated land-making process, according to the proportion of modified solid waste raw materials and guest soil red soil mixed evenly, one-time covered in the demonstration area plots.

2.2. Experimental Design

1) Overview of the experimental site

The test site is located in Anning City, 57 km southwest of Kunming City near Yuntianhua Anning Phosphorus Mine Branch (24˚81' N, 102˚37' E), at an altitude of 2215 m, with an average annual temperature of 14.7˚C and an average annual precipitation of 876.48 mm.

2) Test materials

Two kinds of phosphorus chemical solid wastes and soil were used as raw materials for the test, among which the solid waste materials, phosphorus ointment and phosphorus tailings, both came from Yuntianhua Tian'an Company, and the guest soil was the zonal arable soil (0 - 20 cm) distributed in the unutilized land near the test site, and the basic physicochemical properties of the raw materials and the quality concentration of the heavy metals were as shown in **Table 1**. The test crop was fresh glutinous corn, variety "Tian Zi 23", which is a local staple variety and purchased from local agricultural stores.

Table 1. Main physical and chemical properties and heavy metal content of test materials.

Items	pH	AN	AP	AK	Pb	Cd	Cr	As	Hg
		mg·kg^{-1}							
Soil	5.60	20.16	41.00	67.00	242.00	0.23	86.10	34.70	0.771
Phosphogypsum	3.10	20.14	178.30	88.00	76.10	0.12	13.40	3.30	0.985
Phosphorus tailings	6.80	19.97	167.90	28.00	83.00	0.63	63.80	17.50	0.859

3) Experimental design

The area of the test site was about 1000 m^2, and two land-making processes, A and B, were used, with specific processes and distribution as shown in **Table 2**. The basic physical and chemical properties of the soil in each treatment are shown in **Table 3**, and the pollutant content of each land-making treatment is in line with the "Soil Environmental Quality Agricultural Land Soil Pollution Risk Control Standards" (GB 15618-2018), and the background value of heavy metal elements in the control soil is normal; a total of five treatments, each treatment is 160 m^2, and a 1.5 m spacing zone is set up between the different treatments.

Corn was planted in two rows according to the local planting habits, with a spacing of 45 cm × 55 cm, and the soil was fertilized with 800 kg/acre of ecological organic fertilizer (SOM ≥ 30%, N + P_2O_5 + K_2O ≥ 4%) before corn sowing, and the crop was irrigated, weeded, and de-wormed during the growth period in accordance with normal field practices, and urea was applied at the corn trumpet stage at a rate of 50 kg/acre. The construction of the test site started on May 18, 2023, and was completed on May 27 of the same year. Corn was sown on May 29, 2023, and harvested on September 19 of the same year.

Table 2. Experimental treatments and design.

Treatment	Construction process and proportioning (mass ratio)
CK	100% local guest soil
ZA	Phosphorus tailings layered reconstruction process A
ZB	Integrated construction process B, phosphorus tailing slag: guest soil = 5:5
GA	Phosphogypsum Layered Reconstruction Process A
GB	Integrated construction process B, phosphogypsum: guest soil = 5:5

Table 3. Basic physical and chemical properties of different soil.

Treatment	pH	AN	AP	AK	Pb	Cd	Cr	As	Hg
		mg·kg^{-1}							
CK	6.30	20.16	41.00	67.00	242.00	0.23	86.10	34.70	0.771
ZA	6.30	20.83	155.00	57.66	103.00	0.47	77.30	12.50	0.923
ZB	6.70	23.33	180.00	43.33	165.00	0.51	64.70	22.40	1.100
GA	5.80	20.16	178.00	91.33	50.60	0.15	36.60	5.01	0.967
GB	6.30	20.30	157.00	82.66	123.00	0.24	31.40	10.50	1.320

2.3. Sample Collection and Analytical Testing

2.3.1. Sample Collection and Preparation

Plant samples were collected by five-point sampling method, selecting representative corn plants, each plot to collect 5 whole plants, measuring the growth indexes of selected plants such as plant height and counting the number of plants, brought back to the laboratory, the plant samples were divided into parts according to their nutrient organs, avoiding the use of metal utensils in the preparation process, rinsed with purified water and then washed with deionized water, and so on the moisture air-drying and then weighed, recorded the fresh weight, and then used quartz Knife will be a large piece of plant samples cut small and put into a net bag, leaving part of the fresh samples for the determination of quality indicators, the rest of the samples in the oven at 105˚C to kill the green for 30 minutes, and then adjusted to 65˚C drying until the quality of a constant, the determination of the dry mass of the crusher pulverized through a 100 mesh nylon mesh sieve and then filled with a bag to be measured.

2.3.2. Crop Yield Statistics Method

In the plant samples collected before the measurement of crop growth indicators (plant height, stem thickness, etc.), plant height, leaf length, leaf width, etc. are measured with a tape measure, stem thickness is measured with vernier calipers, and fresh weight is measured with an electronic balance. Then the whole plant samples were collected and immediately brought back to the laboratory in a net bag, the corn was threshed, dried and weighed dry, and finally, the theoretical acre yield of each plot was calculated and used to analyze the effect of crop yield increase.

2.3.3. Determination Methods for Crop Heavy Metal Content and Quality

All heavy metal analysis and crop quality analysis methods are based on national or industry standards, as shown in Table 4 and Table 5.

Table 4. Crop heavy metal detection items, methods and equipment

Heavy metal elements	Standard	Testing instrument name and model
Cd	GB 5009.268-2016	Inductively coupled plasma mass spectrometer ICAP RQ, ACJ36
Hg	GB 5009.17-2021	Atomic fluorescence photometer AFS8520
As	GB 5009.268-2016	Inductively coupled plasma mass spectrometer ICAP RQ, ACJ36
Pb	GB 5009.268-2016	Inductively coupled plasma mass spectrometer ICAP RQ, ACJ36
Cr	GB 5009.268-2016	Inductively coupled plasma mass spectrometer ICAP RQ, ACJ36

Table 5. Crop quality testing items and methods

Nutrients	Standard	Methods of Agricultural Chemical Analysis of Soil (Bao, 2000)
Protein	GB 5009.5-2016	H_2SO_4-K_2SO_4-$CuSO_4$-Se Fading method
Vitamin C	GB/T 5009.82-2016	2,4-Dinitrophenylhydrazine colorimetric method
Total soluble sugar	NY/T 1278-2007	Acid hydrolysis copper reduction direct titration method
Soluble proteins	GB 5009.5-2016	G-250 Staining Method of Kaomas Brilliant Blue
Organic acid	GB 5009.157-2016	Acid-base titration method
Proline	GB 5009.124-2016	Colorimetric method

2.4. Data Processing and Statistics

The data were statistically analyzed using Excel 2021 and SPSS 25 software, and the charts were drawn using Origin 2021 software. The data obtained from the experiment were averaged three times, and the comparison of the means was made using the method of the least significant difference (ANOVE), and the data in the charts were expressed as the mean ± standard deviation (M ± SD), with the significant level of difference being $P < 0.05$.

2.4.1. Bioconcentration Factor (*BCF*)

Bioconcentration factor (*BCF*) is an important indicator of heavy metal accumulation in crops, which is used to evaluate the enrichment ability of heavy metals in various parts of crops, the larger the *BCF* is, the stronger the ability to accumulate heavy metals (Chen et al., 2019; Tang et al., 2023), when the *BCF* is greater than 1, it indicates that crops have a strong enrichment ability for heavy metals, the calculation formula is:

$$BCF_i = C_i / C_s \tag{3}$$

In the formula (1), BCF_i is the enrichment coefficient of each heavy metal element in the i part of the test crop, C_i is the heavy metal content in the i part of the test crop, and C_s is the content of heavy metal elements in the corresponding inter-root soil.

2.4.2. Translocation Factor (*TF*)

Translocation factor (*TF*) indicates the ability of heavy metal transportation and distribution among various parts of the crop, the larger the *TF* is, the stronger the ability of heavy metal transportation is, and the calculation formula is as follows:

$$TF_{lower\ part-upper\ part} = C_{lower\ part} / C_{upper\ part} \tag{2}$$

In the formula (2), $TF_{lower\ part-upper\ part}$ is the heavy metal in each nutrient part of the test crop from the lower part to the upper part of the TF, and C is the heavy metal content in each nutrient part of the test crop.

3. Results

3.1. Analysis of Corn Yield and Biological Traits under Different Treatments

The effects of different land planting treatments on corn growth traits are shown in Table 6. There were significant differences in plant height, stem thickness, leaf area, biomass, hundred grain weight and yield of the corn variety "Tian Zi 23" under different treatments. The mean corn yield of different treatments was 9308.47 kg·hm^{-2} with a coefficient of variation of 5.38%. The yields of GA and GB increased by 19.34% and 12.71%, respectively, compared with CK, while the yields of ZA and ZB decreased by 6.47% and 5.84%, respectively, compared with CK, which showed ZA < ZB < CK < GB < GA. The yields of different treatments were higher than those of CK by 19.34% and 12.71%, respectively. Thickness, leaf area, biomass and 100-kernel weight averaged 181.27 cm, 28.93 mm, 522.03 cm^2, 325.53 g and 26.57 g, respectively, with coefficients of variation ranging from 4.24% to 8.90%. GA and GB treatments significantly increased leaf area and biomass compared to CK ($P < 0.05$), with GA treatments increasing by 27.89% and 17.33%, GB and treatments increased by 24.87% and 2.50%, respectively, on the contrary, ZA and ZB showed significant decrease in plant height, biomass and 100-grain weight compared to CK.

Table 6. Biological characteristics and yield of corn under different treatments.

Treatment	Plant height (cm)	Stem thickness (mm)	Leaf area (cm^2)	Biomass ($g \cdot plant^{-1}$)	Hundred grain weight (g)	Yield ($kg \cdot hm^{-2}$)
CK	189.50 ± 0.71ab	26.17 ± 2.17a	487.17 ± 57.63b	335.93 ± 22.88b	28.53 ± 0.43a	8942.74 ± 621.04bc
ZA	171.33 ± 10.43b	27.59 ± 1.61a	411.88 ± 50.16b	275.70 ± 12.47c	22.76 ± 0.18b	8399.25 ± 551.44c
ZB	169.67 ± 2.66b	29.50 ± 2.92a	479.71 ± 55.47b	277.57 ± 8.50c	22.76 ± 0.49b	8449.25 ± 431.98c
GA	179.33 ± 6.06ab	30.57 ± 1.64a	623.03 ± 39.64a	394.13 ± 26.25a	29.45 ± 0.43a	10672.03 ± 670.95a
GB	196.50 ± 18.61a	30.84 ± 3.02a	608.34 ± 29.49a	344.33 ± 16.33ab	29.37 ± 0.46a	10079.1 ± 229.03ab
mean value	181.27	28.93	522.03	325.53	26.57	9308.47
Coefficient of variation	4.24%	7.85%	8.90%	5.31%	7.49%	5.38%

Note: Different lowercase letters in the same column indicate significant differences ($P < 0.05$) among different corn varieties, respectively, as follows.

3.2. Nutritional Quality Analysis of Corn under Different Treatments

The effect of different land formation treatments on the nutritional quality of maize is shown in Table 7. The mean values of total soluble sugar, soluble protein, vitamin C, protein and proline contents of corn under different treatments were 11.94 $mg \cdot g^{-1}$, 23.58 $mg \cdot g^{-1}$, 1.95 $mg \cdot g^{-1}$, 4.87% and 0.03%, respectively, with the coefficients of variation (CV) ranging from 2.14% to 33.33%, and GA and GB treatments significantly ($P < 0.05$) increased total soluble sugar, vitamin C and protein, respectively, in comparison with CK. Total soluble sugar, vitamin C and protein were significantly increased ($P < 0.05$) in GA and GB treatments compared with CK, with GA treatment significantly increasing 52.19%, 24.47% and 29.74%, GB treatment significantly increasing 36.74%, 19.15% and 25.42%, respectively, and ZB treatment significantly increasing 36.64% and 16.79% of total soluble sugar and protein content compared with CK. There was no significant change in soluble protein content and proline content of corn under all landraising treatments.

Table 7. Contents of nutritional components in corn under different treatments.

Treatment	Total soluble sugar ($mg \cdot g^{-1}$)	Soluble proteins ($mg \cdot g^{-1}$)	Vitamin C ($mg \cdot 100g^{-1}$)	Protein (%)	Proline (%)
CK	9.58 ± 0.95b	24.05 ± 0.14a	1.88 ± 0.17ab	4.17 ± 0.44c	0.02 ± 0.00a
ZA	9.35 ± 0.07b	25.37 ± 0.86a	1.42 ± 0.23b	4.66 ± 0.17bc	0.03 ± 0.02a
ZB	13.09 ± 1.35a	24.94 ± 0.45a	1.88 ± 0.34ab	4.87 ± 0.19ab	0.03 ± 0.01a

Continued

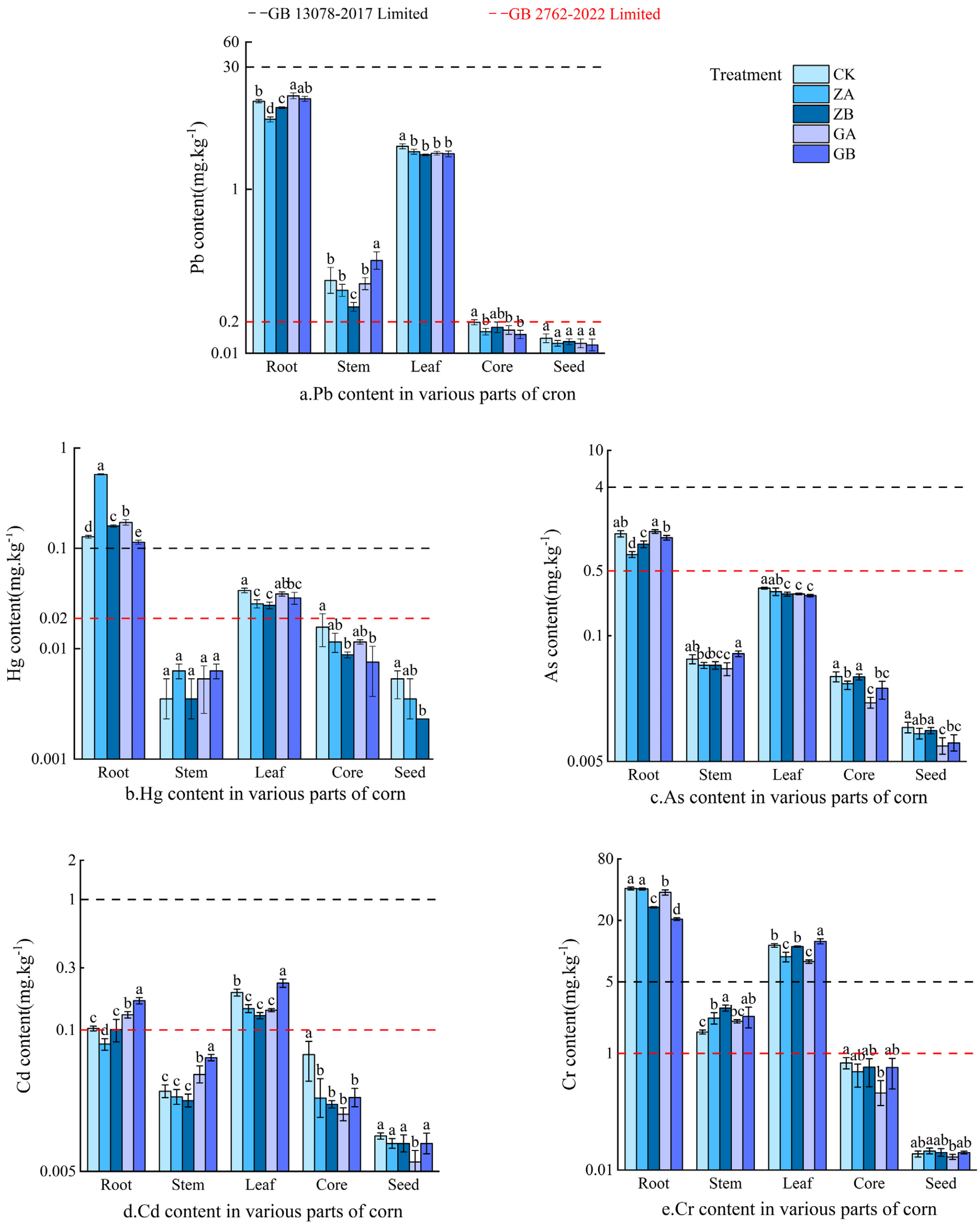
GA	14.58 ± 1.01a	24.91 ± 0.49a	2.34 ± 0.34a	5.41 ± 0.26a	0.04 ± 0.01a
GB	13.10 ± 2.71a	20.61 ± 0.58a	2.24 ± 0.47a	5.23 ± 0.17ab	0.02 ± 0.01a
mean value	11.94	23.58	1.95	4.87	0.03
Coefficient of variation	10.20%	2.14%	15.90%	5.05%	33.33%

3.3. Analysis of Differences in Heavy Metal Content of Corn under Different Treatments

The heavy metal contents of corn under different treatments are shown in **Figure 1**, and there were significant differences ($P < 0.05$) in the contents of Pb, As, Cd, Cr and Hg in all parts of the corn under different treatments. The Pb contents in the roots, stems, leaves, cores and kernels of the test corn under different treatments ranged from 7.01 to 13.50, 0.29 to 0.57, 2.61 to 3.31, 0.123 to 0.197, 0.06 to 0.10 mg·kg^{-1}, with the mean values of 10.84, 0.43, 2.84, 0.155, 0.076 mg·kg^{-1}, and the coefficients of variation ranged between 10.84, 0.43, 2.84, 0.155, 0.076 mg·kg^{-1}, and 0.076 mg·kg^{-1}, respectively, with coefficients of variation ranging from 4.80 to 23.68%; as content ranged from 0.752 to 1.330, 0.044 to 0.064, 0.271 to 0.326, 0.024 to 0.036, and 0.01 to 0.016 mg·kg^{-1}, with mean values of 1.091, 0.052, 0.292, and 0.031, respectively, 0.013 mg·kg^{-1}, with coefficients of variation ranging from 3.42 to 15.38%; Cd content ranged from 0.078 to 0.168, 0.045 to 0.066, 0.129 to 0.229, 0.036 to 0.068, 0.01 to 0.024 mg·kg^{-1}, with mean values of 0.120, 0.052, 0.168, 0.047, 0.019 mg·kg^{-1}, with coefficients of variation ranging from 4.76 to 23.68%; Cr content ranged from 20.60 to 41.10, 1.62 to 2.30, 7.91 to 12.50, 0.537 to 0.807, 0.10 to 0.14 mg·kg^{-1}, with mean values of 33.60, respectively, 2.196, 10.344, 0.698, 0.124 mg·kg^{-1}, with coefficients of variation ranging from 2.60 to 14.33%; Hg content ranged from 0.115 to 0.545, 0.004 to 0.006, 0.027 to 0.038, 0.007 to 0.016, 0.003 to 0.005 mg·kg^{-1}, with average values were 0.228, 0.005, 0.032, 0.011, and 0.004 mg·kg^{-1}, respectively, with coefficients of variation ranging from 2.19 to 20.00%. Overall, the Pb, As, Cd and Hg contents of the edible part of the grains were reduced in ZA, ZB, GA and GB compared with CK.

Since soil heavy metal contamination can accumulate through the food chain and eventually jeopardize human health, the present study was based on the national food safety standards and feed hygiene standards, and the corresponding results are shown in **Figure 1**. In all treatments of this experiment, the contents of Pb, Cd, Cr, As and Hg in corn kernels complied with the limited standards in food of the National Standard for Food Safety Limits of Pollutants in Foods (GB 2762-2022), and the maximum permitted content levels in grains (Pb ≤ 0.2 mg·kg^{-1}, Cd ≤ 0.1 mg·kg^{-1}, Cr ≤ 1.0 mg·kg^{-1}, As ≤ 0.5 mg·kg^{-1} and Hg ≤ 0.02 mg·kg^{-1}) and the compliance rate was 100%. The contents of Pb, Cd, As and Hg in the stems, leaves and cores of corn in all treatments complied with the requirements of the Feed Hygiene Standard (GB 13078-2017) (Pb ≤ 30.0 mg·kg^{-1}, As ≤ 4.0 mg·kg^{-1}, Cd ≤

1.0 mg·kg−1 and Hg ≤ 0.1 mg·kg−1). The Cr content of corn leaves in all treatments ranged from 7.91 to 12.50 mg·kg−1, which exceeded the requirement of GB 13078-2017 (Cr ≤ 5.0 mg·kg−1), and the Cr content of corn leaves in ZA, ZB and GA treatments was lower than that of CK, which showed that GA < ZA < ZB < CK < GB.

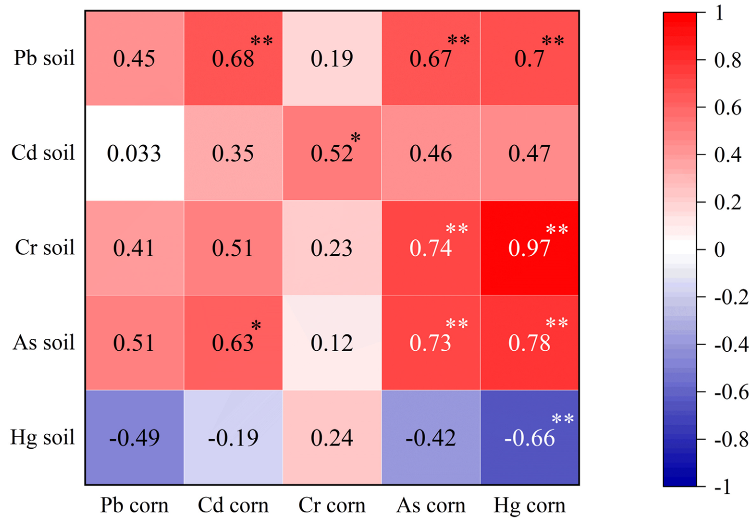


Note: Different lowercase letters indicate significant differences ($P < 0.05$) among different treatments for the same site. The missing treatments in the bar graphs were not detected, and the detection limits of Pb, As, Cd, Cr and Hg were <0.02, <0.002, <0.002, and <0.003 mg·kg−1, respectively, the same below.

Figure 1. Contents of Pb, Cd, Cr, As and Hg in each part of corn.

3.4. Correlation between Heavy Metal Content in Kernels of the Edible Part of Corn and the Soil

There was a correlation between heavy metal content in corn kernels and heavy metal content in soil as shown in Figure 2. Overall, As and Hg in the crop were most affected by the heavy metal content in the soil, followed by Cd and Cr. Corn kernel Cd in the study area showed a significant positive correlation with soil As (R^2 = 0.63) and a highly significant positive correlation with Pb (R^2 = 0.68); corn kernel Cr content was significantly positively correlated with soil Cd, with a correlation coefficient of 0.52; corn kernel As content showed a highly significant positive correlation with soil As, Cr The correlation coefficients were 0.73, 0.74 and 0.67 for As, Cr and Pb, respectively; the Hg content of corn kernels was negatively correlated with soil Hg, and positively correlated with Pb, As and Cr, with correlation coefficients of 0.70, 0.78 and 0.97, respectively; and the correlation coefficients were 0.70, 0.78 and 0.97 for Pb in corn kernels.



Note: *$P \le 0.05$, **$P \le 0.01$

Figure 2. Correlation between corn kernels and soil heavy metal content.

3.5. Analysis of the Differences in Heavy Metal Bioconcentration Factor (*BCF*) of Corn under Different Treatments

The enrichment coefficients of heavy metals in corn under different treatments are shown in Figure 3, and the enrichment coefficients of different parts of corn under different treatments were significantly different ($P < 0.05$). The enrichment coefficients (3a) of Pb in roots, stems, leaves, cores and kernels of corn under different treatments ranged from 0.048 to 0.267, from 0.002 to 0.005, from 0.013 to 0.054, from 0.001 to 0.003, from 0.0001 to 0.0007, with the mean values of 0.108, 0.004, 0.027, 0.001, 0.001, 0.001, respectively, 0.001, 0.001, with coefficients of variation ranging from 4.72% to 28.37%; the enrichment coefficients (3b) of As ranged from 0.03 to 0.26, 0.002 to 0.008, 0.009 to 0.056, 0.001 to 0.005, 0.0005 to 0.002, with mean values of 0.103, 0.004, 0.026 The mean values were 0.103, 0.004, 0.026, 0.003, 0.001, and the coefficients of variation were 3.11% - 15.63%; the enrichment coefficients of Cr (3d) ranged from 0.416 to 1.027, 0.029 to 0.073, 0.114 to 0.398, 0.009 to 0.015, and 0.001 to 0.004, with the mean values of 0.620, 0.044, respectively, 0.206, 0.013, 0.002, with coefficients of variation ranging from 2.93% to 15.12%; the enrichment coefficients (3e) for Hg ranged from 0.152 to 0.169, 0.004 to 0.007, 0.024 to 0.049, 0.006 to 0.021, 0.003 to 0.006, with mean values of 0.237, respectively, 0.005, 0.033, 0.012, 0.003, with coefficients of variation ranging from 2.34% to 19.04%, and the enrichment capacities of Pb, As, Cr and Hg in all parts were as follows: seed < core < stem < leaf < root. The enrichment coefficients (3c) of Cd ranged from 0.166 to 0.873, 0.084 to 0.380, 0.253 to 0.954, 0.080 to 0.294, and 0.040 to 0.100, with the mean values of 0.477, 0.209, 0.662, 0.179, and 0.067, and the coefficients of variation were 4.54% to 21.13%. The coefficient of variation ranged from 4.54% to 21.13%, and the Cd enrichment capacity of each part was as follows: kernel < core < stem < root < leaf. The *BCF* of kernels of edible parts of corn in all treatments was <1, and the enrichment ability of corn kernels for heavy metals was weak.

3.6. Analysis of Differences in Heavy Metal Translocation Factor (*TF*) of Corn under Different Treatments

The heavy metal translocation factor of corn under different treatments is shown in **Figure 4**, and there were significant differences ($P < 0.05$) in the *TF*s of all parts of the test corn under different treatments. The *TF* root-stem, *TF* stem-leaf, *TF* stem-core, *TF* core-seed, and *TF* core-seed (4a) of Pb in the test corn under different treatments were in the ranges of 0.030 - 0.056, 4.746 - 9.055, 0.220 - 0.575, and 0.461 - 0.517, with the mean values of 0.040, 7.019, 0.391, and 0.494 respectively, with coefficients of variation ranging from 7.5% to 29.15%; the transfer coefficients (4b) of As in each transfer site of corn ranged from 0.033 to 0.064, 4.249 to 6.515, 0.451 to 0.758, and 0.381 to 0.460, with mean values of 0.049, 5.755, 0.609, and 0.425, and coefficients of variation of 8.16% to 12.5%, respectively. The transfer coefficients (4c) of Cd in each transfer site of corn ranged from 0.394 to 0.582, 2.503 to 4.064, 0.632 to 1.401, 0.290 to 0.487, with the mean values of 0.463, 3.261, 0.928, 0.411, and the coefficients of variation were 7.21% to 22.63%. The transfer coefficients (4d) of Cr in each transfer site of corn were 0.055 - 0.112, 3.840 - 7.038, 0.261 - 0.499, 0.149 - 0.210, with the mean values of 0.073, 4.899, 0.331, 0.185, and the coefficients of variation of 7.35% - 23.78%, respectively; the transfer coefficients of Hg in each transfer site of corn were 0.290 - 0.487, with the mean values of 0.463, 3.261, 0.928, 0.411, and the coefficients of variation of 7.21%-23.78%. The translocation factor (4e) of Hg in each transport site of corn ranged from 0.011 to 0.052, 4.802 to 9.833, 1.305 to 4.522, and 0.334 to 0.347, with the mean values of 0.049, 5.755, 0.609, and 0.425, and the coefficients of variation ranged from 8.16% to 12.24%, respectively. In this study, the As, Cd, Cr and Hg transporter coefficients of all parts of corn were root-stem < core-seed < core-stem <stem-leaf, and the Pb, As, Cd, Cr and Hg transporter coefficients of all parts of

corn for the test were all less than 1 except for the stem-leaf part which was greater than 1, and the average transporter coefficients of Pb, As, Cd, Cr and Hg in the stem-leaf part were all lower than those of CK for all the land-planting treatments. Coefficients were lower than CK.

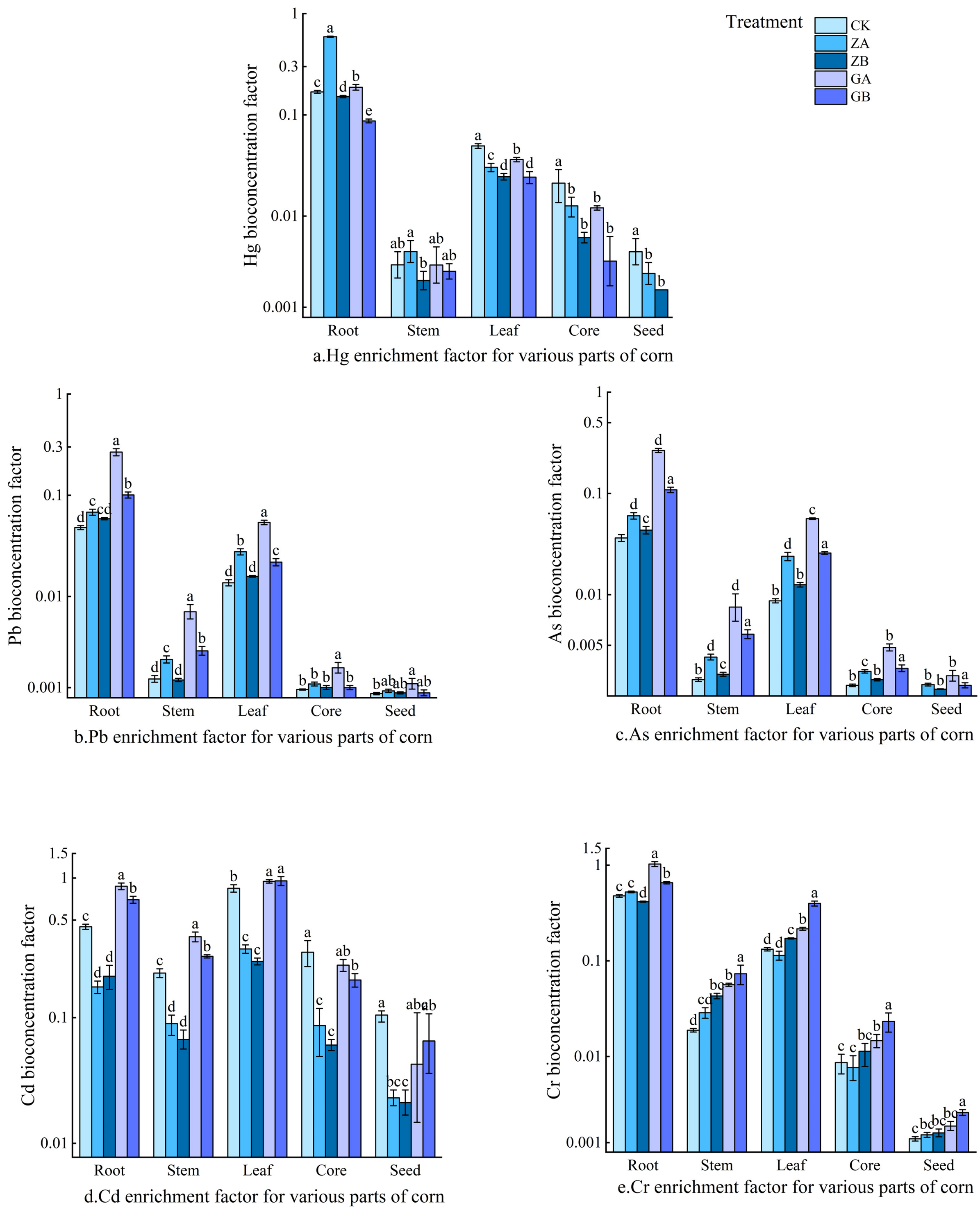


Figure 3. *BCF* of Pb, Cd, Cr, As, and Hg in each part of corn.

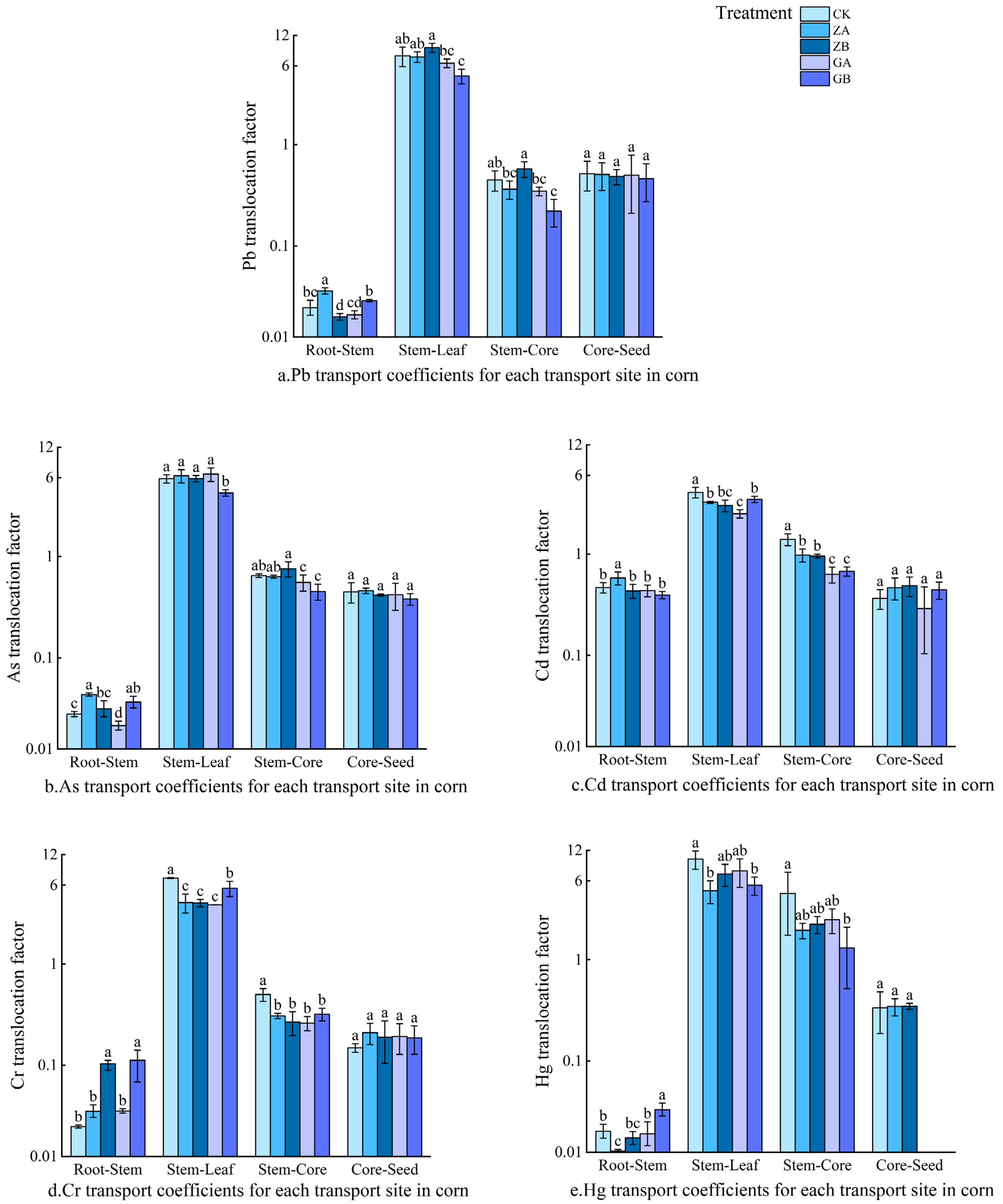


Figure 4. *TF* of Pb, Cd, Cr, As and Hg among different parts of corn.

4. Discussion

4.1. The Effect of Corn Planting in Reclaimed Soil

Crop growth and development indicators and yield are important indicators of soil nutrients and quality, this study found that modified phosphogypsum soil can significantly improve corn plant height, stem thickness, biomass and other biological traits, thus improving crop yield, which is consistent with the results of Karaki et al. [16] in the process of planting fruit trees, grass miscanthus, and corn applied phosphogypsum found that the content of micronutrients in the soil increased, and crop yield was also increased, the phosphogypsum contains large amounts of Ca, S elements and small amounts of P, F, Si, Fe and other nutrients necessary for plant growth. The results are consistent with Karaki et al, who found that after applying phosphogypsum to crops such as fruit trees, grass miscanthus and corn, the content of trace elements in the soil increased and the crop yields were also increased (Karaki & Omoush, 2006). Phosphogypsum contains a large amount of Ca, S elements and a small amount of P, F, Si, Fe and other nutrients essential to plant growth, which can enhance soil fertility and serve as a good source of nutrients for crops, thereby promoting crop growth and development (Cai, 2001; Xu et al., 1999); Chen Yuqi used phosphogypsum to carry out an application test on crops such as corn, soybeans, vegetables and fruit trees, to Research on its impact on crop growth and development, found that the relative reduction of corn empty pole rate of 0.08% - 0.11%, 100-grain weight increased by 0.40 - 1.30 g, soybean podding rate increased by about 5%, crop yield increase range of 5.20% - 19.90% (Chen, 2005), the phosphogypsum land-making treatment in this study under the corn yield compared with the control to enhance the 12.71% - 19.34%, which is in line with the results of existing This is consistent with the existing results (Wang et al., 2018; Xu et al., 2018; Gorbunov et al., 1992), and phosphogypsum used in agricultural production has a significant role in promoting crop growth and yield.

Phosphorus tailings contain a large number of P, Mg, Ca and other elements, and these elements are essential nutrients in the growth process of plants, many studies have shown that (Miao et al., 2022; Zheng et al., 2019; Yu, 2016) the use of phosphorus tailings as a raw material can be prepared calcium magnesium phosphorus fertilizer, is a very good source of fertilizer, so it is also often used in agriculture. Zheng Junhua et al. mixed phosphorus tailings with straw and soy sauce residue, and prepared organic fertilizer through microbial fermentation, which can significantly improve the physicochemical properties of the soil (Zheng et al., 2014); Wang Xueli et al. added a certain proportion of phosphorus tailings powder, to prepare a phosphorus-containing agricultural water retaining agent, which is excellent in absorbing and retaining water, and also releases phosphorus for crop growth (Wang & Qiu, 2011a, 2011b); Ni et al. used phosphorus tailings, bentonite and other mineral resources to prepare a phosphorus-supplying soil conditioner, which can significantly improve the physicochemical properties of acidic soils (Ni et al., 2018); existing studies mainly focus on calcium and magnesium phosphate fertilizers, soil conditioners, and water retention agents, etc. (Sanga et al., 2023; Panda et al., 2022; Yan et al., 2022), and in this study, phosphorus tailings were modified for artificial land formation, which is different from the previous studies that used it as a source of crop fertilizer. However, previous studies have demonstrated the feasibility of phosphorus tailings as a fertilizer source, supporting its potential for use in land reclamation. For example, China's Bantan Mine successfully converted more than 120 ha of arable land using phosphorus tailings in the 1960s and 1970s, and the yield of the converted crops was on par with that of other arable land in the area 4 - 5 years after resumption of cultivation, with significant economic benefits (Yang et al., 2010). In this study, corn plant height, stem thickness, 100-kernel weight and yield decreased in the phosphorus tailings land formation treatment compared with the control, with a decrease of 5.84% to 6.47%. This phenomenon may be attributed to the fact that the beneficial nutrients in phosphorus tailings have not been fully released at the early stage of land reclamation, which needs to be verified by further research. Nevertheless, the corn yield was still within the average mu yield range of fresh glutinous corn in Yunnan Province (500 - 700 kg), indicating that phosphorus tailings still have very good prospects for land reclamation.

4.2. Impact of Modified Solid Waste Land-Making Soil on Crop Nutritional Quality

Nutritional quality indicators include vitamin content, protein content and sugar content, etc. Nutritional quality indicators are important indicators for measuring the food value of agricultural products, which is conducive to the selection of varieties and quality evaluation of crops, corn and other cereal crops, which are rich in nutrients, are high-quality food. The results of the study by Mullins et al. showed that wheat planted in soil with phosphogypsum applied, compared with the no-added control, wheat quality and quality were improved (Mullins & Mitchell, 1989); the study by Fu Qiangqiang et al. found that using some techniques to modify the land-creation of phosphorus waste soil, the quality and quality of wheat improved (Fu et al., 2020). The research of Fu Qiangqiang et al. found that the transformation of phosphogypsum using some techniques can produce highly water-soluble nitrate-phosphate fertilizer with water solubility ≥ 99.9%, which is highly utilized and meets the needs of some cash crops, so as to make the crops increase in yield and improve the quality of agricultural products at the same time. The results of this study showed that the soluble sugar content, protein content and vitamin C content of corn were significantly increased compared with the control under the modified phosphogypsum land-making treatment, of which the layered treatment had a better effect, which was the same as the results of the previous study. It has also been found that silicon contained in phosphorus chemical solid waste can stimulate sugar metabolism and has a bioactivation effect on the growth of many crops (Artyszak, 2018), and that phosphogypsum and phosphorus tailings resources have a certain effect on the nutritional quality of crops, which is due to the fact that phosphogypsum and phosphorus tailings contain a high content of nutrients that can be used as a fertilizer to replenish the soil (Wang et al., 1995; Zhang, 2023), thus promoting crop growth and development and nutritional quality improvement.

4.3. On the Safety of Agricultural Products in Modified Solid Waste Land-Making Soil

Phosphogypsum and phosphorus tailings contain heavy metals and other harmful impurities, which may accumulate in the soil during land formation and utilization, affecting the soil quality and being enriched by plant uptake, and then accumulating step by step through the food chain, posing a potential threat to human health (Chavez et al., 1982; Wang et al., 2019). Therefore, it is crucial to evaluate the safety of soil and agricultural products. The study of Xiao Houjun et al. showed that the Cd content in grains after phosphogypsum application were within the safe range, and the heavy metal content in crop seeds was lower than the national feed control standard (Xiao et al., 2008). Wang Chengbao et al. found that phosphogypsum was safe and effective in agricultural production in coastal saline soils, but in alkaline soils in Tianshui City, Gansu Province, increasing phosphogypsum dosage elevated the level of heavy metal contamination in soybean seeds and stems, and the ability of stems to enrich heavy metals was higher than that of seeds (Wang et al., 2010). The study of Zhou Jinhua et al. showed that phosphorus tailings are used in agricultural production without risk and can improve the soil structure and environment and increase the nutrients required by plants (Zhou et al., 2021). In this study, the content of five heavy metals in maize kernels met the safe eating standard, and the heavy metal content of some treatment crops was lower than that of the control soil, which might be related to the high background value of heavy metals in the land-making guest soil. However, the Cr content of maize leaves exceeded the limit value ($Cr \leq 5.0\ mg \cdot kg^{-1}$) of the Feed Hygiene Standard (GB 13078-2017), and despite the fact that the Cr content of the kernels complied with the food safety standards, the excess Cr in the leaves may still pose a potential risk to the environment and food safety (Chen et al., 2022). Therefore, techniques such as soil improvement, phytoremediation, optimization of agricultural management and bioremediation (Yang et al., 2025; Xu et al., 2024) are needed to reduce the accumulation of Cr in crops and reduce its potential threat to the environment and food safety.

Wang Xiaobin et al. pointed out that the agricultural use of phosphogypsum may lead to the migration, accumulation and transformation of pollutants through the soil-crop system, threatening the ecosystem and human health (Wang et al., 2019). Shi Yaxing et al. found that there were differences in the enrichment capacity of heavy metals in different crops or different parts of the same crop, and the enrichment capacity of crop stalks was stronger than that of seeds (Shi et al., 2016). In the present study, we found that the enrichment and translocation capacities of heavy metals in the non-edible parts of corn were stronger than those in the edible parts of seeds, which is consistent with previous studies (Pan et al., 2006; Wang et al., 2005a). Therefore, whether the enrichment and translocation capacities of other crop non-edible parts are stronger than those of edible parts (Li et al., 2008; Wang et al., 2005b), as well as food safety, still need to be further investigated. There is a correlation between crop heavy metal content and soil heavy metal content (Zhang et al., 2024b). Ma Chengwei et al. found a correlation between some heavy metal elements in corn kernels and soil heavy metal elements through a study of farmland soil-corn crop in the northwestern Sichuan Basin (Ma et al., 2022). The results of the present study are consistent with this, and the heavy metal contents of corn edible parts are correlated with soil heavy metal contents.

5. Conclusion

In this study, the effects of phosphorus chemical solid wastes (phosphogypsum and phosphorus tailings) modified land reclamation soil on corn growth, yield, nutrient quality and heavy metal uptake were systematically investigated through locational tests, and the following conclusions were drawn:

1) Phosphogypsum landforming soil significantly improved biological traits such as plant height, stem thickness and biomass of corn, which in turn enhanced crop yield. The layered reconfiguration process (Process A) and integrated land reclamation process (Process B) increased corn yield by 19.34% and 12.71%, respectively, indicating that phosphogypsum can effectively enhance soil fertility and promote corn growth and development. In contrast, the phosphorus tailings land formation soil negatively affected the growth and yield of corn, with corn yield decreasing by 5.84% to 6.47% compared with the control. This phenomenon may be related to the release dynamics of essential plant elements such as P, Mg, and Ca from phosphorus tailings and their interaction with soil properties. Future studies need to further explore the mechanism of nutrient release from phosphorus tailings and its interaction with soil physicochemical properties in order to optimize its agricultural utilization.

2) Phosphogypsum landforming soil significantly increased total soluble sugar, protein and vitamin C contents of corn. The enhancement effect of the layered treatment (A process) was particularly significant, with total soluble sugar, protein and vitamin C contents increased by 52.19%, 29.74% and 24.47%, respectively. The integrated phosphorus tailings process (Process B) also had a certain enhancement effect on the nutritional quality of corn, indicating that the nutrients in phosphogypsum and phosphorus tailings can effectively promote the improvement of the nutritional quality of corn.

3) The contents of heavy metals (Pb, Cd, Cr, As and Hg) in all treated corn kernels complied with the requirements of the National Standard for Food Safety Limits of Pollutants in Food (GB 2762-2022), with a compliance rate of 100%. The levels of Pb, Cd, As and Hg in corn stems, leaves and cobs also met the requirements of the Feed Hygiene Standard (GB 13078-2017). Although the Cr content of corn leaf exceeded the national standard limit, the Cr content under phosphogypsum and phosphorus tailings treatments was reduced compared to the control, indicating that the modified solid waste landmaking soil has a high level of safety under reasonable use. However, this study failed to fully explore the long-term effects of heavy metal accumulation. Over time, the accumulation of heavy metals in soil may pose a potential threat to the environment and crop safety. Therefore, future research should focus on the long-term transport, accumulation and transformation patterns of heavy metals in the soil-crop system to assess their potential risks to the ecosystem and human health.

4) The enrichment capacity of corn non-edible parts (roots, stems and leaves) for heavy metals was significantly higher than that of edible parts (kernels). The enrichment coefficients (*BCF*) and transport factors (*TF*) of heavy metals in corn kernels were less than 1, indicating that the enrichment and transport capacities of kernels for heavy metals were low. There was a significant correlation between the heavy metal contents of corn kernels and those of soil, especially As and Hg were most affected by soil heavy metal contents, followed by Cd and Cr. Although the heavy metal contents of corn kernels comply with the food safety standards, the enrichment of heavy metals in the non-edible parts still needs to be paid attention to, especially in the area of feed and straw utilization.

In summary, the results of this study showed that phosphorus chemical solid waste-modified landforming soil has a high potential for agricultural utilization while ensuring the quality of guest soil. Phosphogypsum landforming soil can not only significantly improve the yield and nutritional quality of corn, but also effectively control the accumulation of heavy metals in corn kernels and ensure the food safety of agricultural products. The layered reconfiguration process (Process A) was superior to the integrated land reclamation process (Process B) in promoting corn growth and yield enhancement. Therefore, the application of phosphogypsum-modified landforming soil in agriculture is feasible, especially in soil improvement and crop yield enhancement. However, the application of phosphorus tailings landforming soil still needs further research to optimize its nutrient release mechanism and enhance its role in promoting crop growth.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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