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Evaluation of the Effect of Modified Phosphogypsum Landforming Soil on Lettuce Growth and Its Safety

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Abstract

The low comprehensive utilisation rate of PG has become a key issue restricting the sustainable development of the phosphorus chemical industry, and modifying PG to make land is a new way to improve the utilisation rate of PG resources and increase the amount of arable land. In this paper, lettuce was used as the test crop for potting simulation experiments, and three proportions of PG and soil were set up to study the effects of different treatments on the physicochemical properties of lettuce inter-root soil, the growth and development of lettuce, and to evaluate the quality of the land-creation soil environment and the safety of lettuce consumption. The results showed that the content of quick-acting phosphorus and quick-acting potassium increased significantly in all treatments compared with CK, with the T1 treatment showing the best enhancement effect, with a significant increase of 369.06% and 53.24% compared with CK; Among all the treatments, the T1 treatment was the most effective in enhancing the biological traits of lettuce, with biomass, stem thickness and stoutness index significantly enhanced by 30.06%, 17.70% and 28.77%, respectively, compared with CK; The heavy metal content of each treatment soil did not exceed the GB15618-2018 national standard limit value, T1 treatment lettuce edible part heavy metal content in line with the GB2762-2022 national standard limit value, indicating that modified PG land making use of the ratio under the feasibility, with the increase of modified PG ratio amount of the risk of heavy metal increases, T2 and T3 treatment lettuce edible part Pb content exceeded the GB2762-2022 national standard limit value, after the evaluation of comprehensive pollution index, T3 treatment soil is lightly polluted by lead. From the combined effect of PG land formation on lettuce

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growth and development and safety evaluation, the addition of PG land formation treatment with 50% of dry mass as the main raw material of PG is the treatment that achieves the maximum amount of PG elimination and safety for agricultural products in this experiment.

Keywords

Modified Phosphogypsum, Soil, Lettuce, Quality, Safety Evaluation

1. Introduction

Phosphogypsum is a general industrial solid waste produced by wet process phosphoric acid. According to statistics, the global annual by-production of phosphogypsum reaches 30 billion tons, and the accumulated stockpile exceeds 6 billion tons, and its huge annual production and discharge and push and store has become a worldwide problem that plagues the world (Ou et al., 2021). As of 2021, China's phosphogypsum emissions have reached 80 million t, but the comprehensive utilization rate is only about 40%, a large amount of phosphogypsum can only be handled by stockpiling, which not only occupies land resources, but also causes environmental pollution (Xu et al., 2023; Yu et al., 2008). The quality and quantity of arable land resources are the basis and key to keep the rice bowls of 1.4 billion people firmly in the hands of Chinese people, and it is of great strategic significance that phosphogypsum can be used to make land after harmless modification, which not only can turn waste into treasure to eliminate the risk of phosphogypsum stockpiling, but also can provide strong support and guarantee for national food security.

Numerous studies have shown that phosphogypsum can be used to improve saline and acidic soils (Wu et al., 2012; Ye, 1998), and the nutrients it contains can supplement effective nutrients such as calcium, sulfur, and phosphorus in the soil (Oszako et al., 2023), which can improve soil fertility and promote crop yields, e.g., Li Ji et al. found that additional phosphogypsum application can significantly promote wheat growth under conventional fertilization conditions through a field plot test (Li et al., 2015); Moussa et al. applied phosphogypsum to alfalfa in acidic Moussa et al. applied phosphogypsum to alfalfa in acidic soil and found that phosphogypsum had a significant effect on the bioavailability of phosphorus and sulfur (Moussa et al., 2020); Xu Jingjing et al. used phosphogypsum to improve acidic red soil under potting conditions and found that phosphogypsum had a promoting effect on the plant height, root length, biomass, and chlorophyll content of Brassica napus (Xu et al., 2018). Therefore, phosphogypsum can be applied to agricultural production as a soil fertilizer source and soil improvement substrate. However, these studies mainly focused on the aspects of soil improvement and fertilization effects of phosphogypsum (Xu et al., 2020), and there are fewer reports on the feasibility of land-forming use of phosphogypsum and the accumulation and evaluation of harmful substances in crops. Since phosphogypsum contains a certain amount of harmful elements, it may cause environmental risks by accumulating in soil and crops (Zhang et al., 2014; Wang et al., 2012; Ma et al., 2023), and direct agricultural use can lead to exceeding the harmful elements in some agricultural products (Wang et al., 2010, 2012), and Wang Xiaobin et al. have reported that phosphogypsum agricultural use may have the possibility of pollutants migrating, accumulating, and transforming through the soil-crop system, which may then jeopardize the ecosystem and human health (Wang et al., 2019b). Therefore, to improve the utilization rate of phosphogypsum in agriculture, to solve the environmental problems caused by it, to ensure the safety of soil and human health, and to make phosphogypsum with high value-added resource utilization technology has attracted much attention, which is of great significance to promote sustainable development.

Yunnan Province is a large province of phosphogypsum production and discharge, and the demand for exploring more ways to utilize phosphogypsum is more urgent, and the land area in urgent need of mine ecological restoration accounts for the first in the country (Yao et al., 2012; Chen et al., 2020), which provides abundant raw materials and a wide space for artificial land formation. Vegetables are the most important source of heavy metal exposure in human daily life (Wang et al., 2019a), and lettuce is widely planted in Yunnan, mainly for raw food, and its safety evaluation has reference value in vegetables. Therefore, this study is based on the agricultural utilization of phosphogypsum, combined with the characteristics of essential plant nutrients contained in phosphogypsum, attempted to use phosphogypsum for modified land formation and utilization, studied the effect of land formation soil on the growth and development of lettuce, evaluated the safety of phosphogypsum land soil and agricultural products, and further explored the potential of phosphogypsum used in the area of artificial land formation, with a view to provide a reference for the safe use of phosphogypsum in the field of agriculture.

2. Materials and Methods

2.1. Materials for Testing

The experiment was conducted from December 2022 to February 2023 in the glass greenhouse of Yunnan Agricultural University. The test soil was collected from the zonal tillage soil (0 - 20 cm) distributed in the unutilized land in Dongchuan District, Kunming City, Yunnan Province, which was air-dried, weed-removed and sieved for use; the test phosphogypsum was collected from the by-products of the production of feed-grade calcium phosphate by a company in Yunnan Province; the corresponding chemical properties and heavy metal contents of the test soil and phosphogypsum are shown in **Table 1**; the test vegetable variety was cream lettuce, which was purchased from the online store of Shandong Shouwo Seed Industry. The test vegetable is cream lettuce, purchased from Shandong Shouhe Seed Industry online store.

Table 1. Main chemical properties of tested soil and phosphogypsum (mg·kg⁻¹).

Items	pH	Available-N	Olsen-P	Available-N	Pb	Cd	Cr	As	Hg	$F_{water\text{-}soluble}$	F_{total}
Soil	5.09	6.50	36.63	114	63.60	0.06	48.83	33.50	0.06	15.10	575
Phosphogypsum	3.60	20.12	183.2	37	57.40	0.29	78.40	40.30	1.14	171	6.59×10^3

2.2. Experimental Design

The test first modified phosphogypsum treatment, after the pre-test to select the best ratio and modification, phosphogypsum grinding into powder, mixed with biochar and lime and stirred well, phosphogypsum, lime, biochar ratio of 94.7%, 0.3%, 5%, and phosphogypsum pH adjusted to 6.8 to 7.3 or so, placed in 3 days when it is fully reactive and then ready for use. Using greenhouse soil cultivation potting experiments, to ensure that the total amount of organic material in each treatment is equal under the premise of setting four levels of phosphogypsum additions according to the dry weight of organic material, respectively: 0 (CK, no phosphogypsum additions), 50%, 60%, and 70% (respectively, recorded as CK, T1, T2 and T3 treatments), and the heavy metal content of each treatment is in line with the soil environmental quality (GB 15618-2018) control standards. Three replications were set for each treatment.

Translated with DeepL.com (free version) Germination rate test: the container used in the experiment was a 250 ml plastic petri dish, filled with 500 g of soil, planted buckwheat, marigold and purple onion seeds, planted 20 seeds for each treatment, cultivated for 15 days, and regularly recorded their germination and growth. Potting test: the container used in the experiment was a plastic pot (60 cm × 20 cm × 16 cm), soil and phosphogypsum were mixed well, each pot was filled with 15 kg of soil, and an equal amount of fermented mushroom residue was added, and lettuce was planted after 2 weeks of equilibrium. The amount of N, P and K fertilizers was the same for each treatment, and the compound fertilizer (15-15-15) was applied as a follow-up fertilizer 15 days after lettuce planting, and harvested 60 days after lettuce growth.

2.3. Sample Collection and Measurement

Three representative lettuce plants were randomly selected in each pot, washed with water to remove excess soil, divided into aboveground and belowground parts, and used a straightedge to determine plant height, leaf length and leaf width, and vernier calipers to determine stem thickness. After that, the washed plant samples were dried with surface water, weighed fresh weight, and a part of the fresh samples was kept for the determination of quality indexes, and the rest of the samples were killed in an oven at 105˚C for 30 min, and then dried at 65˚C to constant weight, ground through a 200-mesh sieve, and distributed for use. Collect the soil around the root system of each pot, put the soil on kraft paper to dry naturally, grind it after drying, pass it through a sieve of 2 mm, 1 mm, and 0.149 mm aperture, respectively, and equip it for use.

Soil physicochemical properties were determined with reference to Soil Agrochemical Analysis (Bao, 2000). Soil Cd and Pb were determined in accordance with the Determination of Lead and Cadmium in Soil Quality Graphite Furnace Atomic Absorption Spectrophotometry (GB/T 17141-1997), and soil Cr, As and Hg were determined by atomic fluorescence spectrometry and cold atomic absorption. Plant Hg was determined using an atomic fluorescence photometer (AFS8520) with reference to the National Standard for Food Safety Determination of Cadmium in Food (GB 5009.17-2021); plant Cd, Pb, As and Cr were determined using an inductively coupled plasma mass spectrometer (ICAP) with reference to the National Standard for Food Safety Determination of Cadmium in Food (GB 5009.268-2016) RQ, ACJ 36) for determination.

2.4. Evaluation Methodology

The single-factor pollution index method (Equation (1)) and Nemero's comprehensive pollution index method (Equation (2)) were used to evaluate the heavy metal pollution status of the soil; and the potential ecological risk index evaluation method (Equation (3)) was used to analyze the potential risk of the soil in the phosphogypsum land formation. Soil and lettuce quality evaluation standards were adopted from the Soil Environmental Quality Standard (GB 15618-2018) and the National Standard for Food Safety (GB 2762-2022), respectively.

(1) Individual Pollution Index Method and Nemero Composite Pollution Index Method

$$P_i = \frac{C_i}{S_i} \quad (1)$$

$$P_n = \sqrt{\left(\frac{P_{i\max}^2 + P_{i\,\mathrm{ave}}^2}{2}\right)} \quad (2)$$

where: P_i is the single pollution index of pollutant i; C_i is the measured value of pollutant; S_i is the evaluation standard value of pollutant. P_n is the comprehensive pollution index; $P_{i\max}$ is the maximum value of each single pollution index; $P_{i\,\mathrm{ave}}$ is the average value of each single pollution index. According to the size of the P_i value and P_n value, the pollution degree of the factor and the comprehensive soil pollution level can be divided into five levels, which are excellent ($P_i \le 0.70$), safe ($0.7 < P_i \le 1.0$), mildly contaminated ($1.0 < P_i \le 2.0$), moderately contaminated ($2.0 < P_i \le 3.0$), and heavily contaminated ($P_i > 3.0$).

(2) Potential Ecological Risk Index Evaluation Method

$$RI = \sum_{i=1}^{n} E_r = \sum_{i=1}^{n} T_r^i \times \frac{C_i}{C_0^i} \quad (3)$$

where: RI is the comprehensive potential ecological risk index; E_r denotes the single-element potential ecological risk index of heavy metal i; T_r^i denotes the toxicity response coefficient (TRC) of heavy metal i, and the TRCs of As, Cd, Cr, Hg, and Pb are 10, 30, 2, 40, and 5, respectively (Håkanson, 1980); C_i denotes the amount of heavy metal i; and C_0^i denotes the reference value of heavy metal i, with the background values of soil elements in Yunnan Province as reference (China General Environmental Monitoring Station, 1990). The E_r and RI classification criteria proposed by Håkanson were obtained based on eight pollutants, which must be adjusted according to the type and number of participating pollutants in practical application (Ma et al., 2020). In this study, the E_r value of heavy metal Hg was the largest, so the first level of E_r threshold value was 40, and other risk levels were obtained by sequentially doubling the threshold value; the first level of RI threshold value was obtained based on the first threshold value of the original grading standard divided by the total value of toxicity coefficients of the eight pollutants, which yielded a unit toxicity coefficient of 1.13, multiplied by the total value of toxicity coefficients of the pollutants participating in this study of 87, and then took the 10th integer to obtain 90 and then Then double the value to get the subsequent risk level. The classification of the ecological risk index is shown in **Table 2**.

Table 2. Grading standards for potential ecological risk.

Items	Degree of harm				
	Mild	Moderately	Severity	Strong	Vehemence
E_r	<40	40 - 80	80 - 160	160 - 320	≥320
RI	<90	90 - 180	180 - 270	≥270	

2.5. Data Analysis

Excel 2021 was used for data organization, SPSS 25.0 for data analysis, significance of difference test by Duncan's test and Origin 2021 for plotting.

3. Results and Discussion

3.1. Effect of Different Ratio Treatments on Seed Germination

Indicators of the quality of the soil used for land-making are mainly based on the effect of the finished product on plant growth, which includes the rate of seed germination. Phosphogypsum has strong acidity, which may be toxic to plants, and germination rate is the most sensitive indicator to detect the presence or absence of toxicity of this raw material. As shown in **Figure 1**, the average values of germination rate of buckwheat, marigold and purple onion seeds in each treatment were 83.58%, 67.08% and 71.25%, respectively, which showed that buckwheat: CK < T2 < T3 < T1, chrysanthemum: T3 < T1 < CK < T2, and purple onion: CK < T2 < T1 < T3, suggesting that the use of phosphogypsum for land formation can improve the germination rate of the seeds, and the plants can be grow normally, which may be due to the addition of phosphogypsum increased soil porosity, good hydrometeorological conditions plant growth (Lu et al., 2023), this result is corroborated with the results of **Table 4** and **Table 5**.

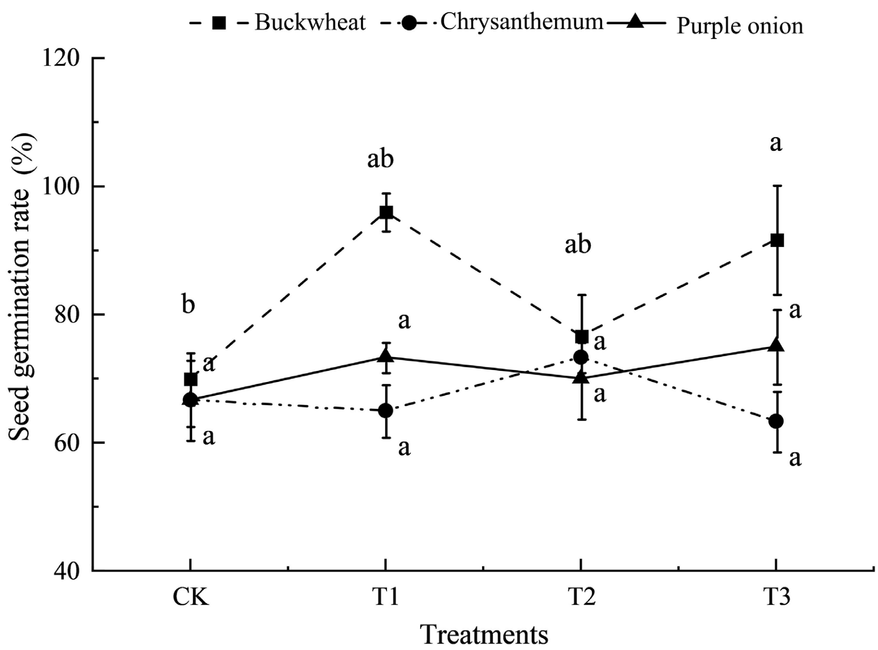

Figure 1. Effect of different treatments on seed germination rate.

3.2. Effects of Different Ratio Treatments on the Physicochemical Properties of Lettuce Inter-Root Soil

Soil physicochemical properties are important for studying the stability and sustainability of soil ecosystems. As can be seen from **Table 3**, the pH values of the soils in each treatment were in the following order from large to small: T1 > T2 > T3. Compared with the control, the pH values of the three land-forming soils decreased with the increase of the phosphogypsum ratios, which was related to the strong acidity of phosphogypsum itself. Soil nutrients are important indexes to characterize soil quality, and a comparative analysis of alkaline dissolved nitrogen (ADN), quick-acting phosphorus (QAP), quick-acting potassium (KAP) and organic matter (OM) contents of the three treatments showed that compared with the control, the QAP and KAP contents of the soils increased significantly with the increase in the modified phosphogypsum ratios ($P < 0.01$), with QAP contents increasing significantly by 369.06%, 381.19% and 387.49%, respectively. and quick-acting potassium content increased significantly by 53.24%, 52.14% and 41.78%, respectively, which was consistent with the findings of Moussa et al. and Gu Linjing et al. (Moussa et al., 2020; Zhang et al., 2016), mainly due to the fact that phosphogypsum's fractions contain effective elements such as phosphorus and potassium, which can provide more nutrients to the soil, and the overall quality of arable land in Yunnan Province is low (Chen et al., 2020), and most of the soils are deficient in phosphorus, so the phosphogypsum land-making Therefore, the utilization of phosphogypsum land formation is expected to solve the problem of arable land with low fertility and reclamation of abandoned mines in Yunnan Province, and to improve the quantity and quality of arable land. However, the alkaline nitrogen and organic matter contents in this study showed a decreasing trend with the addition of phosphogypsum, and compared with the control, the alkaline nitrogen contents of the three treatments were significantly reduced by 37.47%, 38.05%, and 62.06%, respectively ($P < 0.05$), and the organic matter contents were reduced by 20.81%, 26.14%, and 43.68%, respectively, with the T1 treatment having the smallest reduction, which may be due to the decrease of organic matter in phosphogypsum, which may be attributed to the decrease of organic matter in the land formation material, and the decrease of organic matter in the T1 treatment. The low organic matter and nitrogen content in the phosphogypsum of the material can be supplemented by applying more nitrogen fertilizer and organic fertilizer when performing phosphogypsum land creation and utilization (Gu et al., 2013; Shu, 2019). On the whole, T1 treatment had the best effect on the enhancement of inter-root soil nutrients in lettuce.

Table 3. Effect of different phosphogypsum soil chemistry ratios on inter-root soil nutrients in lettuce.

Treatment	pH	Available-N mg·kg^{-1})	Olsen-P (mg·kg^{-1})	Available-K (mg·kg^{-1})	SOM (g·kg^{-1})
CK	6.46 ± 0.04 a	99.63 ± 17.78 a	21.27 ± 5.28 bB	161.1 ± 7.28 cB	14.57 ± 1.07 a
T1	6.49 ± 0.07 a	62.30 ± 14.95 b	99.77 ± 1.29 aA	246.9 ± 11.24 aA	12.06 ± 0.33 a
T2	6.21 ± 0.28 a	61.72 ± 12.57 b	102.35 ± 1.42 aA	245.1 ± 21.17 abA	11.55 ± 0.89 a
T3	6.14 ± 0.10 a	37.80 ± 6.63 c	103.69 ± 2.47 aA	228.4 ± 4.70 bA	10.14 ± 0.92 a
Average Value	6.33	65.36	81.77	220.37	12.08
Coefficient of Variation	7.74%	19.86%	3.20%	5.04%	6.64%

Note: The above data represent the mean ± standard deviation (n = 3), and different lowercase and uppercase letters in the same column indicate significant ($P < 0.05$) and highly significant ($P < 0.01$) differences between treatments, respectively, as follows.

Table 4. Distribution characteristics of soil grain size with different proportions (%).

Treatment	Agglomerate < 2 μm	Granule 2 - 50 μm	Sand 50 - 1000 μm			
			Very fine sand 50 - 125 μm	Fine sand 125 - 250 μm	Middle sand 250 - 500 μm	Thick sand 500 - 1000 μm
CK	10.4	81.71	7.37	0.52	0	0
T1	11.01	77.14	9.89	1.96	0	0
T2	12.35	75.02	9.99	2.62	0.02	0
T3	11.11	72.55	13.05	3.27	0.02	0

From the distribution of soil particle size of the three treatments (**Table 4**), all of them showed the highest content of powder particles, followed by sticky particles and the lowest content of sand particles, and the soils of T1 and T2 treatments were dominated by powdery and sticky particles, which accounted for 88.15% and 87.37%, respectively, and the T3 showed powdery and sandy soils. Compared with the control, the treatments showed a trend of increasing soil powder and sand content with the increase of modified phosphogypsum ratio, indicating that the phosphogypsum land-making soil reduced the soil viscosity, increased the powder and sand content in the soil, and enhanced the soil aeration and water permeability, which is consistent with the results of the previous research on the utilization of phosphogypsum as a soil conditioner (Lu et al., 2023; Shu & Peng, 2019). Phosphogypsum can make the soil tillage layer loose and porous, create a suitable environment for the activities of soil microorganisms, promote the transformation of soil nutrients, and promote the transformation of delayed-acting phosphorus in the soil, which is conducive to moisture retention, drought prevention, and flood prevention. Thus, it improves the physical and chemical properties of the soil and the soil environment for crop growth.

3.3. Effects of Different Soil Ratios on the Growth and Development of Lettuce

Crop growth and development indexes are important indicators for testing soil nutrients and quality. In this study, different land-making treatments affected lettuce growth and development to different degrees, as shown in **Table 5**, there were significant differences in plant height, stem thickness, biomass, root-crown ratio and seedling index of the test lettuce under different treatments, and the mean value of biomass of lettuce under different treatments was 7.64 g·plant^{-1}, with a coefficient of variation of 11.26%, and the biomass of T1 treatment was significantly increased by 19.34% compared with CK, which was consistent with that of Cai Liang et al. and Micha et al. and T2 < CK < T1, respectively. The overall performance was T1 < T2 < CK < T1. This is similar to the findings of Cai Liang et al. and Micha et al. who examined the effect of phosphogypsum application using oilseed crops, maize, and wheat as the research subjects (Cai, 2001; Michalovicz et al., 2019). phosphogypsum's fractions contain phytonutrient elements such as calcium, sulphur, silicon, and phosphorus, which are known to have a promoting effect on plant growth, and may be applied as a fertilizer directly to farmland to improve soil fertility (Liu et al., 2023; Ghazi et al., 2002). The mean values of lettuce plant height, stem thickness, root-crown ratio and strong seedling index in different treatments were 21.71 cm, 2.71 mm, 0.10 and 0.46, respectively, with coefficients of variation ranging from 5.72% to 22.83%, and the stem thickness was significantly increased ($P < 0.05$) in T1 and T2 treatments compared to CK, by 21.51% and 4.15%, respectively; whereas, the T3 treatment significantly reduced the lettuce root-crown ratio, which was significantly reduced by 36.36% ($P < 0.05$), indicating that the root functional activity of lettuce in T3 treatment was weaker. In conclusion, the low ratio T1 treatment had the best effect on the enhancement of lettuce stem thickness, leaf area, root-crown ratio, and strong seedling index, which may be due to the fact that the low ratio phosphogypsum land-forming soil can improve soil fertility while decreasing soil cohesion and increasing soil porosity, and the good water and air condition promotes the growth of the crop (Mao et al., 2023), which results corroborate with those of **Table 3** and **Table 4**, and have a similarity with Surendra et al.'s (Surendra et al., 2016). study; Bai Laihan et al. applied phosphogypsum as a soil amendment and found that maize biomass increased with increasing level of phosphogypsum addition (Bai et al., 2011), which is slightly different from the results of the present study, this is due to the fact that the present study used phosphogypsum for land formation and utilization, and the amount of phosphogypsum was higher compared to previous studies used as a soil amendment, therefore, care should be taken to use the right proportionate amount of phosphogypsum when using phosphogypsum as a soil amendment, otherwise it will reduce crop yield.

Table 5. Effects of different proportions of phosphogypsum soil fertilization on lettuce growth.

Treatment	Plant height (cm)	Stem diameter (cm)	Leaf area (cm^2)	Biomass ($g \cdot plant^{-1}$)	Root-top ratio	Seedling-index
CK	19.81 ± 2.56 b	2.65 ± 0.15 b	144.64 ± 4.72 a	7.63 ± 1.35 ab	0.11 ± 0.03 a	0.52 ± 0.13 b
T1	17.63 ± 1.75 b	3.22 ± 0.15 a	161.81 ± 28.1 a	10.91 ± 1.32 a	0.12 ± 0.01 a	0.73 ± 0.02 a
T2	21.38 ± 0.63 b	2.76 ± 0.11 ab	133.55 ± 26.59 a	7.39 ± 0.41 ab	0.10 ± 0.01 ab	0.42 ± 0.03 b
T3	28.00 ± 0.75 a	2.21 ± 0.21 b	120.34 ± 12.70 a	4.63 ± 0.36 b	0.07 ± 0.01 b	0.17 ± 0.06 c
Average Value	21.71	2.71	140.09	7.64	0.10	0.46
Coefficient of Variation	6.55%	5.72%	32.08%	11.26%	12.50%	22.83%

3.4. Evaluation of Soil Safety in Phosphogypsum Land Formation

Phosphogypsum contains heavy metals and other harmful impurities, and these impurities will accumulate in the soil when it is utilized for land creation, affecting the quality of the soil, so it is of great significance to conduct a safety evaluation of the soil. Through the heavy metal content statistics of the soil (**Figure 1**), comparing with the Soil Pollution Control Standard for Agricultural Land of Soil Environmental Quality (GB 15618-2018), the Pb, Cd, Cr, As and Hg contents of the soil of each treatment were within the risk control value, among which the Pb and Cd contents had the trend of increasing with the increase of phosphogypsum ration amount. Some studies have shown that different phosphorus fertilizer production processes can make differences in the content of heavy metals and other impurities in phosphogypsum, and the pollutants carried by phosphogypsum can also accumulate in the soil year by year with the increase of the year [15], so it is important to carry out environmentally sound treatment and tracking tests when using phosphogypsum for land creation to ensure clean and healthy soil.

The Nemero comprehensive pollution index is a method that can judge the degree of heavy metal pollution more comprehensively and is widely used. Equation (1) and equation (2) were used to calculate the heavy metal single pollution index and comprehensive pollution index of modified phosphogypsum land-making soil, and the results were shown in **Figure 2(a)**, analyzed by the single pollution index, the soil of T1 and T2 treatments were safe and not polluted by heavy metals, and the T3 treatment was mildly polluted by Pb. After analyzing the comprehensive pollution index, the base soil $P_n = 0.67$ in the control with reference to the soil environmental quality standard for agricultural land (screening value), the soil P_n of T1 and T2 treatments were 0.54 and 0.64 respectively, which were at the clean level, and the soil of T3 treatments was at the mildly polluted level with

P_n = 1.10. Taking the soil background of Yunnan Province as the reference value, the potential ecological risk index of each proportion of heavy metals and the potential ecological risk index of multiple heavy metals of modified phosphogypsum land-making soil were calculated by using Equation (3), and the results were shown in Figure 2(b), the size of the potential ecological risk index of heavy metals of each treatment: T3 > T2 > T1, and the E_r value of Pb, Cd, Cr, As and Hg of each treatment soil was less than 40, which was in the light ecological risk level. The RI values of heavy metals in the treated soils were less than 90, which were lower than that of the control soil, and were in the slight ecological risk level. In conclusion, the low ratio T1 treatment is a safe soil for land reclamation.

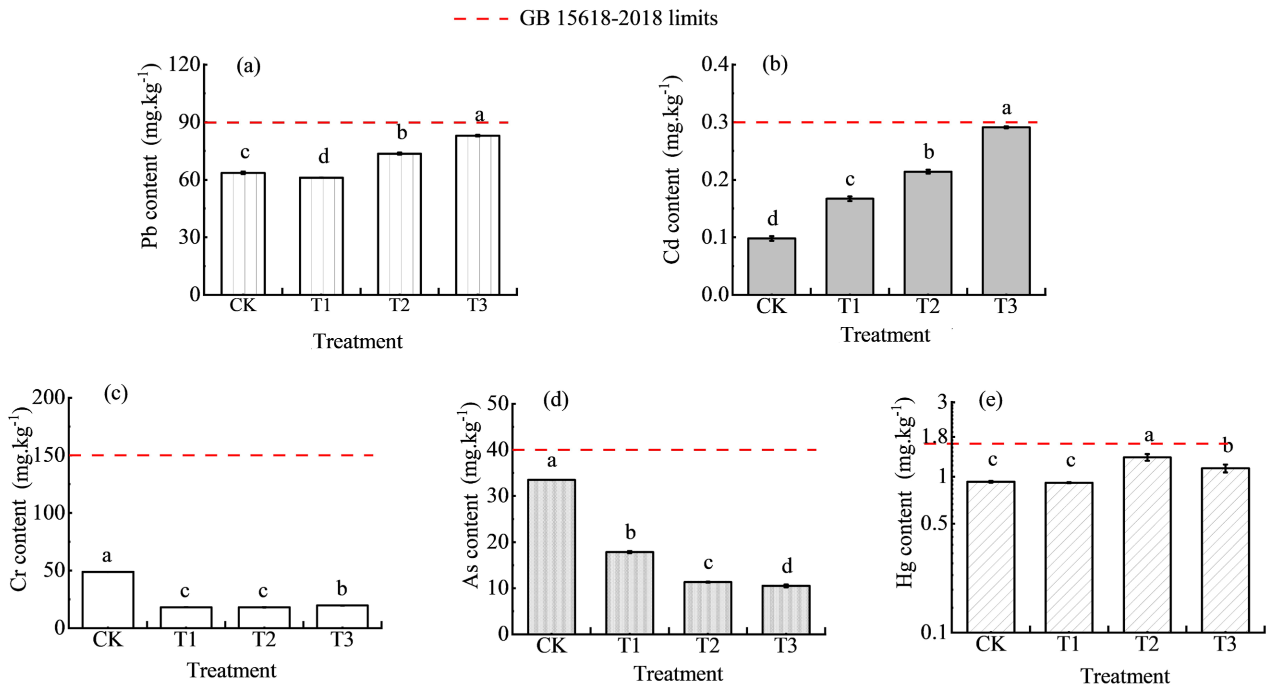

Figure 2. Content and evaluation criteria of heavy metals in soil after harvest.

3.5. Lettuce Safety Evaluation

Since soil heavy metal contamination can be accumulated step by step through the food chain and eventually jeopardize human health, this study was evaluated on the basis of the national food safety standards, and the corresponding results are shown in Figure 3. In all the treatments of this experiment, the contents of Cd, Cr, As and Hg in the edible parts of lettuce in each treatment were in accordance with the "National Standard for Food Safety: Limitations of Pollutants in Foods" (GB 2762-2022) in the food products. The maximum content levels allowed in leafy vegetables (Cd ≤ 0.2 mg·kg^{-1}, Cr ≤ 0.5 mg·kg^{-1}, As ≤ 0.5 mg·kg^{-1} and Hg ≤ 0.01 mg·kg^{-1}) were in the safe range, and the Pb and Cd contents in the edible part of lettuce had a tendency to increase with the increase of modified phosphogypsum ratio, which was in line with the results of Xiao Houjun et al. who compared the phosphogypsum application in various locations with that of Xiao Haujun et al (Xiao et al., 2008). Phosphogypsum application in various places and found that the Cd accumulated in the grain was within the permissible range. However, as shown in **Figure 4**, the Pb content in the edible part of lettuce from T2 and T3 treatments exceeded the national limit (Pb ≤ 0.3 $mg \cdot kg^{-1}$) by 1.5 and 1.9 times, respectively, which is consistent with the findings of Wang Chengbao et al. (Wang et al., 2010). Phosphogypsum should be used for agricultural purposes with attention to the dosage and find the right ratio to ensure the safe production of agricultural products, and the optimal ratio of phosphogypsum land-forming soil for growing lettuce in this study was the low ratio T1 treatment. From the point of view of soil environment and food safety, there is a possibility of promoting the use of the low-ratio treatment. The amount of phosphogypsum per mu calculated by the low-ratio treatment in this study is about 160 tons, which is expected to solve the problem of phosphogypsum stockpiling. Due to the limitation of experimental conditions, only one crop and three ratios were selected in this study to conduct a preliminary investigation on the feasibility of land use of modified phosphogypsum, and the study of Shi Yaxing et al. observed that there were differences in the enrichment capacity of different crop species or different parts of the same crop for heavy metals (Shi et al., 2016), so whether the food safety of planting other crops or different varieties of vegetables can be guaranteed needs to be further researched.

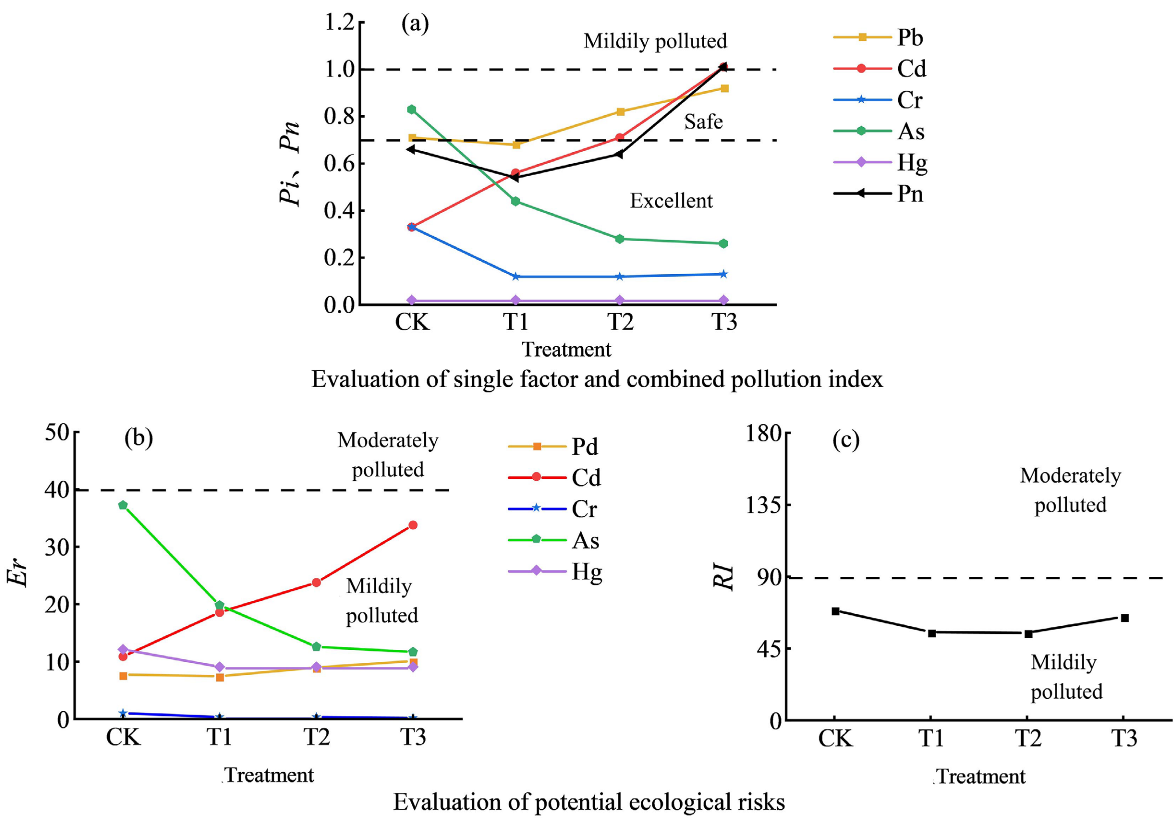

Figure 3. Evaluation of environmental quality and potential ecological risk of heavy metals in soil.

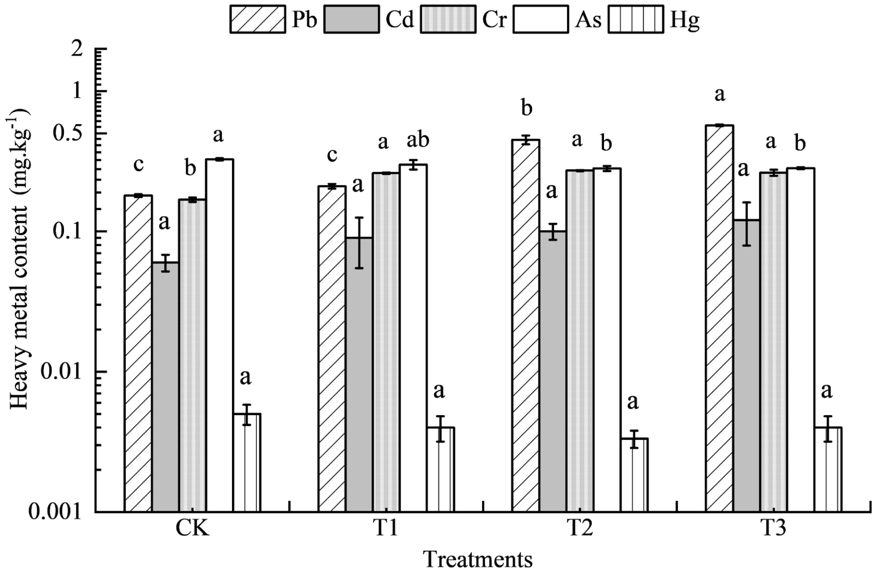

Figure 4. Heavy metal content and evaluation criteria in lettuce (GB 2762-2022).

3.6. Correlation Analysis

There was a correlation between heavy metal content in vegetables and heavy metals in soil as shown in **Table 6**. Overall, Pb and As in crops were most affected by heavy metal contents in soil, followed by Cr. In this study, soil Pb, Cd and Hg in Pb content in lettuce showed highly significant positive correlation, with correlation coefficients of 0.97, 0.94 and 0.71, respectively, highly significant negative correlation with As, and highly significant negative correlation with Cr, with correlation coefficients of −0.81 and −0.58; lettuce Cr showed highly significant negative correlation (R^2 =−0.98 and −0.95, respectively) with soil Cr and As were highly significant negatively correlated (R^2 = −0.98 and −0.95), and significantly positively correlated with Cd (R^2 = 0.76); the As content of lettuce was highly significant negatively correlated with soil Cd with a correlation coefficient of 0.74, and significantly negatively correlated with Pb and Hg with correlation coefficients of −0.58 and −0.61, respectively, and highly significant positively correlated

Table 6. Correlation between lettuce and heavy metal content in soil.

Item	Element	soil				
		Pb	Cd	Cr	As	Hg
Lettuce	Pb	0.97**	0.94**	−0.58*	−0.81**	0.71**
	Cd	0.38	0.50	−0.41	−0.46	0.17
	Cr	0.46	0.76**	−0.98**	−0.95**	0.53
	As	−0.58*	−0.74**	0.73**	0.80**	−0.61*
	Hg	−0.29	−0.38	0.56	0.57	−0.48

Note: * is $P < 0.05$, indicating that vegetables are significantly correlated with soil heavy metal content, and ** is $P < 0.01$, vegetables are highly significantly correlated with soil heavy metal content.

with Cr and As with correlation coefficients of 0.73 and 0.80, respectively, which indicated that Pb, Cd, Cr, As and Hg in soil could promote the uptake of Pb, Cr and As by vegetables, while Pb, Cd, Cr, As and Hg in soil could inhibit the uptake of As, Pb and Cr by vegetables. There was no significant correlation between Cd and Hg in vegetables and the five heavy metals in soil.

4. Conclusion

Compared with the heavy metal screening values in GB 15618-2018, the Pb, Cd, Cr, As and Hg contents of the phosphogypsum land-forming soil in this study met the control standards of the Soil Environmental Quality Soil Pollution Risk Control Standards for Agricultural Land. After the germination rate test and pot planting test, the phosphogypsum soil in this study could meet the requirements of normal crop growth and development, and compared with the pure soil treatment (CK), the modified phosphogypsum soil significantly increased the soil nutrient content, and promoted the growth and development of lettuce to different degrees.

T1 ratio treatment is a more ideal modified phosphogypsum land preparation ratio, planted lettuce food Pb, Cd, Cr, As and Hg content are within the screening range of the "National Standard for Food Safety, Pollutant Limits in Food" (GB 2762-2022), although the ecological risk index of heavy metal content of soil in T2 and T3 ratio treatments are in the ecological risk level of a slight, but the heavy metal content of lettuce increased and the risk of lettuce consumption increased.

The physical and chemical properties of the modified phosphogypsum soil and the safety of lettuce growth and consumption were comprehensively analyzed, and the T1 ratio was the best ratio in this study, which significantly increased lettuce production, indicating that the use of modified phosphogypsum for land use is feasible and of great significance for ensuring the safe production of agricultural products and promoting sustainable development.

However, this study only covered a single crop (lettuce) and a specific soil type, and the results may not be widely generalizable to other crops or applications under different soil conditions; therefore, further research is important to verify the applicability in different agricultural environments. In addition, the short experimental period of this study (December 2022 to February 2023) only reflects the short-term effects of phosphogypsum-modified soils and lacks the assessment of long-term effects on soil health, nutrient cycling, and heavy metal accumulation. Therefore, in-depth studies of multi-seasonal effects through long-term field trials are needed to more fully assess the impacts of modified phosphogypsum on soil sustainability and potential environmental risks.

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Conflicts of Interest

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

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