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Influence of Sedum Spectabile on Cd Concentration in Soil and Runoff

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Abstract

To research how planting Sedum spectabile affects Cd loss, in this experiment, the impact of soil pollution level (low, medium, high), rainfall intensity (30, 60, 90 mm·h^{-1}), and slope (6˚, 12˚, 18˚, 24˚) on Cd concentration in soil and runoff after planting Sedum spectabile are investigating using an indoor artificial rainfall simulation method. The results showed that: 1) The mean values of agricultural soils in the study area reached 38.52 and 1073.28 mg·kg^{-1} for Cd and Zn, respectively, which were 176.70 and 11.96 times higher than the background values of soil environment in southern Yunnan. 2) The decrease of total Cd in the soil after planting Sedum spectabile ranged from 17.52% to 31.09%, and the decrease of effective state Cd ranged from 14.36% to 21.81%. The higher the pollution level, the more significant the decrease of effective state Cd. 3) After 120 days of planting, the Cd concentration in runoff decreased between 22.40% and 89.23% compared to 15 days, with the more significant decrease in low Cd pollution, 90 mm·h^{-1} rainfall, medium Cd pollution, 30 mm·h^{-1} rainfall, and high Cd pollution, 90 mm·h^{-1}, reaching 81.14% - 87.43%, 82.21% - 89.00%, and 37.57% - 89.23%. 4) The pollution level and rainfall intensity were significantly and positively correlated with Cd concentration in runoff at 15 and 120 days of planting Sedum spectabile, with correlation coefficients of 0.498, 0.641, and 0.435, 0.464. Research shows that planting Sedum spectabile can reduce the Cd concentration in soil and runoff, which is essential for the remediation of Cd-contaminated farmland.

Keywords

Sedum Spectabile, Pollution Level, Rainfall Intensity, Slope, Cd

1. Introduction

The emission of heavy metal pollution in China has gradually increased with the development of the social economy, resulting in an increasingly severe problem of soil heavy metal pollution. According to the Ministry of Environmental Protection and the Ministry of Land's 2014 National Soil Pollution Survey Bulletin, the total exceedance rate of soil nationwide was 16.1%, with the proportion of slightly, mildly, moderately, and severely polluted spots being 11.2%, 2.3%, 1.5%, and 1.1%, respectively. Cadmium had a point exceedance rate of 7.0% among inorganic substances (National Soil Pollution Survey Bulletin, 2014). According to the "National Ecological Environment Quality Profile 2020" published by the Ministry of Ecology and Environment in March 2021, cadmium was the primary pollutant among heavy metals in the soil environmental quality of agricultural land (Sun, 2021). Due to cadmium's high mobility and bio toxicity, enrichment of humans through the food chain, and accumulation by plants, cadmium in the environment is particularly vulnerable to uptake and accumulation by plants (Lin et al., 2017). According to relevant studies conducted in the United States and Japan, cadmium has a biological half-life of up to 10 - 35 years in the human body (Huang et al., 2018; Rahimzadeh et al., 2017). When cadmium accumulates in the body to a certain level, it can seriously damage human health, cause kidney failure (Järup, 2002), and even lead to cancer or death (Yang & Lin, 2015).

High background of Cd is mostly present in soils in areas where carbonate rocks (including limestone and dolomite, etc.) are developed (Lalor et al., 1998; Quezada-Hinojosa et al., 2009). Yunnan Province is located in the Yunnan-Kweichow Plateau Plateau, distributed with extensive mountainous terrain, karst landscapes, and the Cd content in limestone soils and limestone is about 1.5 times higher than the provincial average (Li & Wang, 2008). Yunnan Province is in the intersection of East Asian monsoon and South Asian monsoon, and the province is divided into 6 climatic zones (Duan et al., 2011). The complex natural geographical environment and climatic conditions have created the phenomenon of frequent heavy and stormy rainfall (Peng & Liu, 2009; Yang et al., 2021a), resulting in Yunnan Province becoming an area with high Cd concentration and easy loss (Zhao et al., 2015). Rain causes the accumulated Cd in the soil to migrate with surface runoff, which expands the soil's heavy metal contamination area (Guo et al., 2000) and impacts the ecological environment.

As a newly discovered Cd-enriched plant in recent years, Sedum spectabile can tolerate 100 μmol·L^{-1} Cd $(NO_3)_2$ stress (Jiao & Zhu, 2014) and has the characteristic that the higher the concentration of heavy metal Cd, the greater the effect on its biomass (Wang & Bai, 2016). Studies have shown that Sedum spectabile can enrich soil Cd content 8 to 18 times on Cd-contaminated farmland in northern China (Guo, 2018), indicating its application value in the remediation of heavy metal Cd contamination. Many domestic and overseas studies have revealed the migration pattern of soil heavy metal with surface runoff water and have achieved remarkable results (Qiao et al., 2019). However, there are fewer reports on the study of the characteristics and influencing factors of Cd loss after remediation on different contaminated soils. In this study, simulated rainfall is applied to compare the migration patterns of Cd with surface runoff after planting sedum spectabile under different Cd contamination levels, rainfall intensities, and slope conditions. By investigating the effects of different pollution levels, rainfall intensity and slope on Cd migration in remediated soils, we provide a theoretical basis for the control and remediation of Cd-contaminated farmland and realize the safe use of agricultural soils.

2. Material and Methods

2.1. Overview of the Study Area

Luoping County, Yunnan Province, is located between 24˚31' - 25˚52'N and 103˚57' - 104˚43'E (**Figure 1**). Except for the southern part of Badahe, Luoping County has a southern subtropical climate, and the rest of the county has a highland monsoon climate. The average annual temperature is 15.1˚C, and the average annual rainfall is 1743.9 mm. The sampling site in this study area is located in the village of Yidule, Luoping County, at an altitude of 1250 m, surrounded by mountains on three sides, with the Jiu Long River waterfall group located to the north. The creek was used for water for people and animals in Kowloon Falls Scenic Area Management Office and Yidule Village and irrigation.

2.2. Test Material

2.2.1. Test Soil

This study collected samples from 0 - 20 cm of cultivated soil in Yidule Village, Luoping County, Qujing City, Yunnan Province, according to the "S" shaped

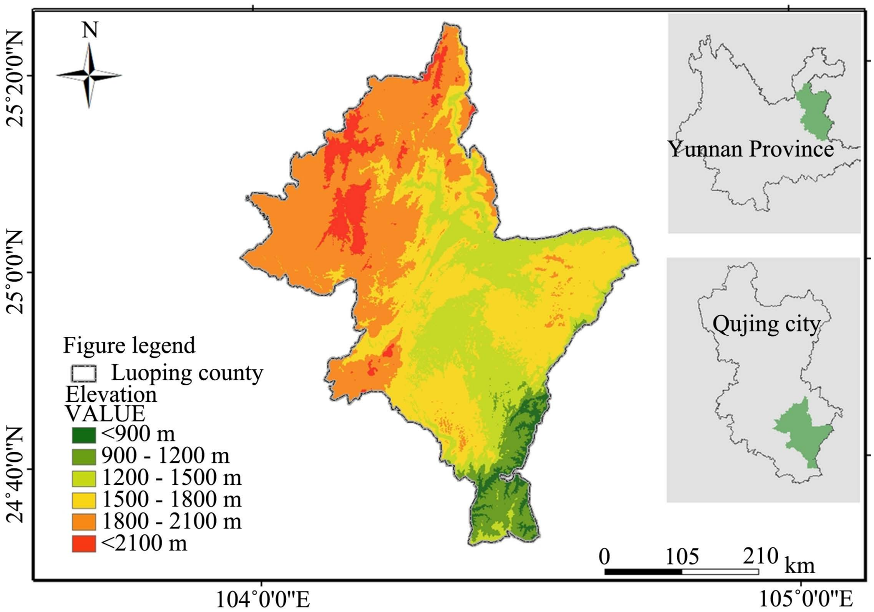


Figure 1. Geographical location of the study area.

5-point sampling method. The collected soils were classified into three Cd levels: low (L-Cd), medium (M-Cd), and high (H-Cd), according to the soil Cd content. The collected soil samples were taken back to the laboratory to remove debris such as root stubble, animal residues, and stones, and the soil was air-dried and sieved through 2 mm sieve. The main properties of the test soils are shown in Table 1.

2.2.2. Test Plants

The test plant samples in this study were collected from the rehabilitated farmland with Cd contaminated soil by plugging, and 20 plants of uniform growth were washed and transplanted in runoff tanks containing different Cd concentrations.

2.3. Experimental Protocol Design

2.3.1. Runoff Test Protocol Design

The NLJY-10 artificial simulated rainfall control system produced by Nanjing Forestry University (Nanlin Electronics) was used for the artificial simulated rainfall test. The rainfall height was 16 m, and the rainfall uniformity coefficient was over 95%. The rainfall uniformity coefficient was over 95%. Fill the soil holding container (100 × 35 × 30 cm) with an equal amount of soil samples, each container for one treatment, and collect the runoff water solution in a wide-mouth bottle.

The land resource area of slopes from 8˚ to 25˚ in Luoping County accounted for 58.21% of the total land resource area in the county, so the experiment was set up with four slope treatments (6˚, 12˚, 18˚, 24˚). The maximum rainfall intensity in Luoping County was 72 mm·h^{-1} by searching and analyzing the rainfall data of the area, so three rainfall intensity treatments of 30 mm·h^{-1}, 60 mm·h^{-1}, and 90 mm·h^{-1} were set up with a gradient of 30 mm·h^{-1}. The rainfall duration was set to 30 min (from the time of runoff generation), and three parallel groups were set for each test to ensure the accuracy of the test. After the test started, the rainfall start time and surface runoff production time were recorded, the sampling interval was 1 sample every 5 min, the volume of runoff was measured by the volume method, and the importance of runoff was recorded.

2.3.2. Experimental Design for the Remediation of Contaminated Soil by Sedum Spectabile

The Sedum spectabile were cultivated in a greenhouse with regular management,

Table 1. Basic properties of tested soil.

level of pollutant	pH	OM (mg·kg^{-1})	Total Cd (mg·kg^{-1})	Cd effective state (mg·kg^{-1})
L-Cd	7.53	23.59	7.43	3.62
M-Cd	7.58	29.51	42.23	11.04
H-Cd	7.57	37.33	94.2	67.53

watered, and weeded regularly during the growth period, and runoff tests were conducted once after 15 days of stable growth and again after 120 days of development.

2.4. Measurement Items and Analytical Methods

Soil pH was determined by pH meter with a solid-liquid ratio of 1:2.5; soil organic matter was resolved by potassium dichromate volumetric method-external heating method (NY/T 1121.6-2006); soil Cd content was determined by HF-$HClO_4$-HNO_3 digestion concerning GB/T 17141-1997 "Determination of soil quality of lead and cadmium by graphite furnace atomic absorption spectrophotometry". The compelling state of soil Cd was determined by DTPA (diethylenetriaminepentaacetic acid) leaching/atomic fluorescence method; the content of Cd in water was determined by inductively coupled plasma mass spectrometer, referring to HJ700-2014 "Determination of 65 elements of water quality by inductively coupled plasma mass spectrometry".

2.5. Data Processing and Analysis

All data were counted using Excel 2019, analyzed, and processed using SPSS 18, graphs and charts were created using Origin 2021, and statistical analysis and mapping were done in ArcGIS10.6.

3. Results and Analysis

3.1. Characteristics of the Heavy Metal Content of Surface Soil in the Study Area

The characteristics of heavy metal contamination content in the surface soil of the study area are shown in Table 2. The mean values of As, Cd, Cr, Ni, and Zn in all soil samples, except for Pb and Cu, were more significant than the background values of Yunnan soil elements, indicating that the soil in the study area had accumulated heavy metals to different degrees. The accumulation levels of various heavy metals were different, with Cd > Zn > Cr > As > Ni and the exceedance rates of Cd and Zn were the highest, reaching 176.70 and 11.96 times

Table 2. Statistical analysis of soil heavy metals in the study area.

Item	As	Pb	Cd	Cr	Ni	Cu	Zn
Mix ($mg \cdot kg^{-1}$)	14.21	24.77	4.11	75.86	33.21	21.63	208.80
Max ($mg \cdot kg^{-1}$)	40.57	60.01	110.40	148.06	84.54	71.73	2444.00
Mean ($mg \cdot kg^{-1}$)	22.20	35.27	38.52	116.59	50.30	45.69	1073.28
SD	5.53	7.49	28.82	15.51	10.38	9.82	641.78
CV%	24.91	21.25	74.81	13.30	21.53	21.49	59.80
Background value*	18.40	46.60	0.218	65.20	42.50	46.30	89.70

*(EPA China National Environmental Monitoring Centre, 1990).

the background values of soil elements in Yunnan, respectively, and the Cd content of soils in this area was seriously exceeded.

The coefficient of variation indicates the degree of dispersion of the data, and the higher the coefficient of variation, the greater the influence of heavy metals on human activities. The data in the table show that the magnitude of the coefficients of variation of soil elements in this study area is as follows: Cd > Zn > As > Cu > Ni > Pb > Cr. The coefficients of variation of Cd and Zn are the highest and have a significant degree of dispersion, with coefficients of variation reaching 74.81% and 59.80%, respectively, indicating that the contents of heavy metals Cd and Zn in the soil of this study area are most influenced by anthropogenic factors.

3.2. Effect of Planting Sedum Spectabile on the Concentration of Cd in Soil

Sedum spectabile has a strong enrichment capacity for Cd, strong regeneration ability, and a wide adaptation range. Under different Cd contamination levels, there were significant decreases in both total Cd (**Figure 2**) and effective state Cd (**Figure 3**) in the soil after planting Sedum spectabile, and the decreases were

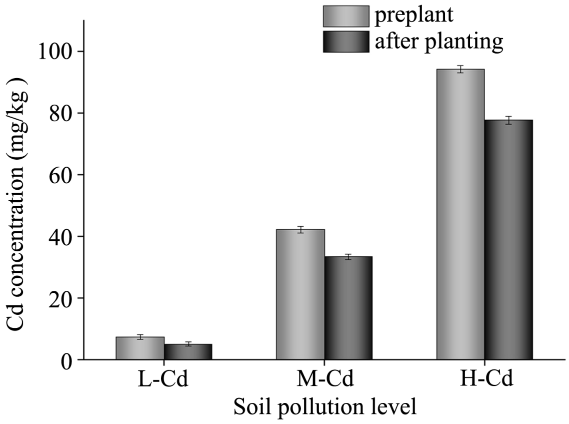


Figure 2. Total Cd concentration in soil under different pollution levels.

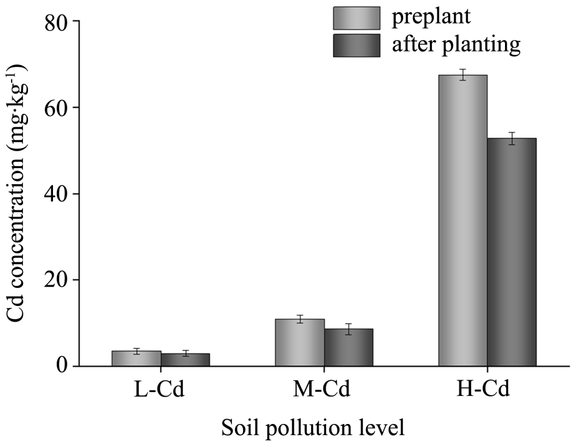


Figure 3. Effective Cd concentration in soil under different pollution levels.

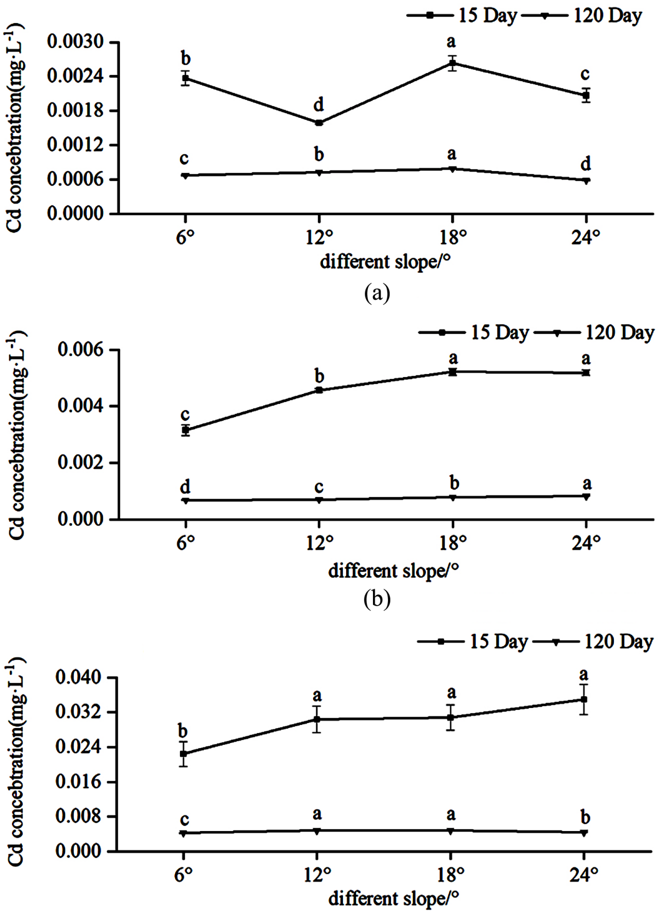
more pronounced with increasing Cd concentrations. The concentrations of total Cd in soil ranged from 7.42 - 94.2 mg·kg^{-1} before planting and from 5.12 - 77.7 mg·kg^{-1} after planting; the concentrations of effective state Cd in soil ranged from 3.62 - 67.53 mg·kg^{-1} before planting and from 3.1 - 52.8 mg·kg^{-1} after planting. in L-Cd soil, the concentrations of total Cd in the soil before and after planting In the L-Cd soil, the total amount of Cd in the soil decreased by 31.09% and the effective Cd decreased by 14.36% before and after planting; in the M-Cd soil, the total amount of Cd in the soil decreased by 20.91% and the effective Cd decreased by 21.20 before and after planting; in the H-Cd soil, the total amount of Cd in the soil decreased by 17.52% and the effective Cd decreased by 21.80% before and after planting. Therefore, the effective state Cd content in the soil decreased more after planting Sedum spectabile in soils with higher Cd contamination levels, while the total Cd amount decreased less and less with increasing Cd concentration.

3.3. Effects on Cd Concentrations in a Runoff after Planting of Sedum Spectabile under Different Slope and Rainfall Conditions

The Cd concentrations in runoff water after planting Sedum spectabile under 30 mm·h^{-1} L-Cd soil are shown in **Figure 4(a)**, and it can be seen from the figure that with the increase of slope, the Cd concentration in runoff ranged from 0.00159 mg·L^{-1} to 0.00263 mg·L^{-1} after 15 days of planting Sedum spectabile, and the Cd concentration fluctuated with the increase of slope; after 120 days of producing Sedum spectabile, The Cd concentration in runoff water ranged from 0.00059 mg·L^{-1} - 0.00079 mg·L^{-1} after 120 days of planting. Under this rainfall condition, the Cd concentration in runoff water reached the highest at a slope of 18˚ after 15 days of planting and 120 days of planting, and the reduction rate of Cd concentration in runoff water reached 71.4% after 120 days of planting. Analysis of variance (ANOVA) showed that the difference in Cd concentration in runoff water between slopes was significant at 15 and 120 days of planting.

Under the rain intensity of 60 mm·h^{-1} (**Figure 4(b)**), the Cd concentration in runoff showed a trend of rapid increase followed by a slow decrease with increasing slope at 15 days of planting and reached a maximum value of 0.00522 mg·L^{-1} at 18˚; when planted for 120 days, the Cd concentration in runoff showed a smooth increase and arrived a maximum weight of 0.00082 mg·L^{-1} at 24˚. The ANOVA showed that the differences between slopes of 18˚ and 24˚ were not significant at 15 days, and the differences among slopes were substantial at 120 days of planting.

Under the rain intensity condition of 90 mm·h^{-1} (**Figure 4(c)**), the Cd concentration in runoff showed an increasing trend in runoff under different slope conditions at 15 days of planting, while the Cd concentration in runoff showed an expanding trend followed by a decreasing trend at 120 days of planting. The minimum values of Cd concentration in runoff at both day 15 and 120 occurred



(a)

(b)

(c)

Figure 4. Cd concentration in runoff water of L-Cd soil. (a) 30 mm·h⁻¹; (b) 60 mm·h⁻¹; (c) 90 mm·h⁻¹.

at slope 6˚ with values of 0.0224 mg·L^{-1} and 0.00423 mg·L^{-1}, respectively, while the maximum values occurred at 24˚ and 18˚ with values of 0.0349 mg·L^{-1} and 0.00481 mg·L^{-1}, respectively.

In M-Cd soil, the Cd concentrations under different rainfall conditions are shown in **Figure 5**. Under the rainfall intensity of 30 mm·L^{-1}, the Cd concentration in runoff ranged from 0.00512 mg·L^{-1} to 0.00832 mg·L^{-1} at day 15, and the difference was not significant except at 6˚. At day 120, the Cd concentration in runoff did not vary much, and the highest value of C appeared at the slope of 18˚ with a value of 0.00111 mg·L^{-1}. The Cd concentration in the runoff under 60 mm·L^{-1} of rainfall increased on day 15 and then decreased on day 120, peaking at 0.00981 mg·L^{-1} at a slope of 18˚ and 0.00362 mg·L^{-1} at a slope of 15˚. From day 15, the Cd concentration in the runoff exhibited an undulating waveform, with concentration magnitude as follows (under 90 mm·L^{-1} rainfall): 24˚ > 12˚ > 6˚ > 18˚, with the difference between the slopes at 24˚ and 12˚ being insignificant; on day 120, the Cd concentration in the runoff exhibited a smooth increasing trend, with the maximum concentration reaching 0.02420 mg·L^{-1} when the slope was 24˚, with the difference between the slopes.

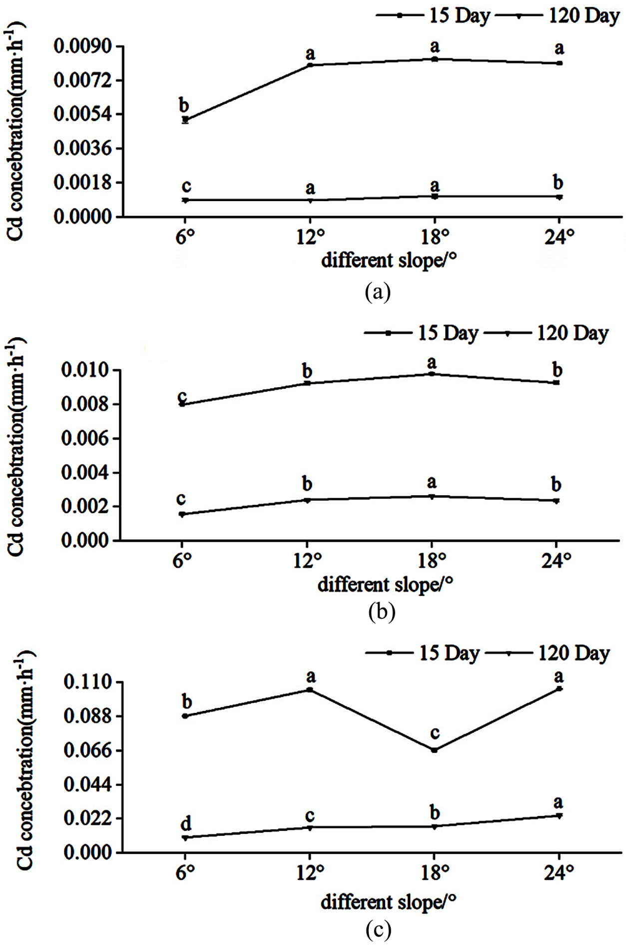
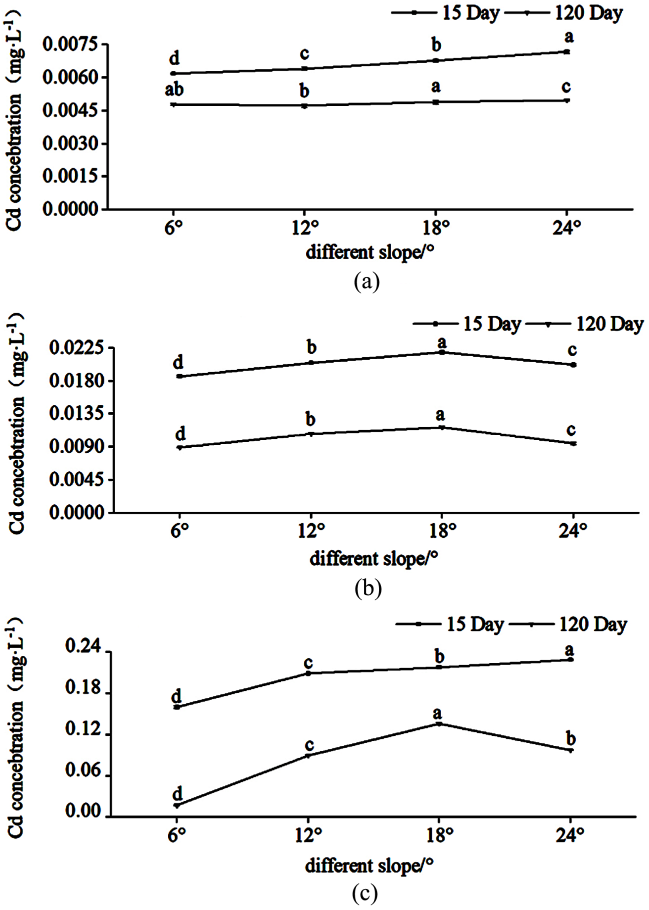


Figure 5. Cd concentration in runoff water of M-Cd soil. (a) 30 mm·h^{-1}; (b) 60 mm·h^{-1}; (c) 90 mm·h^{-1}.

Figure 6 depicts the shift in Cd concentration in runoff from H-Cd soil as the slope and precipitation change. Cd concentrations in runoff increased with slope from 0.006190 mg·L^{-1} 0.007173 mg·L^{-1} on day 15 to 0.004730 mg·L^{-1} 0.004930 mg·L^{-1} on day 120, with concentrations exhibiting 24˚ > 18˚ > 6˚ > 12˚. Cd concentration in the runoff on day 15 and day 120 under different slope conditions showed an increasing and then decreasing trend with the increase of slope, with the maximum value at 18˚ with 0.02190 mg·L^{-1} and 0.01170 mg·L^{-1}, respectively; the difference was significant among all slopes. The Cd concentration in runoff under 90 mm·L^{-1} of rainfall varied greatly between day 15 and day 120, with a maximum concentration of 0.13617 mg·L^{-1} at 18 degrees Celsius and a minimum of 0.16000 mg·L^{-1} at 24 degrees Centigrade.

3.4. Correlation Analysis between Cd Concentration in Runoff and Rainfall Intensity and Slope

Figure 7 and **Figure 8** illustrate the correlation analysis between Cd concentration in the runoff, pollution level, rainfall intensity, and slope following Sedum spectabile planting. The Cd content in runoff was positively and significantly



(a)

(b)

(c)

Figure 6. Cd concentration in runoff water of H-Cd soil. (a) 30 mm·h^{-1}; (b) 60 mm·h^{-1}; (c) 90 mm·h^{-1}.

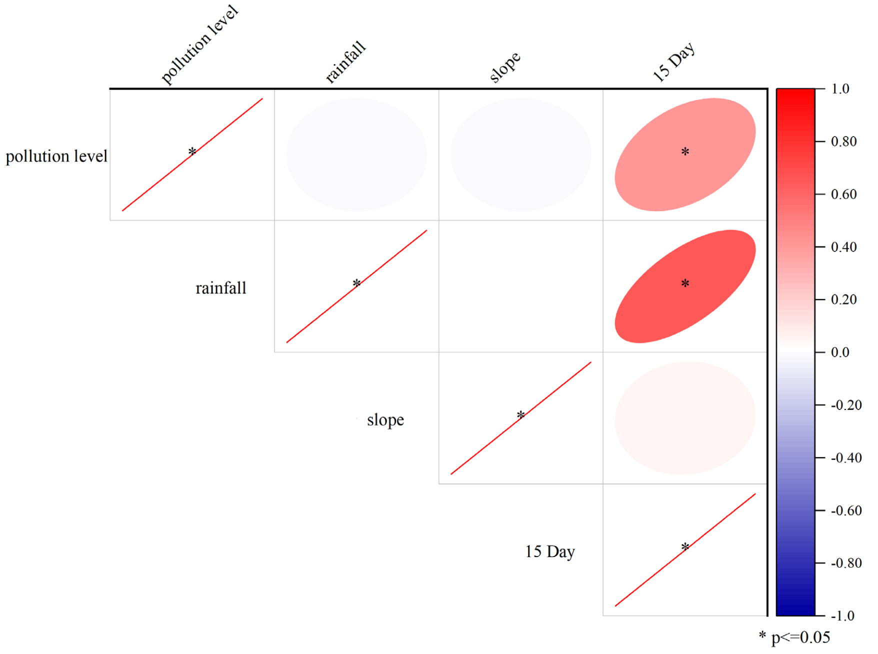


Figure 7. 15 days after planting.

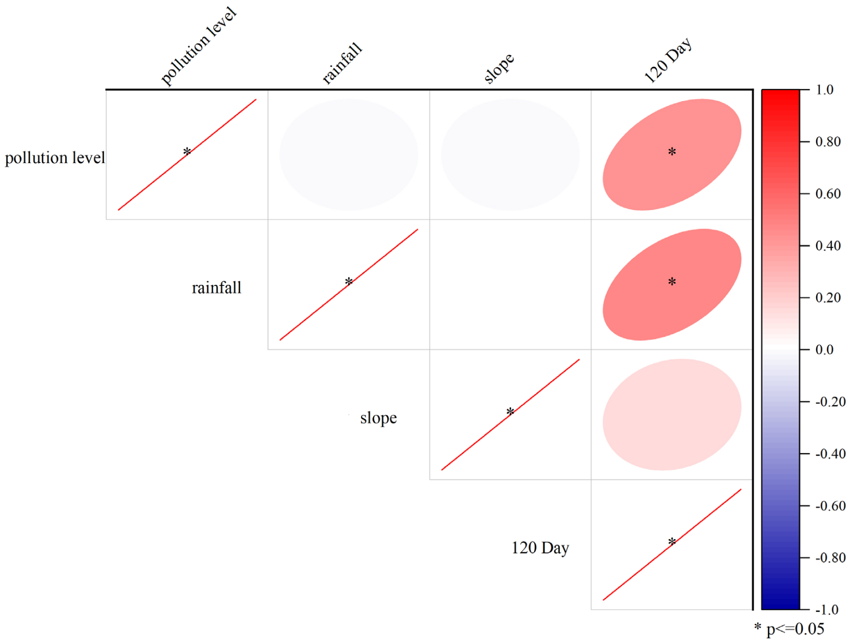


Figure 8. 120 days after planting.

correlated with the pollution level and rainfall intensity of cultivated land between 15 and 120 days after Sedum spectabile planting. The correlation size was all shown as rainfall intensity > pollution level, and there was no significant correlation between the Cd concentration in runoff and slope.

4. Discussion

There is a cumulative effect of heavy metals in farmland systems (Liu et al., 2022), and the process of carbonate weathering into soils in karst areas is prone to high enrichment of Cd and Zn elements (Yang et al., 2021b; Xiao et al., 2021). According to this study, the levels of As, Cd, Cr, Ni, and Zn in farmland soils were higher than 1.21, 176.70, 1.79, 1.18, and 11.96 times the background values of soil elements in Yunnan. This shows the cumulative effect of heavy metals in this farmland system and that Cd and Zn are the most polluted. Treatment for Cd and Zn should begin right away.

The application potential of Sedum spectabile for the remediation of Cd-contaminated farmland is enormous. Still, there are few studies on the remediation of Cd-contaminated soil by this highly Cd-rich tourist flowering plant with cold tolerance, drought tolerance, salinity tolerance, and a fast growth cycle. According to the findings of the current study, Eight Treasure Sedum had a Cd remediation rate that ranged from 17.51% to 31.09%, which was comparable to Cheng (2017) remediation rate of (7% - 30.1%) in Cd-contaminated fields planted with companion Sedum. Additionally, it was discovered in this study that as the amount of Cd in the soil increased, Sedum spectacle's rate of total Cd remediation gradually decreased while its rate of remediation of effective state Cd steadily increased. Additionally, after the Sedum spectabile was planted, the Cd concentration in runoff dropped significantly, proving that Sedum spectabile planting is crucial for halting Cd loss.

Slope and rainfall both have a significant impact on how soil Cd migrates with the surface. In this study, Sedum spectabile was planted. The simulated rainfall test showed that in soils with the same pollution level, the Cd concentration in runoff increased with rainfall. The Cd content in runoff increased significantly when the rainfall increased from 60 mm·h^{-1} to 90 mm·h^{-1}. In this study, the Cd concentration in runoff varied with slope, and the majority reached a maximum of 18˚, demonstrating a critical slope (18˚) for Cd loss at various inclines. Wang et al. (2006) and Zheng et al. (2013) discovered a necessary pitch for runoff soil denudation and loss of nitrogen and phosphorus. The correlation analysis showed no significant correlation between slope and Cd content in the runoff. Still, there was a significant and positive correlation between soil pollution level and rainfall intensity.

5. Conclusion

1) The mean soil values of As, Cd, Cr, Ni, and Zn in the study area's agricultural soils were higher than the background soil values in Yunnan Province, with Cd and Zn reaching 176.70 and 11.96 times, respectively, the background soil environmental values in Yunnan. The study area had a significant buildup of heavy metals.

2) Planting Sedum spectabile could significantly lower the amount of Cd in the soil, with the total amount of Cd reduced by 17.52% to 31.09% and the compelling state Cd reduced by 14.36% to 21.81%. The reduction in effective state Cd increased with the level of pollution.

3) The test with simulated rainfall revealed that after 120 days of planting Jingtian, as opposed to 15 days, the Cd concentration in runoff was better. About these, the restoration effect was more pronounced in the cases of medium Cd pollution and low rainfall intensity as well as low and high Cd pollution and increased rainfall intensity.

4) After the Sedum spectabile was planted, correlation analysis revealed a significant positive correlation between the pollution level of Cd concentration in runoff and rainfall intensity, but not with slope. This suggests that Sedum spectabile planting could lessen the impact of pitch on Cd loss.

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Conflicts of Interest

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

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