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Microbial–Plant Collaborative Remediation of Cd-Contaminated Wastewater and Soil in the Surrounding Area of Nuclear Power Plants and Risk Assessment

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Abstract: The continuous development of China's nuclear industry has caused an increasingly serious problem of heavy metal pollution in the ecological environment. A survey of the current situation shows that the quality of China's groundwater bodies and their surrounding ecological environment has been severely affected. China has started to devote more attention to the issue of nuclear emissions and pollution. In view of this, this study takes an area contaminated by nuclear power plant emissions as the object of research and uses plant–microbe synergy to remediate the cadmium-contaminated environment. Cadmium-tolerant strains were isolated from the soil and identified as Serratia marcescens. The morphological characteristics of the cadmium-tolerant strains were observed with electron microscopy in the presence or absence of cadmium ions. The removal of Cd^{2+} from wastewater was analyzed in four experimental groups: Cd^{2+} removal from Cd^{2+}-contaminated wastewater by combining a Cd-tolerant strain with Cd-flower, Cd-tolerant strain with Cd-flower, Cd-flower with alkali treatment, and Cd-tolerant strain with alkali treatment. This study innovatively treated Cd ion concentrations of 50 mg/L, 100 mg/L, 200 mg/L, and 300 mg/L. The results showed that the cadmium-tolerant strains were more densely concentrated in the treated Phyllostachys than in the untreated condition. This indicates that the Cd-tolerant strains were effectively enhanced by the alkali treatment of Phyllostachys spp. and that the adsorption of Cd ions to the Cd-tolerant strains was improved. In the presence of Cd^{2+} flowers only, the best removal of Cd^{2+} was achieved at a concentration of 50 mg/L, with a removal rate of 74.10%; the addition of Cd-tolerant strains resulted in a removal rate of 91.21%. When the alkali treatment was applied to the flat bamboo flowers, the removal rate was 84.36% when the concentration of Cd^{2+} was 100 mg/L. Then, when the cadmium-tolerant strain was added to the treated flat bamboo flower group, the maximum removal rate was 89.74% when the concentration of Cd^{2+} was 100 mg/L. The cadmium ion content of Cd^{2+} increased positively with increasing experimental time. In addition, the quasi-secondary correlation coefficients for cadmium ions in Lobelia were all greater than 0.9905, indicating that the adsorption kinetics were significantly correlated with the quasi-secondary kinetics. The analysis of heavy metal enrichment in Lobelia was divided into four groups, with Lobelia showing the best tolerance and cadmium adsorption capacity at a cadmium concentration of 20 mg/L. The results of super-enrichment coefficients showed that the enrichment coefficients of Lobelia ranged from 1.03 to 1.97, with values greater than 1. All these results indicate that the combination of cadmium-tolerant strains and plants can effectively remediate nuclear-contaminated soil and wastewater, thus improving soil availability and water regeneration, and improving the human living environment.

Keywords: cadmium-resistant strains; flat bamboo flowers; *Solanum nigrum*; cadmium pollution; soil remediation

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1. Introduction

With the development of China's heavy industry, heavy metal pollution is becoming increasingly serious. Investigations have shown that the groundwater and ecological environmental quality in the area around the discharge of nuclear power plants have been severely affected, and the quality of life of residents has been greatly reduced [1]. The construction and operation of nuclear power plants often generates large amounts of waste and wastewater. This waste contains many heavy metals, the most common of which are cadmium and lead. Improper disposal of this waste can cause serious contamination of soil and vegetation. Heavy metals have a certain degree of corrosiveness and often cause serious damage to land and building foundations. Meanwhile, numerous heavy metal pollution problems make it difficult to effectively ensure the safety of life and property, and the treatment of heavy metal pollution needs urgent solution. Heavy metals are metals with a specific gravity exceeding 5. Currently, 10 metals, including cadmium, lead, and copper, are classified as heavy metals in industrial production [2]. Usually, a small number of trace heavy metals are considered essential elements (i.e., nutrients) for plants/microorganisms, such as copper, iron, etc. For certain microorganisms, heavy metals mainly play a role in enhancing growth; for certain microorganisms on plants, such as rhizosphere microorganisms, they are mainly used to absorb metal ions to enhance metal activity in the soil. However, for biological needs, there is no unlimited absorption of heavy metal ions [3,4]. When the amount of ions reaches a certain level, they will have negative effects and cause serious harm to the health of organisms. Heavy metal pollution is environmental pollution caused by heavy metals or their compounds, and ranks among the most serious environmental pollutants. Emission pollution from nuclear power plants is an important source of heavy metal pollution, which not only reduces the quality of the ecological environment, but also is hazardous to human health. Cadmium pollution is a major source of pollution in nuclear power plant emissions, and mainly affects soil and water pollution. Its potential ecological risk is at a high level. When it accumulates in soil or water to a certain extent, it will cause incalculable economic and ecological losses [5,6]. Feng W et al. analyzed the relationship between soil minerals, bacteria and heavy metals and found that bacterial–soil–mineral complexes were effective in remediating heavy-metal-contaminated soils. This ultimately promotes the formation of soil aggregates, positively improves the physical structure of the soil and retards soil degradation [7]. Al-Afify et al. analyzed water, sediment and two naturally growing plant samples collected seasonally from eight sites to investigate the level of heavy metal contamination in the Nile River. The results showed that cadmium and nickel contributed 80% and 10%, respectively, to the ecological risk assessment [8]. Fayuan W's team proposed the inoculation of soil with Mycorrhizal Fungi (AMF) for the purpose of heavy metal phytoremediation in response to heavy metal contamination in sweet sorghum. The data showed that AMF inoculation reduced sweet sorghum root colonization by 16–128%, effectively reducing the inhibitory effect of HAP. AMF was able to effectively characterize sweet sorghum crops contaminated with heavy metals under soil amendments [9]. In conclusion, there is a lack of research on cadmium contamination of nuclear power plants and phyto-microbial remediation agents in the current study, i.e., ignoring the characteristics of the soil and the importance of heavy metal contamination in specific areas. Therefore, research is conducted on the remediation of cadmium-contaminated environments through the synergistic effect of plants and microorganisms, and the combination of flat bamboo flowers and cadmium-resistant strains is used to remediate and treat cadmium-contaminated wastewater to improve the effectiveness of Cd-contaminated wastewater treatment and soil remediation.

This study uses an innovative combination of cadmium-tolerant bacterial strains isolated from soil and bamboo flowers to remediate cadmium-contaminated soil. Cadmium-tolerant strains live in the rhizosphere of cadmium-rich plants. The combination of the two can affect the inter-root environment of the plant through respiration and metabolite shading, ultimately altering the sorption and morphology of heavy metals and achieving bioavailability.

2. Materials and Methods

2.1. Selection of Cadmium-Resistant Strains and Other Materials and Equipment

2.1.1. Basic Culture Medium Preparation

This study focuses on the Hongyanhe Nuclear Power Plant in Dalian, Liaoning, China. This nuclear power plant is situated in Hongyanhe Town, Wafangdian, Dalian City, Liaoning Province, and was the first nuclear power project to be approved for construction during the 11th Five-Year Plan period. The project aims to construct six-million-kilowatt pressurized water reactor nuclear power units, with the initial phase targeting the building of four units. It will be the first nuclear power plant in Northeast China [7]. This study isolated and screened cadmium-resistant strains required for the experiment from the soil of the nuclear power plant, and cultured them in a basic culture medium. The preparation of the basic culture medium is shown in Table 1.

Table 1. Preparation of the basic media.

Beef Paste (g)	Peptone (g)	Sodium Chloride (g)	Agar (g)	pH	Deionized Water (L)
3.00	10.00	10.00	15.00	7	1

In Table 1, the backup water for the basic culture medium is deionized water, with a dosage of about 1 L, sourced from the laboratory of the School of Environmental Energy, Liaoning University. No agar was added to the liquid culture medium; peptone and beef extract were used as biochemical reagent BR grade, produced by Shanghai Fanke Biotechnology Co., Ltd. The concentrations of NaOH and HCl used for the culture medium's pH were both 0.1 mol/L.

2.1.2. Experimental Equipment and Instruments

In general, themicroorganisms used in actual experiments to repair heavy metal pollution from nuclear power plants are cultured on a large scale under specific conditions. This study mainly observed the effect of Cd^{2+} on microbial morphology under different conditions to determine the removal efficiency of Cd^{2+} by microorganisms. The experimental equipment and instruments are shown below (Table 2).

Table 2. Main instruments and equipment of the experiment.

Instrument	Model	Manufacturer
Electronic analytical balance	AL204	Mettler toledo instruments (Shanghai) Co., Ltd.
Box-type resistance furnace	SX2-4-10Z	Shanghai youyi instrument Co., Ltd.
Vertical double-layer double-door large-capacity shaking table	SPH-2 102	Shanghai shiping experimental equipment Co., Ltd.
Electric blast constant-temperature drying oven	DGG-9070B	Shanghai senxin experimental instrument Co., Ltd.
Biochemical incubator	SHX70III	Shanghai jianzhu instrument Co., Ltd.
Atomic fluorescence spectrophotometer	AFS-230E	Beijing haiguang instrument Co., Ltd.

2.1.3. Material Handling Methods

The cadmium-resistant strain was isolated from soil samples around the nuclear power plant and identified as Serratia marcescens after multiple analyses of morphological, physiological, biochemical, and molecular biological characteristics. Experiments on the strain's tolerance to heavy metals have shown that the strain is not only highly tolerant to metals such as manganese and zinc, but also highly resistant to them. In other words, the strain has a wide tolerance range and is highly adaptable, which is important for soil remediation.

Cadmium-resistant strains obtained from contaminated soil were separated using the coating plate method. A 10 g soil sample was selected from the area polluted by cadmium emitted by the nuclear plant, and was put into a conical flask with 90 mL sterilized liquid beef extract peptone with glass beads under a sterile environment. The obtained conical flask was placed into a shaker and shaken to obtain a uniformly mixed soil–liquid sample [8,9]. During the process, the shaking table speed and temperature were set to 150 rmp and 37 °C, and oscillated continuously for 12 h. The uniformly mixed soil–liquid sample was applied on different agar culture media, with 4 replicates set for each group. After completing the coating operation, the obtained culture dish was placed upside down in a 28 °C biochemical incubator for 24 h. Then, the strains were lined and inoculated on a culture dish containing 100 and 200 mg/L medium. After completing the line, the culture dish was inverted. Afterwards, it was placed in a biochemical incubator with set parameters for 24 h to observe the specific growth of the cadmium-resistant strains. Finally, further isolation and purification of the obtained cadmium-resistant strains was carried out, and they were stored in a refrigerator at 4 °C for future use. Cadmium-resistant bacteria were identified using 16SrDNA technology and submitted to Shanghai Shenggong Biotechnology Co., Ltd. for testing.

This study selected normally growing flat bamboo flowers as the experimental materials. During the process, the flat bamboo flowers were first treated with sterilization and dried to a constant temperature. Afterwards, they were treated with NaOH solution for a period of time, rinsed and dried, and stored for future use.

2.2. Wastewater Source and Data Analysis

2.2.1. Wastewater Source

The wastewater used in the experiment was taken from the laboratory of the School of Environmental Energy, Liaoning University. Aquatic flat bamboo flowers were selected as the experimental material, and all seedlings were from a large flower company in Shenyang, Liaoning Province. Before the official experiment, the selected plants were subjected to a 7-day recovery culture to ensure good root growth. In addition, the experiment was conducted on flat bamboo flowers, flat bamboo flowers with cadmium-resistant strains, treated flat bamboo flowers, treated flat bamboo flowers with cadmium-resistant strains, and a blank control, with a total of five treated and four control groups [10,11]. The concentrations of cadmium in each group were 0 mg/L, 50 mg/L, 100 mg/L, and 200 mg/L, imitating the pollution of cadmium in water bodies. The experiment was repeated for all groups three times, and the hydroponic experiment was conducted using a 1 L container. The experiment was conducted in the laboratory of the School of Environmental Energy to ensure sufficient lighting, and deionized water prepared in the laboratory was used to supplement the evaporated water of the flat bamboo flowers [11,12]. The experiment was carried out for 12 days, and sampling analysis was conducted every 3 days to determine the removal effect of aquatic plants on cadmium concentration in water. The treatment method for flat bamboo flowers was the same as above.

2.2.2. Data Analysis and Processing Methods

The method of processing flat bamboo flower samples was as follows: The whole plant was removed and placed in different containers. The containers were placed in a cool and dry place to drain all the water, and then the flat bamboo flower was placed in an oven [13,14]. The oven temperature was set to 105 °C for 30 min for blanching treatment, and then the flat bamboo flowers were dried to a constant weight at 70 °C. Finally, the obtained materials were placed in a sealed bag, properly numbered, and stored for future use [15,16].

The method for treating wastewater samples was as follows: A certain amount of test liquid was taken each time, placed in a pre-cleaned container, and marked for the next step of operation.

To avoid the influence of random errors during the experiment, the experiment was repeated three times under the same experimental conditions for all groups. If the data from the repeated experiments were very close, then the results of that experiment had effectively excluded the influence of chance and were more accurate. The final data values of the experimental procedure were taken as the average of the replicate groups. The data were processed using Excel 2007 software and graphically processed using Origin software 2020. The cadmium content was measured in the sample in the laboratory of the Environmental Energy College, and an atomic fluorescence spectrophotometer was used for detection [17].

2.2.3. Adsorption Kinetics

When using flat bamboo flowers to treat cadmium in wastewater, adsorption effects may occur during the process. In general, without considering the movement of solutes in the liquid film around the adsorbent surface, the adsorption process of porous solids has three stages. Ion transfer and internal diffusion rate significantly influence the diffusion process of ions in the liquid phase [18,19]. In the experiment of ion diffusion, the diffusion rate is represented by the square root of time, as shown in Equation (1).

$$K_p = Q/\sqrt{t} \tag{1}$$

In Equation (1), Q represents the amount of heavy metals contained in the flat bamboo flower body at time t, in mg/L; K_p represents the internal diffusion rate constant, in units of $\mathrm{mg \cdot g^{-1} \cdot min^{-0.5}}$. Then, by simulating the data obtained from different kinetic models and the adsorption capacity of heavy metals, the quasi-first- and second-order kinetic equations can be accurately distinguished [20]. This equation was used to test the adsorption of heavy metals by flat bamboo flowers, and the expression of the quasi-first-order equation is shown in Equation (2).

$$\ln(q_e - q_t) = \ln q_e - k_1 t \tag{2}$$

In Equation (2), q_e represents the amount of heavy metal adsorption; q is the adsorption amount over time, in mg/g; k_1 is the adsorption rate constant. The equation is obtained by integrating between $t = 0$ and $t = t$, $q = 0$ and $q = q_e$, as shown in Equation (3).

$$\log(q_e - q) = \log q_e - (k_1/2.303)t \tag{3}$$

If the adsorption change conforms to the quasi-first-order kinetic equation, there should be a good linear relationship between $\log(q_e - q)$ and t. In most cases, the fitting effect of the quasi-first-order kinetic equation on the adsorption of flat bamboo flowers was not good, so a quasi-second-order kinetic equation is proposed for simulation. The equation's conclusion implies that the occupancy rate of adsorption sites increases proportionally to the square of the number of unoccupied adsorption sites [21,22]. The quasi-second-order kinetic equation is shown in Equation (4).

$$dq_t/dt = k(q_e - q_t)^2 \tag{4}$$

By integrating again, Equation (5) is obtained.

$$t/q_t = 1/k_2{q_e}^2 + t/q_e \tag{5}$$

In Equation (5), k_2 is the secondary adsorption rate constant. If the fitting process conforms to the quasi-second-order kinetic equation, then there is a corresponding linear relationship between t/q and t.

2.3. Polluted Soil Selection and Data Analysis

2.3.1. Tested Soil Selection and Physicochemical Properties

The soil used for the research experiment was taken from a field near the nuclear power plant, and laboratory-planted *Solanum nigrum* was selected as the experimental material. The *Solanum nigrum* seeds were purchased from a large flower market in Shenyang. The purchased seeds were spread flat on a wet cloth and then placed in a biochemical incubator at 28 °C for 7 days; the seedlings with better growth were selected and transplanted to prepared plant pots [23,24]. When the *Solanum nigrum* had grown to about 5 cm, a total of 2 kg of fresh soil was passed through a 2 mm sieve, and an appropriate amount of distilled water was added to make the soil moisture suitable for plant survival and growth. All transplanted plants were numbered in the pot and cultured together for 2 days to observe their survival status. A new round of cultivation was then started for 7 days. When the plants were growing well, the prepared $CdCl\text{-}2.5H_2O$ solutions of different concentrations were evenly added to the potted plants. The concentration of individual Cd^{2+} contamination was set at 0, 20, 40, and 60 mg/kg, making a total of 4 concentration levels. Cultivated cadmium-resistant strains were inoculated under Cd^{2+} pollution, and laboratory deionized water was added to reach the soil field capacity. Watering was performed daily based on the actual soil moisture capacity. The amount of irrigation was generally between 50 and 100 mL [25,26]. On this basis, an experimental period of 45 days was used, with fertilization and plant height measurements carried out every 15 days. All plants were harvested at the end of the experiment. The specific physical and chemical properties covered by the experimental soil are listed below (Table 3).

Table 3. Basic physicochemical properties of the experimental soil.

pH	Total P(g/kg)	Effective P (g/kg)	Total N (%)	Total Cd(%)	Effective Cd (g/kg)	Effective K(g/kg)	Quick-Acting k(g/kg)
5.90	0.115	14	0.19	0.07	0.32	15	27.5

2.3.2. Data Analysis and Processing

The method for processing *Solanum nigrum* samples was as follows: First, the plants were taken out along with the potted planting soil. Then, the collected plants were cut into two parts—aboveground and underground at the connection between the soil and air—and the plant roots were rinsed with deionized water. The washed mud and water were collected as part of the soil to be tested, and then deionized water was used to clean the roots of *Solanum nigrum* for a second time [27,28]. The aboveground and underground parts of the plant were placed in different containers and aired in a cool place with the water drained. The oven temperature was set to 105 °C, continuing for 30 min to blanch the sunflower, and dried to constant weight at 70 °C. The dry weight of each part of the plant was measured, numbered in a sealed bag, and stored for future use [29,30].

The method for handling soil samples was as follows: Soil near and washed out from the roots of plants was collected. A certain amount of soil was extracted using two quartering methods. The soil samples were numbered, placed in a cool place in the laboratory for drying with impurities thoroughly removed, numbered in bags, stored for future use, and sent to relevant testing units for testing [31,32].

Bioconcentration factor (BCF) represents the concentration of heavy metals in plant samples/soil. Biological transfer factor (BTF) is the heavy metal content in the aboveground part/underground parts.

2.4. Risk Assessment Methods for Microbial–Plant Collaborative Remediation of Cd-Contaminated Environment

2.4.1. Pollution Environmental Assessment Model and Risk Assessment Procedure

The pollution environment assessment model mainly includes key elements such as pollutants, human exposure to pollution media, pollutant migration pathways, and the contact mode between pollutants and the environment, which can comprehensively characterize the pollutants in the polluted environment. It is a relationship model of pollutants that directly affect the health of future workers and residents in the surrounding area and environment by entering the human body through environmental media such as water, soil, and the atmosphere. Through the analysis and testing of samples from the study area, it can be determined that the main heavy metal pollutant in the study area is Cd^{2+} in soil [33]. Therefore, the source of soil and wastewater contamination that pose a risk to human health in the selected study area is the heavy metal cadmium in the vicinity of nuclear power plants. The exposure pathways of the pollutants are shown below.

In Table 4, the pollutants reflected by exposure pathways are mainly from the source of pollution to the human body, where the characteristics of the pollutants, the purpose of the selected object, and the activities of the population are jointly determined. According to domestic and international research and environmental pollution risk assessment practices, the main process of risk assessment usually includes four steps: pollution analysis, exposure analysis, toxicity analysis, and risk assessment.

Table 4. Pollutant exposure pathways.

Source	Pollutant Exposure Pathways
Surface soil	Direct intake Human skin contact Inhaling volatile vapors from surface soil Inhaling volatile vapors from surface soil
Subsoil	Inhaling vapor that migrates from the lower soil layer into the room

2.4.2. Risk Assessment Calculation Model

The risk assessment model consists of three aspects: pollutant exposure calculation, pollutant toxicity calculation, and risk calculation. The first two calculations are based on the model recommended in the "Technical Guidelines for Risk Assessment of Polluted Sites" issued by the Ministry of Environmental Protection of China [34].

3. Microorganisms and Plants in the Treatment Analysis and Risk Assessment of Cadmium-Contaminated Wastewater and Soil Remediation

3.1. Growth Analysis of Cadmium-Resistant Strains in Different Concentrations of Cd^{2+} Solution

This study used software such as Word 2016, Excel 2007, Origin 2020, Visio 2016, and SPSS24.0 to conduct statistical analyses of all experimental data. The sample was measured using Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES). The final sample obtained from the experiment was sent to Guangzhou Zhebo Testing Technology Co., Ltd. [35]. Firstly, the growth of cadmium-resistant strains in solutions with different Cd^{2+} concentrations was analyzed, and the specific results are shown in Figure 1.

In Figure 1, the bacterial communities of cadmium-resistant strains exhibited different forms with or without Cd^{2+}. When the cadmium concentration was 0, the growth of cadmium-resistant strains was more likely to exhibit a single and dispersed state. When the cadmium concentration was not 0, the cadmium-resistant bacteria exhibited high aggregation. As the concentration of cadmium continued to increase, the growth of cadmium-resistant strains began to move closer from the periphery to the middle; the higher the degree of aggregation of cadmium-resistant strains, the less contact they had with external cadmium ions, and the stronger their resistance. At this time, the flat bamboo flowers were not treated, and in all the spectra, the morphology of cadmium-resistant strains was relatively dispersed.

In Figure 2, there is a significant difference in the morphology of cadmium-resistant strains measured from the treated flat bamboo flowers compared to the untreated cadmium-resistant strains. After the treatment of the flat bamboo flowers, the morphology of the cadmium-resistant strains was more aggregated and mostly adhered to the surface of the treated flat bamboo flowers due to their larger attachment area and contact points. Comparing the growth status of bacteria with different cadmium concentrations, the cadmium-resistant strains in the treated flat bamboo flowers were more dense than those without treatment. This indicated that the treatment of flat bamboo flowers can effectively improve the tolerance of cadmium-resistant strains to cadmium ions, which was conducive to the adsorption of cadmium-resistant bacteria [36].

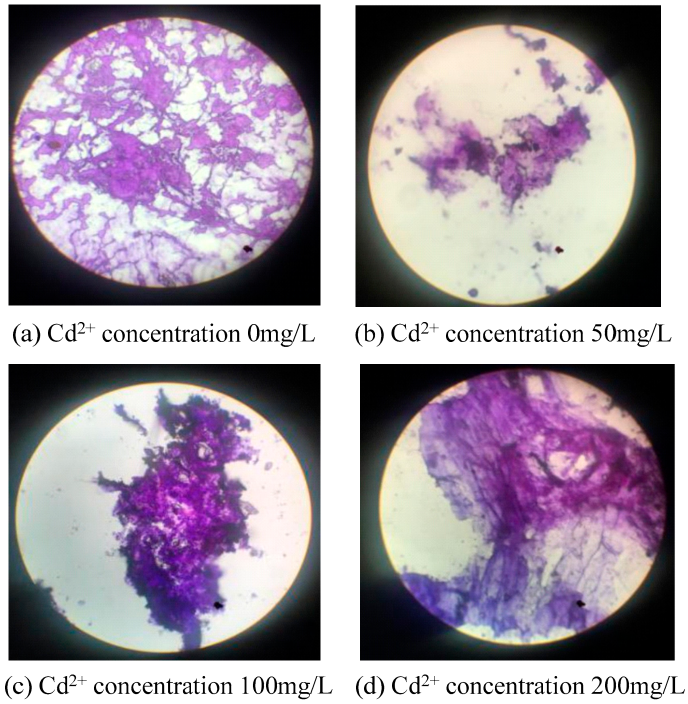


Figure 1. Growth morphology of cadmium-resistant strains under different cadmium concentrations.

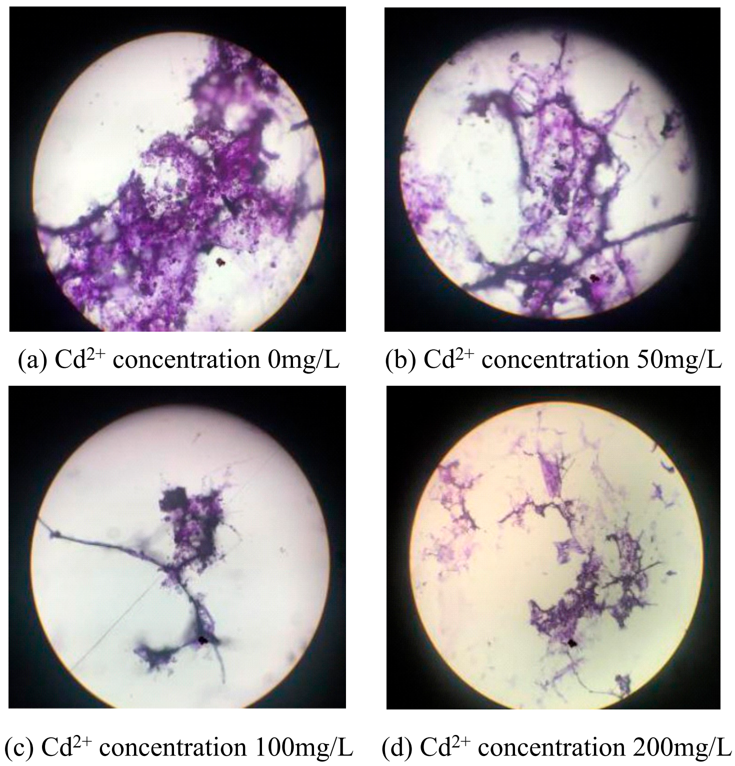


Figure 2. Growth of cadmium-resistant strains at different cadmium concentrations after treatment.

3.2. Analysis of the Effect of Flat Bamboo Flower with Cadmium-Resistant Strain in the Treatment of Cadmium-Contaminated Wastewater from Nuclear Discharge

To study the specific effect of the combination of flat bamboo flowers and cadmium-tolerant strains on the treatment of cadmium-contaminated wastewater from nuclear emissions, cadmium-tolerant strains isolated and screened from soil contaminated with cadmium from nuclear emissions were selected for hydroponic experiments [37,38]. The specific validation of the treatment effect of the flat bamboo flowers and cadmium-resistant strain on cadmium-polluted water bodies was conducted. Among them, the removal rate represented the ratio of the heavy metal content adsorbed and transferred to the interior of the plant to the total amount of metal in the solution, and the magnitude of the value can indicate the effectiveness of the flat bamboo flower in removing heavy metals from wastewater. The cadmium removal rate (adsorption rate) by the combination of flat bamboo flowers and cadmium-resistant strains under different treatment conditions is shown in Figure 3.

Comparative analysis was conducted on the removal rates of four control groups: flat bamboo flower, flat bamboo flower+cadmium-resistant strain, processed flat bamboo flower, and treated flat bamboo flower+cadmium-resistant strain. Figure 3a shows that in the presence of flat bamboo flower alone, when the concentration of Cd^{2+} was 50 mg/L, the removal effect of flat bamboo flowers on Cd^{2+} was the best, with a removal rate of up to 74.10%. Adding the cadmium-resistant strain to flat bamboo flower significantly enhanced their treatment effect on Cd^{2+}, but the trend of removal rate change was similar to that without adding cadmium-resistant strains. The maximum removal rate was still recorded when the concentration of Cd^{2+} was 50 mg/L, reaching 91.21%. Later, when the concentration of Cd^{2+} increased again, the removal rate gradually decreased. When only flat bamboo flowers were present and the concentration of Cd^{2+} was 300 mg/L, the removal rate was the lowest, at only 37.45%. Figure 3b shows that the alkali-treated flat bamboo flowers had a significant positive effect on the removal rate of Cd^{2+}. When the concentration of Cd^{2+} was 100 mg/L, there was a maximum removal rate of 84.36%; after that, when the concentration of Cd^{2+} was increased again, the removal rate decreased instead of increasing. The main reason may be that the adsorption of heavy metal ions on the surface of the treated flat bamboo flowers increased under the influence of the alkaline environment compared to the untreated group, resulting in an enhanced adsorption capacity for Cd^{2+}. The removal of Cd^{2+} by adding cadmium-tolerant strains to the treated flat bamboo flower group was significantly higher than that of the group without the addition of cadmium-tolerant strains under different concentration conditions; there was a maximum removal rate of 89.74% when the concentration of Cd^{2+} was 100 mg/L; the removal rate was lower—35.12%—at a Cd^{2+} concentration of 300 mg/L. Comparing the above results, it is clear that the flat bamboo flower has a strong ability to adsorb Cd^{2+} and is a good material for Cd^{2+} removal. The alkali-treated flat bamboo flower had a better effect on solutions with higher concentrations of Cd^{2+}. This indicated that the addition of Cd-tolerant strains effectively promoted the treatment effect of flat bamboo flowers on Cd^{2+}, with an increase of 15.64% compared to the maximum removal rate of normal flat bamboo flowers and 5.38% compared to the maximum removal rate of treated flat bamboo flowers. The internal diffusion curves of Cd^{2+} adsorption by flat bamboo flowers under different treatment conditions are shown in Figure 4.

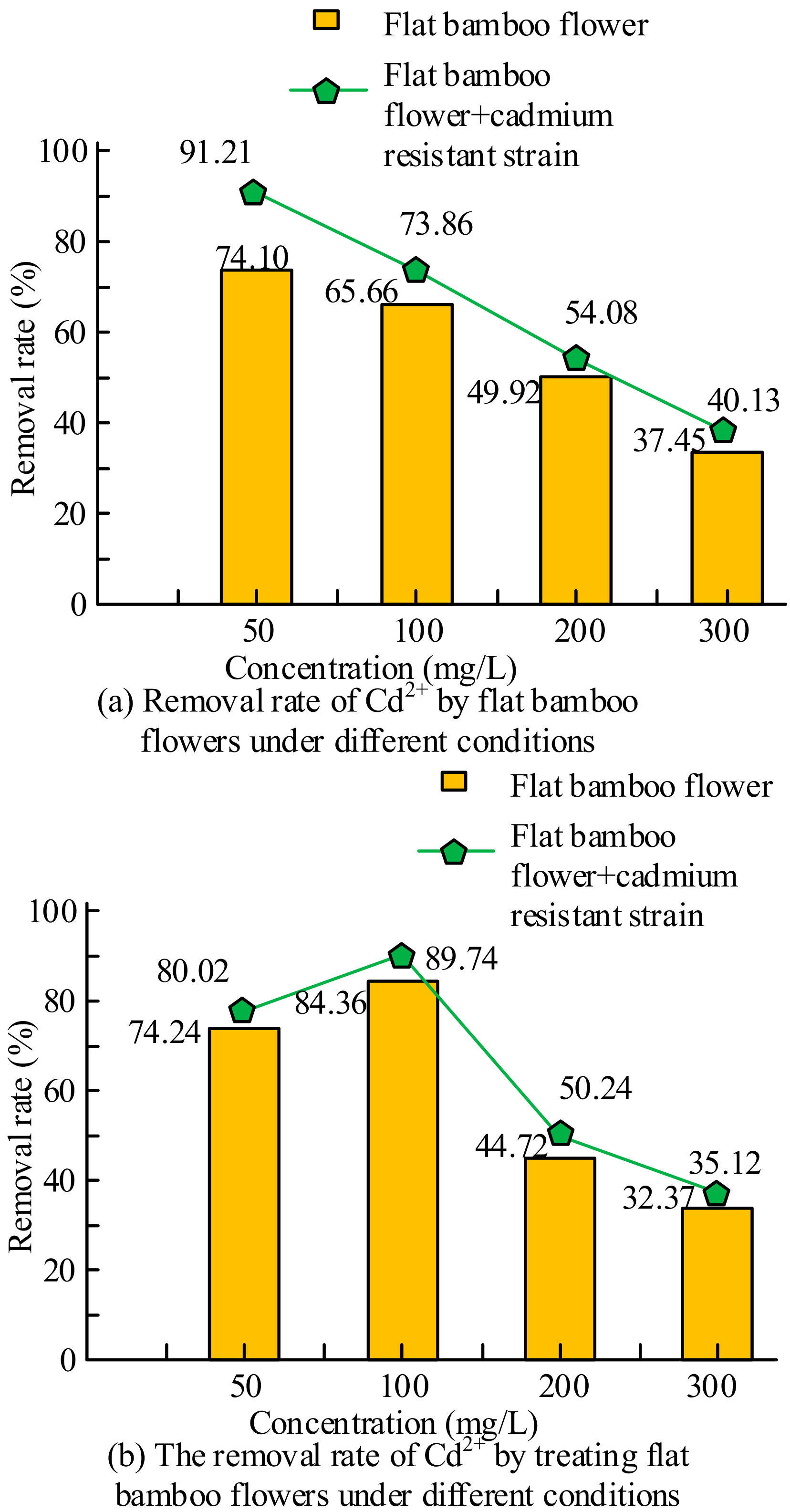
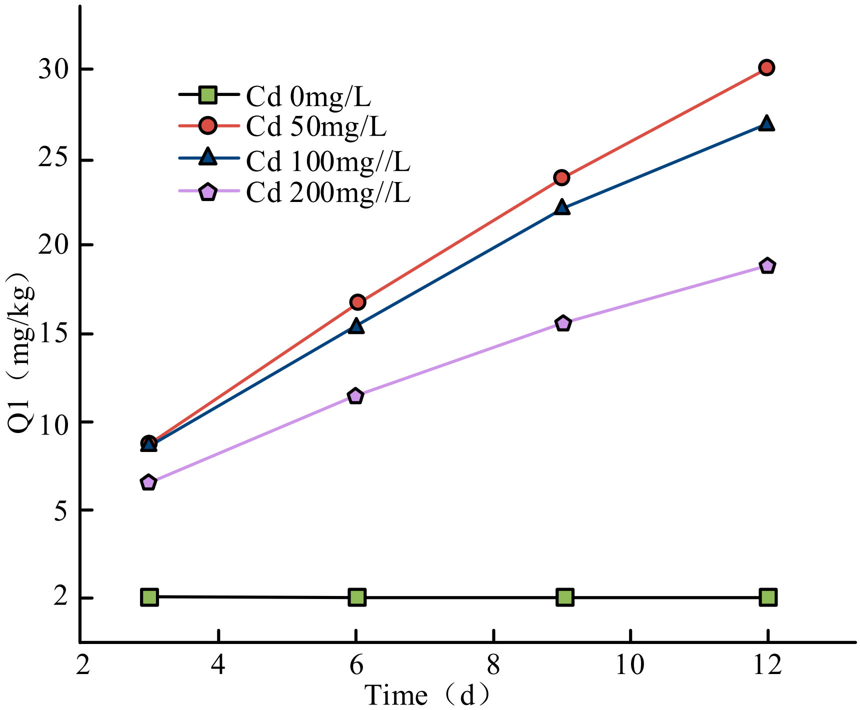
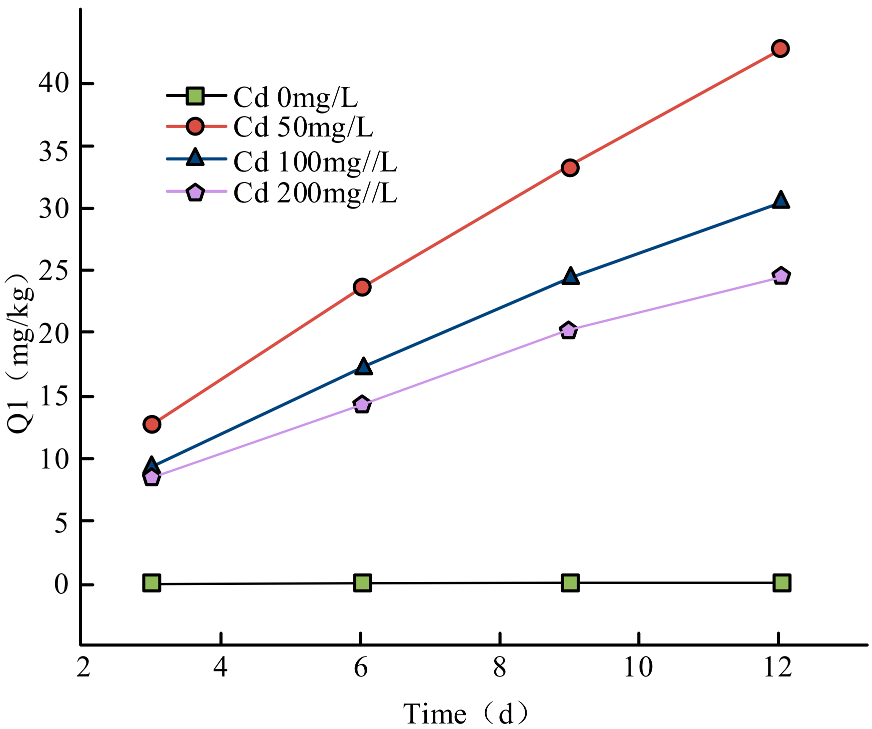


Figure 3. Removal rate of cadmium ions by flat bamboo flowers under different treatment conditions.

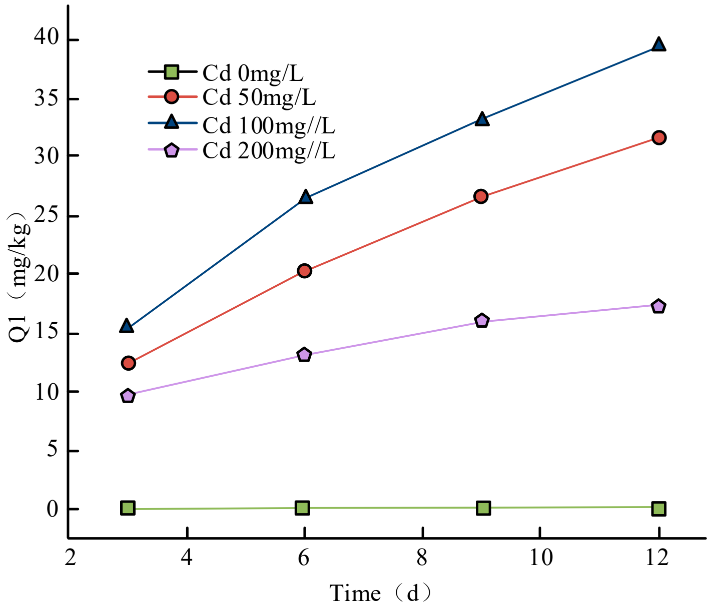


(a) Flat bamboo flower

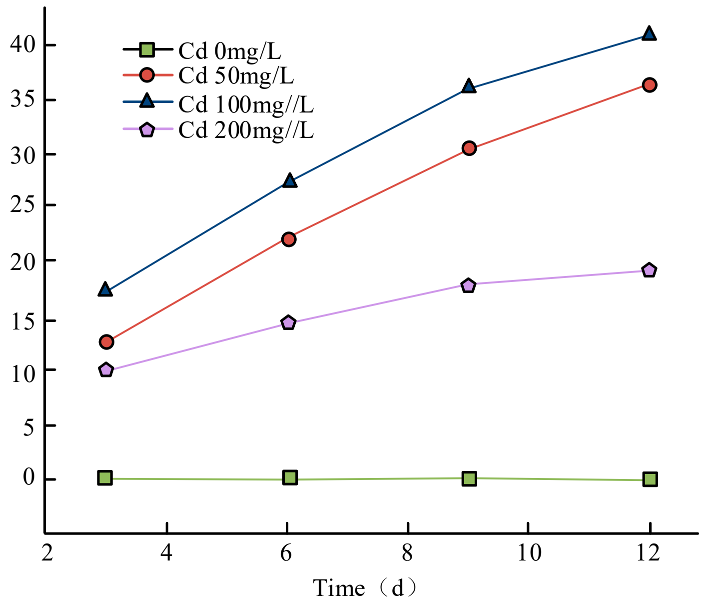


(b) Flat Bamboo Flower - Cadmium Resistant Strain

Figure 4. *Cont.*



(c) Processed flat bamboo flowers



(d) Processed flat bamboo flowers - cadmium resistant strains

Figure 4. Internal diffusion curve of adsorbed cadmium ions under different treatment conditions.

In Figure 4, under four different conditions, the q_t to $t^{\frac{1}{2}}$ curve of the flat bamboo flower on Cd^{2+} is a straight line crossing the origin only when the concentration of Cd^{2+} in the solution is 0. In other cases, the internal diffusion curve was not linear.

The cadmium ion content in the flower increased positively with the increase of the experimental time under the influence of different cadmium concentrations. When the experimental time was 12 days, the cadmium ion concentration had a maximum value in all groups. As shown in Figure 4a,b, the maximum cadmium ion concentrations in *C. lentiscus* were 29.97 mg/kg and 42.64 mg/kg when the cadmium ion concentration was added at 50 mg/L. As shown in Figure 4c,d, the maximum cadmium ion concentrations in *C. lentiscus* were 39.98 mg/kg and 40.77 mg/kg when the cadmium ion concentration was added at 100 mg/L.

All curve changes indicate that the adsorption of cadmium ions by flat bamboo flowers exhibited an internal diffusion trend, which was divided into two stages. The slope of the straight line in the first stage was relatively large, indicating a faster initial rate of internal diffusion. After entering the second stage, the straight line began to flatten, indicating that the flat bamboo flower quickly reached an adsorption equilibrium state after being immersed in the wastewater solution. With time, the adsorption rate slowed down and the effect was not as significant as before, indicating that the interaction between the adsorption site and Cd^{2+} became stronger. The ion diffusion parameters during the adsorption process of Cd^{2+} by flat bamboo flowers are shown in Table 5.

Table 5. Intra-ion diffusion parameters during the adsorption of Cd^{2+}.

Concentration (mg/L)	**Cd^{2+} Internal Diffusion Equation**							
	Flat Bamboo Flower		**Flat Bamboo Flower–Cadmium Resistant Strain**		**Processed Flat Bamboo Flowers**		**Processed Flat Bamboo Flower–Cadmium-Resistant Strain**	
-	K_p	R^2	K_p	R^2	K_p	R^2	K_p	R^2
50	2.7370	0.8553	10.9196	0.8879	8.7105	0.9523	9.8011	0.9060
100	7.0526	0.8804	7.8883	0.6176	10.9112	0.9528	11.5366	0.9639
200	5.0730	0.9145	6.5347	0.4279	5.2296	0.9704	5.7189	0.9805
300	4.2136	0.9251	0.5645	0.3548	4.2518	0.9701	6.2571	0.9701

As shown in Table 4, the correlation coefficients R^2 were 0.8553, 0.8804, 0.9145, and 0.9251 when the concentrations of Cd^{2+} were 50 mg/L, 100 mg/L, 200 mg/L, and 300 mg/L, respectively, in the presence of only flat bamboo flowers. The addition of the cadmium-tolerant strain to the flat bamboo flowers had a maximum correlation coefficient of 0.8879 at a cadmium concentration of 50 mg/L. At a cadmium ion concentration of 200 mg/L, the alkali-treated flat bamboo flowers had maximum correlation coefficients of 0.9704 and 0.9805 with the treated and added cadmium-tolerant strain group, respectively. collectively, it can be seen that all the correlation coefficients for internal diffusion R^2 were less than 0.99. This indicates that the process of sorption kinetics is not only controlled by internal diffusion, but may also be related to quasi-secondary kinetics. The quasi-secondary kinetic equations are used to describe the behavior of the entire sorption process and can generally be used to reflect the complete chemical mechanism. This study simulates all reaction data for the full process accordingly, see Figure 5.

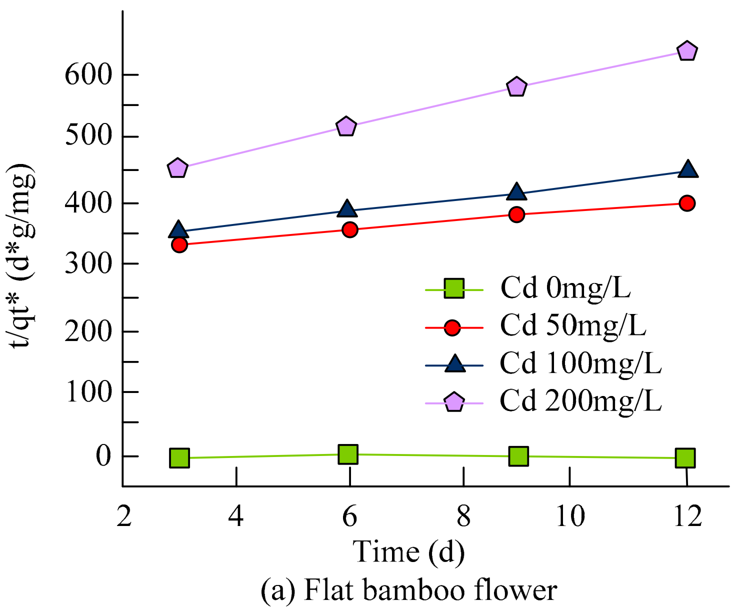
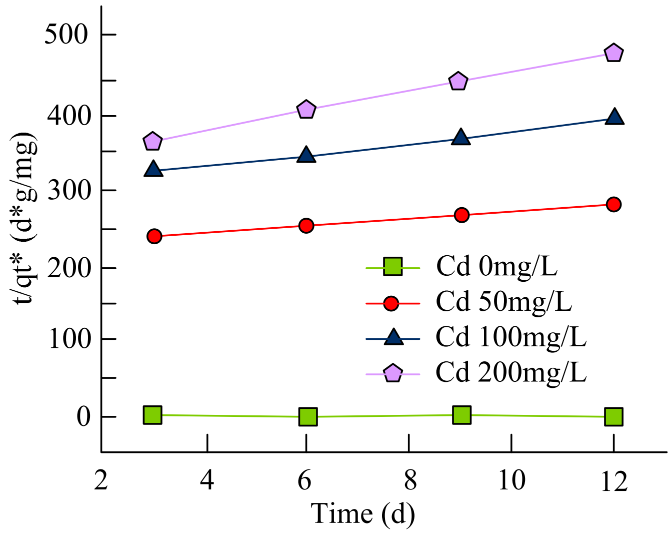
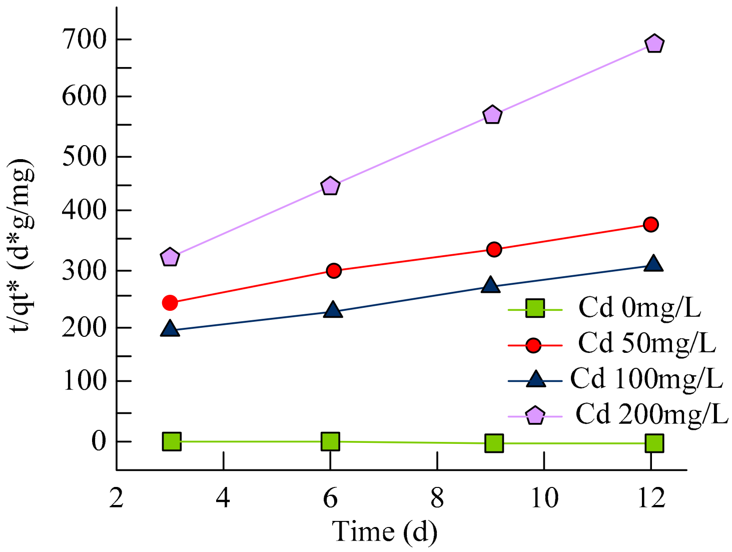


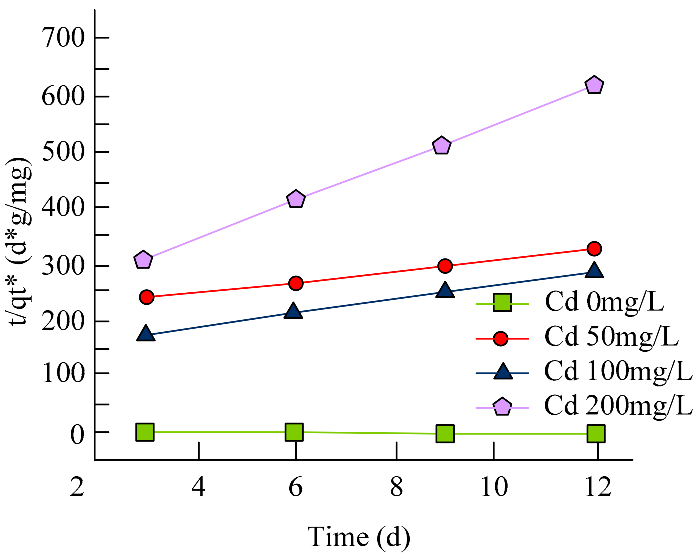
Figure 5. *Cont.*



(b) Flat bamboo flower-cadmium resistant strain



(c) Processed flat bamboo flowers



(d) Processed flat bamboo flowers-cadmium resistant

Figure 5. Second-order kinetic fitting curve of cadmium ion adsorption under different treatment conditions.

In Figure 5, all the data obtained from the experiment showed an upward trend as the number of days of the experiment increased. In four different cases, there was a straight line through the origin only when the concentration of Cd^{2+} in the solution was 0. In other cases, all the fitted curves showed a significant slope trend. All fitting curves showed that the flat bamboo flower had a strong adsorption capacity for Cd^{2+}. The second-order kinetic constants for the adsorption of flat bamboo flower are shown in Table 6.

Table 6. Second-order kinetic constants of floral adsorption.

/	Cd^{2+} Quasi-Second-Order Kinetic Equation				
	Concentration	Qe_{ex} **(mg/L)**	K	Qe **(mg/L)**	R^2
Flat bamboo flower	50	36.8	0.0182	34.53	0.9917
	100	65.66.	0.0106	67.58	0.9908
	200	99.84	0.0022	91.83	0.9945
	300	99.98	00.0021	90.28	0.9932
Flat bamboo flower–cadmium-resistant strain	50	45.5	0.054	43.2	0.9968
	100	73.86	0.031	74.43	0.9985
	200	54.08.	0.0019	54.42	0.9989
	300	49.79	0.0015	62.35	0.9981
Alkali-treated flat bamboo flowers	50	37.12	0.0048	38	0.9911
	100	84.35.	0.0032	85.62.	0.9963
	200	89.44.	0.0018	93.68	0.9941
	300	89.22	0.0011	92.81	0.9924
Alkali-treated flat bamboo flowers–cadmium-resistant strain	50	39.01	0.0054	38.48	0.9973
	100	89.74	0.0018	88.12	0.9906
	200	100.48	0.0017	104.64	0.9939
	300	100.06	0.0014	100.05	0.9937

In Table 6, the sorption coefficient Qe increases and then decreases with increasing cadmium ion concentration when only flat bamboo flowers are available. When the cadmium ion concentration was 50 mg/L, 100 mg/L, 200 mg/L, and 300 mg/L, the adsorption Qe was 34.53, 67.58, 91.83, and 90.28, respectively. The equilibrium adsorption and the quasi-secondary kinetic constants did not increase after the cadmium ion concentration was increased to 50 mg/L. The maximum value of K was 0.0182. When the cadmium-tolerant strain was added to the Cd solution, it was clear that both the equilibrium adsorption and the quasi-secondary kinetic constants increased. However, the value of K still did not increase with increasing concentration and was 0.0540, 0.0310, 0.0019, and 0.0015, in that order. The secondary correlation coefficients R^2 were greater than 0.9905 for the entire adsorption process. This indicates that the linear correlation of the research model was good. The entire adsorption process of Cd^{2+} by flat bamboo flowers was consistent with the simulation of the quasi-second-order kinetic equation. Meanwhile, the equilibrium adsorption capacity of Cd^{2+} calculated by this equation was very close to the experimental values. Correlation analysis showed that it can well explain the kinetic behavior of Cd^{2+} adsorption on flat bamboo flowers.

3.3. Analysis of the Effect of Solanum nigrum–Cadmium-Resistant Strain in Heavy Metal Soil Remediation

This study used a pot experiment to explore the effect of the hyper-accumulating plant *Solanum nigrum*–cadmium-tolerant strain on cadmium enrichment in soil. The transfer coefficient is generally used to determine whether a plant conforms to the characteristics of hyper-accumulating plants, which represents the pattern of heavy metals being transferred from soil to the plant body [39,40]. The effect of Cd^{2+} concentration on the dry weight of *Solanum nigrum* and the distribution pattern of Cd^{2+} in the plants are shown in Figure 6.

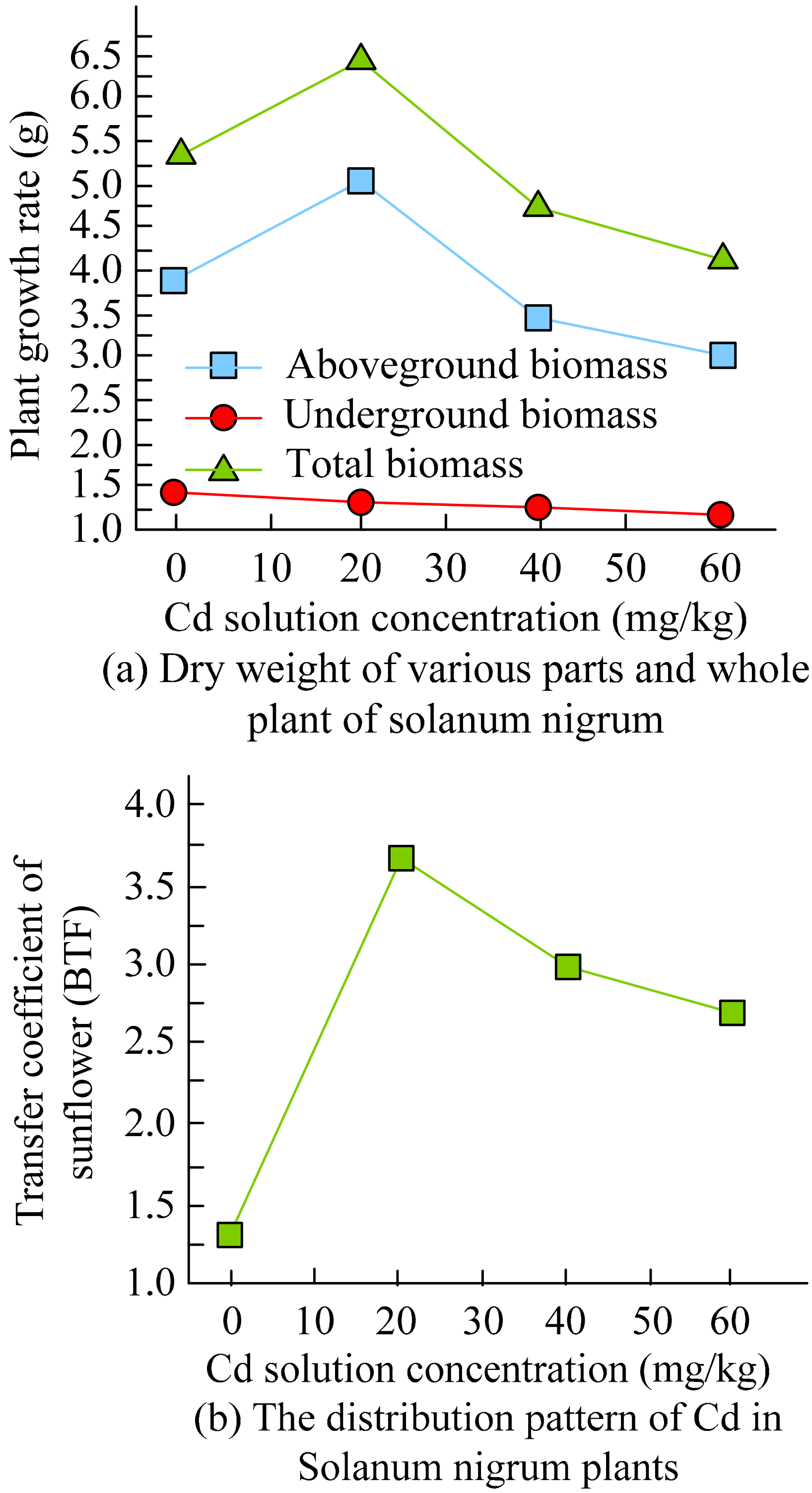


Figure 6. Dry weight of different parts and whole plant.

In Figure 6a, the dry weight of the plant underwent significant changes with the continuous increase in Cd^{2+} concentration. The dry weight of the root gradually decreased, and the dry weight of the aerial part and the whole plant first increased and then decreased, with a significant difference. The aerial part reached 2.69–3.76 times that of the root. When the concentration was low (20 mg/kg), the plant had some ability to resist Cd^{2+} pollution; when the concentration increased (40–60 mg/kg), it inhibited plant growth. The dry weight of the plants in the experimental group was significantly lower. Overall, *Solanum* *nigrum* showed the characteristics of highly enriched plants with a strong tolerance to Cd^{2+}. As shown in Figure 6b, the transfer coefficient first increased and then decreased as the concentration of Cd^{2+} increased. The transfer coefficient was at its maximum when the concentration of Cd^{2+} was around 20 mg/kg. As the concentration of Cd^{2+} continued to increase, the transfer coefficient no longer increased but began to decrease. This indicated that the transfer of Cd^{2+} from the roots of *Solanum nigrum* to the aboveground part was limited. The content of heavy metals in soil under different conditions of action is shown in Table 7.

Table 7. Cadmium content in the soil (mg/kg).

Cd^{2+} Concentration(mg/kg)	Blank Control		*Solanum nigrum*	
	Cadmium-Resistant Strain	Non-Cadmium-Resistant Strain	Cadmium-Resistant Strain	Non-Cadmium-Resistant Strain
0	18.64	20.01	10.64	10.01
20	48.24	46.66	22.92	20.66
40	104.30	98.19	80.32	79.03
60	135.91	136.52	108.73	100.62

Table 7 shows that, when there were no cadmium-tolerant lines, the heavy metal content in the soil where *Solanum nigrum* was grown decreased significantly with increasing cadmium concentration. When the cadmium concentration was 60 mg/kg, the highest reduction in cadmium was 35.9 mg/kg. When the cadmium concentration was 0, but cadmium-tolerant strains were added, the cadmium concentration significantly decreased by 8 mg/kg, indicating that cadmium-tolerant strains significantly promoted the absorption of cadmium elements by *Solanum nigrum*. When the cadmium concentration was 20 mg/kg, cadmium-tolerant strains promoted enhanced absorption of heavy metals by *Solanum nigrum*. However, as the concentration increased, the effect began to weaken. The combination of *Solanum nigrum* and cadmium-tolerant strains can better absorb heavy metals in soil, and the best effect was achieved at a cadmium concentration of 20 mg/kg. The Cd^{2+} content in different parts of *Solanum nigrum* Cadmium-tolerant strains were added is shown in Table 8.

Table 8. Cd^{2+} content in each parts of the nightshade.

Cd^{2+} Concentration (mg/kg)	*Solanum nigrum* +Cd			*Solanum nigrum* + Cadmium-Resistant STRAIN + Cd		
	Aboveground Part	Underground Part	Whole Plant	Aboveground Part	Underground Part	Whole Plant
0	48.24	36.43	84.67	56.78	40.99	97.77
20	153.51	68.17	221.67	185.95	76.18	262.13
40	164.32	89.45	253.77	196.07	105.72	301.79
60	165.42	116.28	281.7	203.61	141.6	345.21

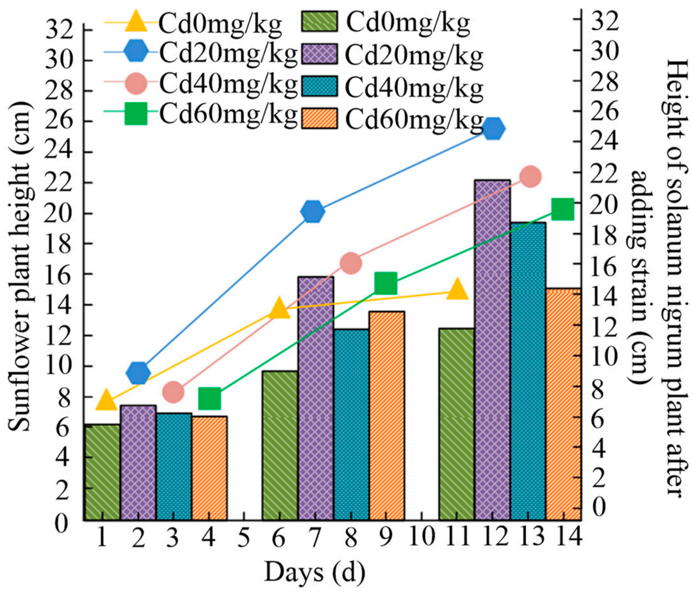
As shown in Table 8, the amount of Cd^{2+} in different parts of *Solanum nigrum* showed an increasing trend with increasing Cd^{2+} content in the soil, and the amount of Cd^{2+} in the aboveground part was greater than that in the underground part. When the concentration of Cd^{2+} in the soil was 20 mg/kg, the measured heavy metal content in the aboveground part was 153.51 mg/kg, which was consistent with the adjacent standard for hyper-accumulating plants. When cadmium-tolerant strains were added, the amount of Cd2 in the whole plant of *Solanum nigrum* increased significantly; at high concentration, the amount extracted from the aerial part increased more. Overall, cadmium-tolerant strains can effectively promote the remediation of Cd2 in soil by *Solanum nigrum*. The super-enrichment coefficient is shown in Table 9.

As shown in Table 9, the enrichment coefficient of *Solanum nigrum* ranged from 1.03 to 1.97, with all transfer coefficients greater than 1. This indicated that *Solanum nigrum* met the critical content characteristics of Cd^{2+}-enriched plants. As the concentration of Cd2 continued to rise, when the concentration of Cd^{2+} was 20 mg/kg, the maximum transfer coefficient of 2.45 was reached, indicating that *Solanum nigrum* reached the critical content standard for the super-accumulation of Cd^{2+}. When the concentration of Cd^{2+} increased again, the enrichment coefficient gradually decreased. This indicated that the cumulative effect of *Solanum nigrum* on Cd^{2+} reached the maximum critical range. A comparison of plant height and dry weight of *Solanum nigrum* under different conditions is shown in Figure 7.

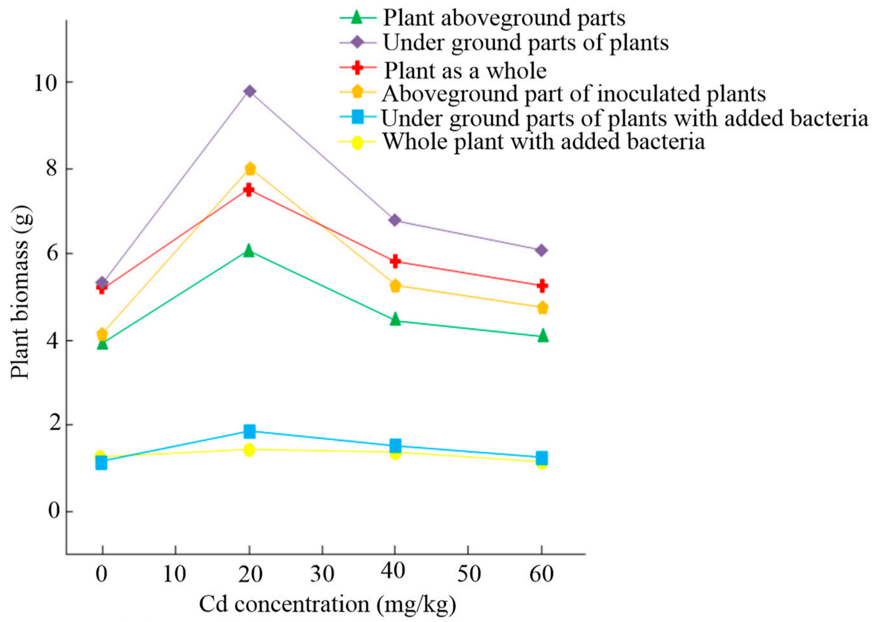
Table 9. The super-enrichment coefficient.

Cd^{2+} Concentration (mg/kg)	*Solanum nigrum*		*Solanum nigrum* + Cadmium-Resistant Strain	
	BCF	**BTF**	**BCF**	**BTF**
0	1.07	1.32	1.21	1.39
20	1.82	2.25	1.97	2.45
40	1.46	2.21	1.57	2.32
60	1.03	1.42	1.14	2.24

Figure 7a shows the plant height of *Solanum nigrum* under different days and cadmium concentration conditions. After adding cadmium-tolerant strains to the potted plant, the overall height of *Solanum nigrum* was greater than that of the group without cadmium-tolerant strains. The trend of plant height variation in *Solanum nigrum* remained basically unchanged under different concentration conditions; however, the height of *Solanum nigrum* significantly increased after adding cadmium-tolerant strains. This shows that cadmium-resistant strains has a certain promoting effect on the growth of super-enriched plants such as *Solanum nigrum*. The presence of a certain concentration of Cd^{2+} in the soil can effectively promote the enrichment of plants to obtain other nutrients in the soil, while *Solanum nigrum* with a cadmium-tolerant strain can effectively enhance the tolerance to Cd^{2+}. Figure 7b shows the dry weight variation curves of various parts of *Solanum nigrum* under different cadmium concentrations. As the cadmium concentration increased, the dry weight of different parts first increased and then decreased. When the cadmium concentration was 20 mg/kg, all parts had the highest growth rate. The underground part of the plant had the highest growth rate, reaching a value of 9.98 g. When the concentration of Cd^{2+} did not increase to 40–60 mg/kg, the dry weight of the above ground part of the plant began to decrease, to a minimum of 4.52 g. The weight of the underground part was significantly reduced, with a minimum of 6.41 g. The whole plant weight of *Solanum nigrum* first increased and then decreased. After the addition of cadmium-tolerant strains, there was no significant difference in the dry weight variation curves of different parts and the whole plant of *Solanum nigrum*. When the Cd^{2+} concentration was not 0, the dry weight of the plant after the addition of cadmium-tolerant strains showed an upward trend compared to that without the addition of cadmium-tolerant strains. This indicated that the addition of cadmium-tolerant strains was beneficial in improving the tolerance of *Solanum nigrum* to Cd^{2+}.



(a) Plant height of solanum nigrum under different days and Cd concentrations



(b) Comparison of dry weight of Cd polluted sunflower under different treatments

Figure 7. Comparing train height and dry weight under different conditions.

3.4. Risk Assessment Results of Microbial Plant Collaborative Remediation of Contaminated Areas

When a risk assessment model was used to calculate the health risk of pollution in the study area due to the presence of a certain population living in the surrounding area, the scenario was considered based on the type of residential area. The risk score was calculated based on the cumulative health risks received through different routes. The various pathways included oral ingestion of contaminated soil particles by people on the ground of the site, skin contact with contaminated soil, and inhalation of dust and contaminant gases through the mouth and nose. In addition, the calculation included the selection of the overall carcinogenic risk and the non-cancer hazard index for regional sites. The research focused on the heavy metal cadmium as a pollutant, so the risk assessment estimated the carcinogenic risk and the non-carcinogenic hazard quotient separately. In order to ensure good representativeness and a high certainty rate in the risk analysis, and to strictly control the risk level, risk calculations were performed using soil and polluted wastewater from the same site. The calculation results are shown below.

The research site was residential land near polluted areas. According to the requirements, the risk value of a single pollutant in carcinogenic risk substances was less than 10^{-6}, which was an acceptable level. For non-carcinogenic pollutants, the acceptable hazard quotient was less than or equal to 1. The risk calculation results in Table 10 indicated that the carcinogenic risk index of cadmium exceeded the acceptable level of 10^{-6} at all four selected points, with the maximum point exceeding the acceptable level being 239 times higher. The non-carcinogenic hazard quotient was also much higher than the acceptable level of 1, with a multiple exceeding the limit ranging from 6.43 to 23.3. This indicated that the surrounding area of the nuclear power plant was obviously polluted by cadmium, and the risk to human health and environmental hazard was the greatest. Therefore, residents in the surrounding area of the nuclear power plant need to focus on the issue of cadmium pollution in their daily lives, and develop scientific and reasonable governance and remediation plans to reduce the risk to the most acceptable level for human health, thereby achieving environmental safety in the polluted area.

Table 10. Calculation results of the risk assessment.

Contaminants	**Super Screening Value Point**	**Risk Value**			
		Cancer Risk Index	**Exceeding Acceptable Level Multiple**	**Non-Carcinogenic Hazard Quotient**	**Exceeding Acceptable Level Multiple**
Cd	1	9.17E−05	91.7	8.93E+00	8.93
	2	1.41E−04	141	1.38E+01	13.8
	3	2.39E−04	238	2.33E+01	23.3
	4	6.61E−05	66.1	6.43E+00	6.43

Note: E indicates the frequency of exposure to hazardous environments.

In conclusion, the treatment method developed in this study can be used effectively. It is also reusable in several ways. First, the microbial–plant synergy mentioned in the paper creates a relatively stable ecosystem in which the microorganisms are responsible for degrading organic matter and transforming pollutants, while the plants absorb and accumulate pollutants through their root systems and promote the growth and activity of the microorganisms. This synergy can be maintained for wastewater treatment and soil remediation, making it sustainable in the long term. Secondly, in microbial–plant synergy, specific microbial strains are introduced into the system for wastewater treatment or soil remediation. These microbial strains can be retained, propagated, and reused to maintain the functional stability and treatment efficiency of the system. In addition, plants play a role in the uptake and accumulation of contaminants in wastewater treatment and soil remediation. Plant material can be collected, treated, and reused. For example, properly treated plant material can be used as fertilizer, as a biomass energy source, or as a soil conditioner, thus enabling the recycling and reuse of resources. Finally, as both micro-organisms and plants are adaptable and transportable, they can be used in different environmental conditions, further demonstrating reusability. Thus, the synergistic microbial–plant approach is reusable in wastewater treatment and soil remediation in different regions and sites.

It is important to note that microbial–phyto synergy may vary from one wastewater treatment and soil remediation project to another and the specific recyclability must be assessed and adapted to the specific environmental conditions, contaminant characteristics, and treatment objectives. In addition, the effectiveness of the synergy may be influenced by other factors such as climate, soil type, and management practices. Therefore, in practical applications, a number of factors need to be considered and properly designed and managed to ensure the recyclability and treatment effectiveness of microbial–plant synergy.

4. Conclusions

The rapid expansion of nuclear power plant construction in recent years has made it increasingly difficult to control the environmental pollution and risk to human habitats caused by the associated waste discharge. Against this background, this study proposes the use of synergistic plant and microbial action for the remediation of cadmium-contaminated soil and wastewater. In this experiment, a strain of Sarcococcus mucilaginous was first isolated as a cadmium-tolerant bacterium from the soil, and the cadmium-contaminated wastewater was remediated by combining the plant with the cadmium-tolerant strain. The data showed that the combination of Cd-tolerant strains with the alkali-treated Phytophthora was more effective, with a maximum removal rate of 84.36% at a Cd^{2+} concentration of 100 mg/L, after which the removal rate decreased rather than increased as the Cd^{2+} concentration was increased. The maximum Cd ion concentration was 29.97 mg/kg when the Cd wastewater was treated with only Lobelia, and 40.77 mg/kg when the Cd-tolerant strain was combined with the alkali treatment of Lobelia, indicating that the Cd ion concentration in Lobelia reached an equilibrium state of adsorption soon after immersion in the wastewater solution. In the remediation of heavy metal soils by the Lobelia and cadmium-tolerant strain, the dry weight of the roots gradually decreased with increasing Cd^{2+} concentration, and the dry weights of the aboveground parts and whole plants showed a trend of increasing and then decreasing. The dry weight of the aboveground part of the plant reached 2.69 to 3.76 times that of the roots. When the concentration was low (20 mg/kg), the plants had some ability to resist Cd^{2+} pollution. As the concentration increased (40–60 mg/kg), plant growth was inhibited. At a Cd concentration of 20 mg/kg, all parts had the highest growth. When the Cd^{2+} concentration did not increase to 40–60 mg/kg, the aboveground dry weight of the plant started to decrease to a minimum of 4.52 g. The subsurface fraction decreased significantly to a minimum of 6.41 g, indicating that the combined Lobelia–cadmium-tolerant strain remediation system was the most effective in remediating Cd^{2+}-contaminated soil. However, due to the limitations of the laboratory, environmental factors such as light, relative humidity, and solubility in the laboratory may have an effect on plant adsorption. The accuracy of sorption measurements is reduced and further research is needed to determine the effect of these factors on experimental results.

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