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Removal of Heavy Metal Cd Element from Paddy Soil by Geo-Electrochemical Technology

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Abstract: A Cd-contaminated paddy field at the Quanzhou County Institute of Agricultural Science in Guilin was selected as the research object, and geo-electrochemical technology (GT) was used to treat the Cd-contaminated paddy field in situ. The technology's effectiveness in removing the heavy metal Cd element from paddy soil and the change rule of Cd accumulation and transport in various parts of rice plants under the action of an electric field were studied. That was to provide a theoretical basis and a new technical choice for remediating paddy soil polluted by Cd. The results showed that the GT effectively removed the heavy metal Cd element from the paddy soil. When the level of soil Cd in the paddy field was 0.58 mg/kg, after in situ treatment with the GT, the soil Cd decreased to 0.39 mg/kg, which met the requirements of soil contamination risk control for agricultural land. Geo-electrochemical technology effectively reduced the content of the Cd element in various tissues and organs of rice plants, made the Cd content in brown rice lower than the requirement of the national food pollutant limit standard of 0.2 mg/kg, and achieved the production of safe rice. Geo-electrochemical technology reduced the enrichment of Cd in the tissues and organs of the rice plants, including roots, stems, leaves, and grains, and at the same time affected the process of rice roots transporting Cd.

Keywords: accumulation; Cd contamination remediation; geo-electrochemical technology; paddy soil transport

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1. Introduction

Cadmium (Cd) is globally regarded as one of the most toxic heavy metals [1]. Excessive Cd in soil disrupts the normal growth of plants, especially food crops, and seriously threatens human health. A large number of studies have demonstrated that excessive intake or inhalation of Cd can cause toxicity to human immune, urinary, skeletal, nervous, circulatory, reproductive, and other systems, resulting in renal insufficiency, cardiovascular diseases, osteoporosis, and other diseases, and even carcinogenic effects [2–4]. In China, rice is the staple food for up to 60% of the population. However, the amount of Cd in paddy soil is as high as 33.2%, of which heavy polluters account for 8.6% [5]. Liu et al. [5] statistically analyzed the Cd content of surface (0−20 cm) paddy soil in China from 2000 to 2015. It was found that the concentration of Cd in that soil ranged from 0.01 to 5.50 mg/kg, with a median of 0.23 mg/kg. The provinces with the highest median Cd concentrations are Hunan (0.73 mg/kg), Guangxi (0.70 mg/kg), and Sichuan (0.46 mg/kg). Many works in the literature have indicated that mining was the main source of Cd contamination in Chinese paddy soils, and pollution incidents from mining activities were the critical driving force [5,6]. Therefore, the remediation and treatment of Cd-contaminated paddy soil are urgently needed.

Currently, remediation of heavy metal pollution in paddy soil focuses on Cd remediation, commonly with the use of agronomic control and soil amendment technologies. Agronomic control includes crop variation [7], optimized fertilization [8,9], and foliar obstruction control [10]. Soil amendment includes chemical leaching [11], in situ passivation [12], plant enrichment [13,14], and electrokinetic remediation [15,16]. Electrokinetic remediation is an emerging in situ technology developed in recent years. It consists of inserting cathodes and anodes of an electric field into Cd-contaminated soil. The application of a direct current facilitates the directional migration of the Cd element toward electrodes due to electromigration, electro-osmotic flow, and electrophoresis in the electric field. Electromigration indicates the movement of charged ions and ionic complexes in soil solutions under the existence of an applied electric field, and it is the dominant transport mechanism for inorganic contaminants [17]. Electro-osmotic flow is the movement of the soil solution containing dissolved pollutant species through the pore system of the soil [18]. For soil heavy metal remediation, metal, or metal-containing species are usually positively charged and therefore migrate to the cathode through electromigration and electro-osmosis (electric attraction) [19]. Electrophoresis refers to the movement of charged particles or colloids under the application of an electric field. Compared with electromigration and electro-osmosis, electrophoresis has a negligible impact on inorganic matter transport in low-permeability soil systems, and thus it is not taken into account in the electrokinetic remediation process [17]. The Cd element is accumulated near the electrodes, and then the pollutants in the soil or electrolyte in the enrichment area are treated centrally to remove them [20].

The geo-electrochemical method is a low-voltage, self-powered, bipolar electrical extraction technology developed by the Hidden Ore Deposit Prediction Research Institute of the Guilin University of Technology. It is protected by independent intellectual property rights. Geo-electrochemical technology (GT) has yielded substantial results in exploring minerals for concealed ore deposits. Its working principle is also based on electrolysis, electromigration, electro-osmosis, electrophoresis, and other electric field actions to achieve directional migration and enrichment of heavy metal elements toward the cathode and anode. Therefore, it can be regarded as a kind of electrokinetic remediation technology. Geo-electrochemical technology uses lightweight and convenient equipment, is simple to use, has rapid and safe applications, and is environmentally friendly.

In this study, the paddy soil and rice plants of the Quanzhou County Institute of Agricultural Science in the north of Guilin were selected as the study subjects. The study preliminarily investigated the removal efficiency of GT on heavy metal Cd elements in paddy soil. That included the distribution rule of heavy metal Cd in the paddy soil–rice system under the influence of an electric field to provide a theoretical basis and a new technical alternative for remediating Cd-contaminated paddy soil.

2. Overview of the Study Area

Quanzhou County (25°37′ to 26°18′ N, 110°41′ to 111°14′ E), located in the northeast of Guangxi, dominates the upper reaches of the Xiang River and serves as a key point on the Hunan–Guangxi corridor. The county is in a sub-tropical humid monsoon climate zone, with a frost-free period of 298 d per year and an average annual temperature of 17.7 °C. Its primary characteristics include strong solar radiation, abundant sunlight for most of the year, an average multi-year sunshine duration of 1404.0 h, and plentiful rainfall with an average multi-year precipitation of 1565.9 mm, although it is unevenly distributed throughout the seasons. The area of Quanzhou County is approximately 4000 km^2, with karst areas accounting for more than one-third of the total land area. It is a typical karst hilly basin region, with carbonate rocks dominating the lithology of the strata [21]. Quanzhou County is a national basic farmland demonstration county and one of the national commodity grain production base counties, making it an important agricultural county in Guangxi province. However, previous investigations found that farmland soil in Quanzhou County is contaminated with heavy metals to varying degrees, with Cd showing the highest level of contamination. The farmland is considered moderately polluted [21]. The average Cd concentration of 288 air-dried farmland soil samples reaches 0.43 mg/kg, exceeding the background value of agricultural soil in the north-eastern region of Guangxi

(0.18 mg/kg) [22]. Therefore, it is urgent to implement effective technical measures to remediate and control Cd contamination of the paddy soil of Quanzhou County. The geo-electrochemical technology is expected to play a key role in the in situ treatment of Cd-contaminated paddy fields.

3. Materials and Methods

3.1. Experiment Site

The experiment site was at the Agricultural Science Institute in Quanzhou County, Guilin City, Guangxi Zhuang Autonomous Region. The experiment paddy field was consistent in fertility level and pollution degree. Before the experiment, soil sampling and related analyses were performed on the paddy soil. The soil's basic physical and chemical properties were determined: the soil type was red soil paddy field, its pH was approximately 6.4, and the total Cd content was approximately 0.58 mg/kg. The content of heavy metals in the soil is detailed in Table 1. The selected evaluation standard was the risk screening of soil contamination of agricultural land with a pH of 5.5 to ≤6.5 in the "Soil Environmental Quality Risk Control Standard for Soil Contamination of Agricultural Land" (GB 15618-2018) [23]. Table 1 shows that the Cd content of the experimental paddy soil exceeded the pollutant screening value for agricultural land (0.4 mg/kg for paddy fields), indicating ecological and environmental risk in that soil. Therefore, appropriate remediation should be performed to reduce the risk of Cd exceeding the limit in agricultural products. Apart from Cd, no other elements exceeded the standard, so Cd was the key element of concern for excessive heavy metals in that area.

Table 1. Heavy metal content of paddy soil in the Agricultural Science Institute experiment site.

Element:	Cr	Ni	Cu	Zn	As	Cd	Hg	Pb
Mean	53.59	19.58	31.99	85.60	20.97	0.58	0.16	63.25
Standard deviation	1.20	0.41	1.31	4.52	1.45	0.04	0.01	2.70
The legal limit for paddy fields	250	70	50	200	30	0.4	0.5	100

Note: Units are mg/kg.

3.2. Experiment Apparatus

The experiment apparatus was the "Low Voltage Bipolar Geo-Electric Extraction Device" developed by the Hidden Ore Deposit Prediction Research Institute of Guilin University of Technology. That device is small, uses a low voltage, has an independent power supply, and is easy to use [24]. The structural composition of the apparatus is shown in Figure 1. The device comprises mainly the cathode and anode extraction electrodes, power supply, and wires. The cathode and anode extraction electrodes comprise primarily cylindrical graphite carbon rods approximately 120 mm long with a 15 mm base diameter. In addition, specific adsorbent materials (high-density sponges) and filter papers (the pore size was about 20 μm) were added to form the cathode and anode extraction electrodes.

3.3. Experiment Method

The experiment started on 29 July 2021, in the paddy field at the Agricultural Science Institute in Quanzhou County. There were three treatments and two repetitions for each treatment. The experimental groups with different conditions were named T1, T2, and T3; the corresponding experimental conditions are listed in Table 2. T1 was the electrokinetic remediation experiment of the GT on paddy soil; T2 was the same experiment but on the paddy soil–rice system; and T3 was the control experiment with rice plants alone and no GT. When installing the GT device, the cathode and anode extraction electrodes were separately buried into the paddy soil, approximately 20 cm deep, with the distance between the electrodes controlled at approximately 20 cm. Figure 2 shows the mechanism related to removing the Cd element from paddy soil by the GT.

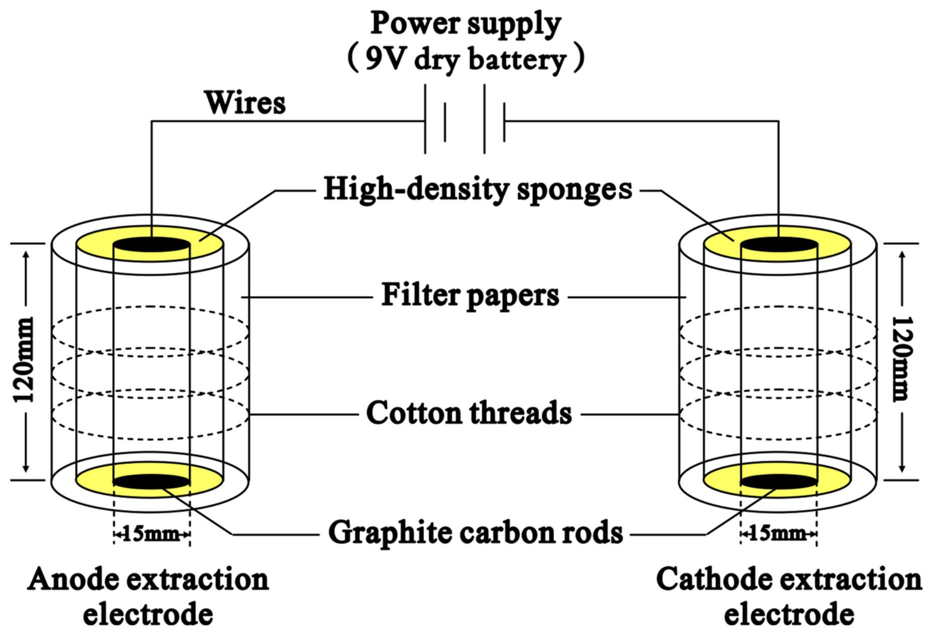

Figure 1. Schematic diagram of the geo-electrochemical technology device.

Table 2. Experimental conditions.

Experimental Group	Power-on Condition	Rice-Planting Situation	Duration of the Experiment
T1	Installation of the GT device in center (9 V direct current)	No rice planting	89 days
T2	Installation of the GT device in center (9 V direct current)	Rice planting	89 days
T3	No electricity	Rice planting	89 days

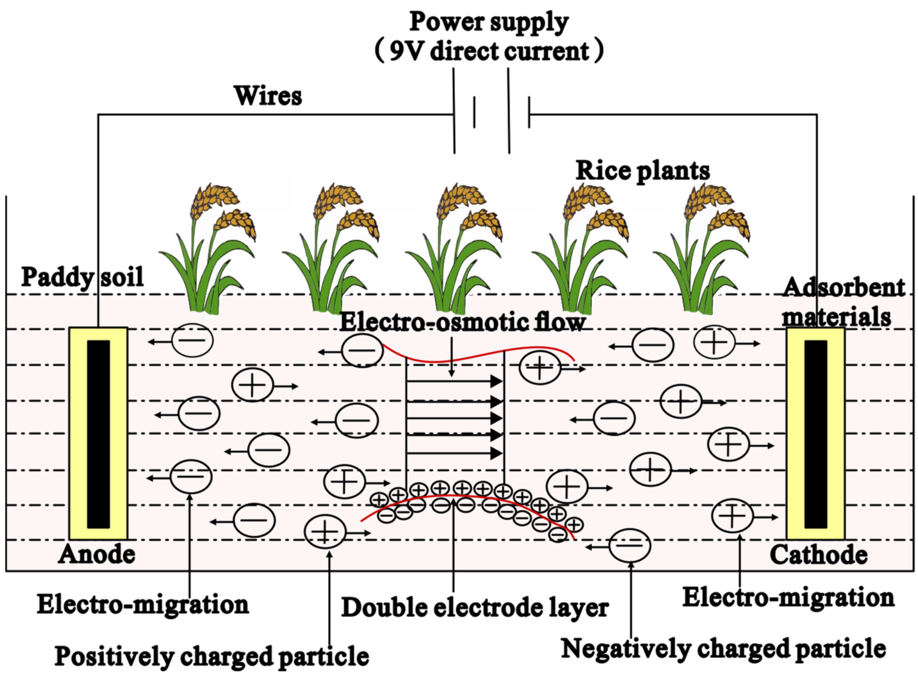

Figure 2. Schematic diagram of geo-electrochemical technology for removing Cd from paddy soil.

The paddy field area for each experimental group was 1 m^2 (1 m × 1 m), and all sides of the experimental groups were separated by polyethylene boards with a thickness of about 1 cm and a height of about 80 cm. For T1 and T2, where GT was applied, the battery and adsorbent materials of the device were replaced every 7 days. T2 and T3 were the rice-planting experimental groups; considering local planting habits, the rice variety was uniformly Nongxiang 32, with consistent seeding and transplanting density. Manual weeding was used within the entire planting area without chemical herbicides; pest control was performed based on local pest information; and the irrigation water was tested free from Cd contamination. No high-concentration pesticides were used, and fertilization and other cultivation management techniques complied with local standards. The experiment began with the rice at the transplanting stage, and sampling was conducted on 25 October 2021, when the rice was mature, with the total duration of the experiment being 89 days.

3.4. Sample Collection and Analytical Testing

3.4.1. Sample Collection and Pretreatment

Field sampling was performed near the end of July before the experiment began and at the end of October during the rice harvest period, with soil samples collected at a depth of 0−20 cm (top tillage layer). A 5-point sampling method was used in each experimental field, with each sample comprising five subsamples mixed together, and approximately 1 kg of thoroughly mixed soil samples were placed in clean cotton bags. Rice samples, including roots, stems, leaves, and panicles, were collected using the 5-point method and were "one-to-one" with the soil samples. They were trimmed and classified on-site, then packaged in sample bags, with each panicle sample weighing more than 500 g.

Soil samples were air-dried in the laboratory, with roots and stones removed, ground with the use of an agate mortar, thoroughly sifted through a 60-mesh (0.25 mm) sieve, and mixed for pH testing. After sifting through the 60-mesh sieve, the soil samples were sifted through a 200-mesh (0.074 mm) sieve, mixed, and stored in polyethylene bags for analysis of total As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn. Rice roots, stems, leaves, and panicles were initially washed in the field canal and then rinsed three times with deionized water in the laboratory. After air drying, the roots, stems, and leaves were chopped, and the panicles were threshed. All rice samples were dried to a constant weight at 60 °C and husked to produce brown rice, then 100 g of each sample was ground through a 60-mesh sieve and stored in polyethylene bags for analysis of total As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn.

3.4.2. Sample Analysis Testing

The collected samples were analyzed for As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn, and soil pH by the China Nonferrous Metals Guilin Geology and Mining Institute Co., Ltd. Soil samples of 10 g were weighed and sifted through a 60-mesh sieve, and the soil pH was determined in accordance with the "Soil Agricultural Chemistry Analysis Method" [25]. Soil samples of 1 g, sifted through a 200-mesh sieve, were microwave-digested and analyzed by atomic absorption for Cd, Cr, Cu, Ni, Pb, Zn and by atomic fluorescence spectrometry for As and Hg [26]. Rice root, stem, leaf, and brown-rice samples were weighed at 0.5 g each, microwave-digested, and analyzed by inductively coupled plasma mass spectrometry for As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn.

3.5. Data Processing and Analysis

All data were statistically analyzed with the use of Microsoft Excel 2010 and IBM's SPSS 22.0 statistical software, with the results displayed as mean ± standard deviation. One-way ANOVA and Duncan's multiple comparison tests ($p < 0.05$) were used for differential analysis. The different letters indicate statistically significant differences. The graphs were drawn with the use of Origin 2018 (OriginLab Corp., Northampton, MA, USA).

4. Results and Discussion

4.1. Effectiveness of Cd Removal from Paddy Soil

The initial concentration of Cd in the paddy soil of the Agricultural Science Institute in Quanzhou County ranged from 0.52 to 0.64 mg/kg, with an average of 0.58 mg/kg.

Figure 3 shows the total soil Cd content changes for the three experimental groups after 89 d of experimental treatment. As shown in the figure, relative to the initial soil Cd content without experimental treatment, the total Cd content in the soil of the T1, T2, and T3 experimental groups all decreased, with a significant reduction ($p < 0.05$) in the T1 experimental group. Among the three experimental groups, the removal effectiveness of Cd in the T1 experimental group, where the GT was applied solely to the paddy soil, was the highest, reaching 36.18%. The removal effectiveness in the T2 experimental group, where the GT was applied to the paddy soil–rice system, was 10.39%. In the T3 control group, where rice was planted alone without the use of the GT, the Cd content in the soil also decreased after planting, with a reduction rate of 21.23%.

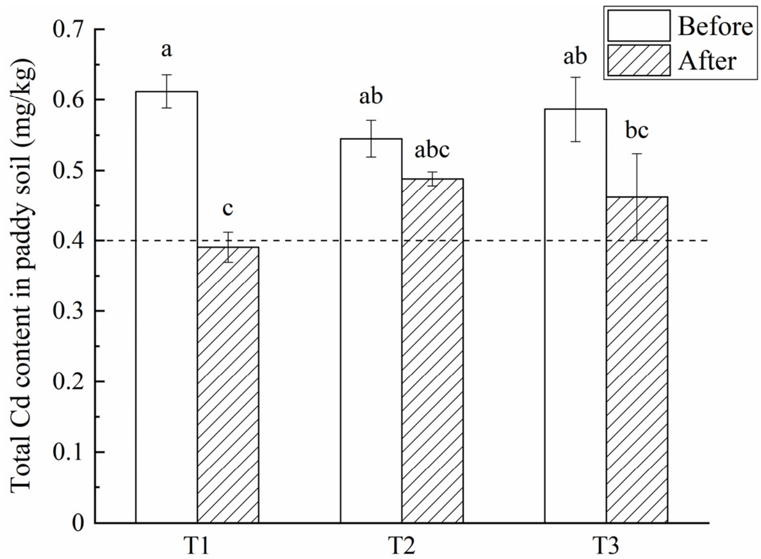

Figure 3. Variation in total Cd content in the soil of experimental groups before and after treatment (T3 was control group). Different letters above the error lines indicate significant differences ($p < 0.05$). The dashed line indicates the legal limit of Cd in the agricultural soil (0.4 mg/kg is derived from the Chinese national standard GB 15618-2018).

In accordance with GB 15618-2018 [23] and Figure 3, in the T1 experimental group, which used the GT solely on paddy soil, the total Cd content in the soil decreased to 0.39 mg/kg after the electrokinetic remediation. That is lower than the risk screening value for agricultural soil contamination (0.4 mg/kg for paddy fields), so it met the national standard. However, the T2 experimental group, which used the GT on planted rice, and the T3 control group with planted rice without the GT had total soil Cd contents of 0.49 mg/kg and 0.46 mg/kg, respectively, after the experiment. Although the total Cd content in the soil decreased in both cases, it was still higher than the risk screening value for agricultural soil contamination.

The experimental results show that the GT was effective in removing heavy metal Cd elements from paddy soil. The T1 paddy-soil-only experimental group had the best Cd-removal effect. After the remediation, the total Cd content in the paddy soil reached a safe threshold. The GT removes Cd elements from paddy soil based on the directional migration and accumulation of Cd elements toward the electrodes. It uses electrochemical effects such as electrolysis, electromigration, electro-osmosis, and electrophoresis. Then, the Cd element in the soil was collected with the use of specific adsorbent materials, thereby achieving the goal of reducing the content of the Cd element in the soil. The decrease in the soil Cd content in the T3 control group planted with rice alone was due to the absorption of Cd in the soil by rice plants. The less effective Cd removal in the T2 soil–rice system group might be related to the rice plants' absorption mechanism of Cd from the soil. According to the literature, Cd is a non-essential element of plants and enters into their roots through the absorption channels of Ca, Fe, Mn, Zn, and other essential elements [27]. For Cd-contaminated soil, the toxic effects of Cd on crops can be alleviated to a certain extent by applying a certain amount of exogenous substances (such as Ca, Fe, Zn, Mn, Mg, and other elements) to the contaminated soil [28–30]. Because the above elements and Cd have similar ionic radii and chemical properties, they can share many transport proteins, ion transport channels, and binding sites in crop roots, thereby inhibiting the accumulation and transport of Cd in crops [30]. Therefore, it can be preliminarily speculated that under the application of GT, the migration and enrichment of Ca, Fe, Mn, Zn, and other metal elements in the soil inhibited the absorption of Cd by rice plants (especially in the roots), which resulted in the insignificant reduction of soil Cd content in the T2 experiment group. However, the actual mechanism is still unclear, and further research is undoubtedly required.

4.2. Variation in Cd Content in Various Parts of Rice

For the T2 and T3 experimental groups, after 89 d of experimental treatment, the changes in Cd content in various tissues and organs of the rice in both groups were recorded. Figure 4 shows a reduction in Cd content in various tissues and organs of rice in the T3 control group, which did not use the GT, and in the T2 planted-rice experimental group, which used the GT. In both groups, the Cd content in rice plants from high to low was in the order of rice roots > rice stems > rice leaves > rice grains (brown rice). That was basically consistent with the research of Zhou et al. [31], Zhao et al. [32], and others, i.e., the Cd content in organs storing nutrients (rice grains) is lower than that in organs with vigorous metabolisms (rice roots, rice stems, and rice leaves).

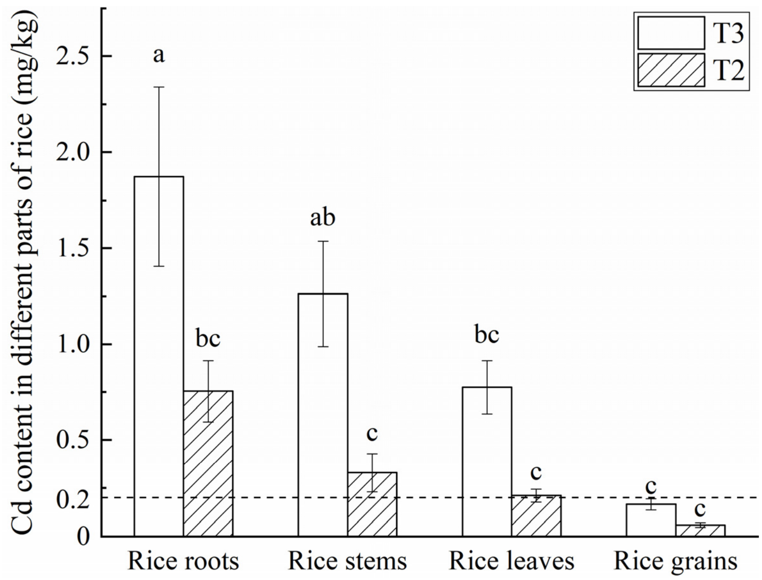

Figure 4. Variations in Cd contents in various tissues and organs of rice. The T3 group was the control group, and the T2 group used the geo-electrochemical technology. Different letters above the error lines indicate significant differences ($p < 0.05$). The dashed line indicates the legal limit of Cd in brown rice (0.2 mg/kg is derived from the Chinese national standard GB 2762-2022).

According to Figure 4, relative to the T3 control group without the technology, the Cd content in various parts of rice in the T2 experimental group decreased significantly, especially in the roots and stems of rice, where there was a significant difference ($p < 0.05$) compared with the T3 control group. Relative to the T3 control group, the Cd content in the roots, stems, leaves, and grains of the T2 experimental group decreased by 59.78%, 73.95%, 72.76%, and 64.56%, respectively. That shows that the GT effectively reduced the Cd element content in the tissues and organs of the rice plants. The Cd content in brown rice samples from the T2 and T3 experimental groups was evaluated in accordance with the "National Standard for Food Safety: Maximum Residue Limits for Pollutants in Food" (GB 2762-2022) [33] to determine whether it exceeded the limited standard of 0.2 mg/kg. It was found that neither group's brown rice exceeded the limit of heavy metal Cd, indicating good food safety.

That shows that although the initial total soil Cd content of the T2 and T3 experimental groups exceeded the risk screening value for agricultural soil contamination, indicating that there might be ecological and environmental risks in that soil, brown rice had no above-standard Cd content after actual rice planting. In addition to the GT's reduction of the Cd content of the entire paddy soil–rice system, it also shows that the Cd content of rice grains did not have a strong positive correlation with soil Cd content. That is consistent with the views of Wang et al. [34], Wang et al. [35], and others; i.e., at the regional scale, the correlation between rice Cd content and soil Cd content is usually low, with a correlation coefficient R^2 of typically less than 0.2. The Cd content of rice is related to the Cd content in the soil but also to rice variety, soil pH, soil organic matter content, and soil moisture content. Huang et al. [36] found that low-accumulation rice varieties can still guarantee the safety of rice consumption when grown in paddy fields where the Cd content exceeds the risk screening value for agricultural soil contamination. Through research, Liu et al. [37] found that the soil pH value has an important effect on the Cd content of rice. As the soil pH value rises from 5.5 to 7.5, the safe critical value of soil Cd content to ensure that the Cd content in rice does not exceed the standard rises from 0.27 mg/kg to 0.8 mg/kg. Xue et al. [38] studied the effect of organic fertilizer on the Cd content in double-season rice. They found that the organic carbon components in organic fertilizer can reduce the availability of Cd in the soil and ultimately reduce the Cd content in rice. Chen et al. [39] found that over 90% of the Cd in rice is directly absorbed from the soil by the rice root system during the grain-filling period and transported to the grains. The higher the soil moisture content during the rice grain-filling period, the lower the activity of Cd in the soil and the lower the Cd content in the rice. Conversely, in the mid-to-late stage of rice grain filling, the lower the soil moisture content due to the dry climate or early drainage of the paddy field, the higher the activity of Cd in the soil and the higher the Cd content in the rice.

4.3. Variation in Cd Accumulation and Transport Capacity in Various Parts of Rice

The capacity of heavy metals to accumulate and be transported to different parts of rice can be reflected by the bioconcentration factor (BCF) and the translocation factor (TF) [40]. The BCF is the ratio of the heavy metal element content in various rice organs to the heavy metal element content in the soil. It can be used to characterize the difficulty of heavy metal element migration in the soil–rice system. The larger the coefficient, the stronger the ability of heavy metals to migrate from the soil to the plant. The BCF of Cd in various tissues and organs of rice in the T2 and T3 experimental groups is shown in Figure 5. According to Figure 5, there was a certain difference in the Cd BCF in various tissues and organs of rice in the T3 control group, which did not use the GT, and the T2 experimental group, which used the GT. In both experimental groups, the Cd BCF in rice plants from high to low was in the order of rice roots > rice stems > rice leaves > rice grains (brown rice), which is consistent with the change characteristics of Cd content in various parts of rice discussed in Section 4.2. At the same time, according to Figure 5, relative to the T3 control group, the Cd BCF in various parts of rice in the T2 experimental group decreased, among which the decrease in the root BCF was the most significant ($p < 0.05$). That shows that the GT had an influence on the accumulation capacity of Cd in the paddy soil in various tissues and organs of rice.

The TF refers to the ratio of the heavy metal content in the subsequent parts of rice (stem, leaf, and brown rice) to that in the antecedent parts (root, stem, and leaf) [41]. The TF is used to evaluate the transport capacity of heavy metals between different parts of the plant. The larger the TF, the stronger the transport capacity of that part for heavy metals [42]. Figure 6 shows the translocation factors of Cd from root to stem, stem to leaf, and leaf to brown rice in the T3 control group with no GT and the T2 experimental group with the GT. According to Figure 6, the translocation factors of Cd in rice plants in the T3 control group from high to low were in the order of $TF_{stem/root}$ > $TF_{leaf/stem}$ > $TF_{brown\ rice/leaf}$. That indicates that the roots and stems of rice had a strong transport capacity for Cd, whereas the leaves had a relatively weak capacity. Relative to the T3 control group, the $TF_{stem/root}$ of the T2 group that used the GT significantly decreased ($p < 0.05$), but the $TF_{leaf/stem}$ and $TF_{brown\ rice/leaf}$ increased. This result indicates that the GT affects the process of rice stems and leaves to transport Cd, but the most crucial aspect is that it affects the process of rice roots to transport Cd. That reduced the accumulation of Cd in the aboveground parts of rice plants from the source, ultimately reducing the Cd content in brown rice. The combined effect of the BCF and the TF made the Cd content in the rice grains of the T2 experimental group that used the GT the lowest, meeting the national food safety standard.

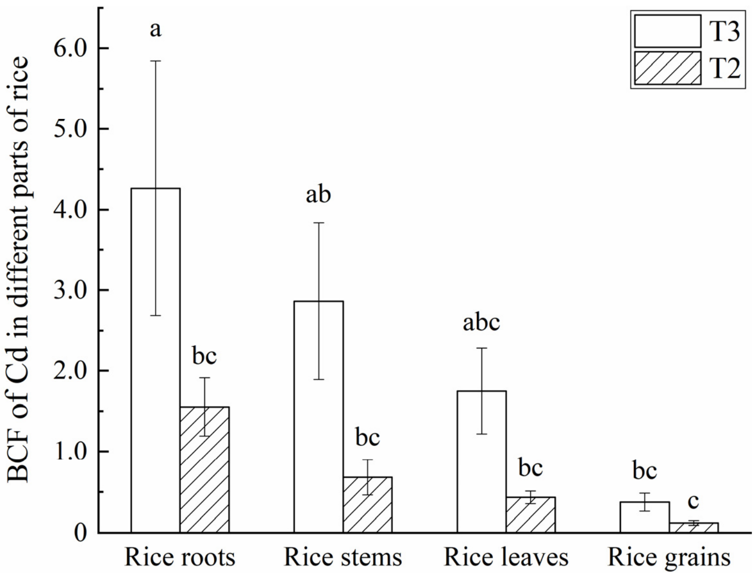

Figure 5. Variation in Cd bioconcentration factor in various tissues and organs of rice. The T3 group was the control group, and the T2 group used the geo-electrochemical technology. Different letters above the error lines indicate significant differences ($p < 0.05$).

4.4. Variation in the Content of the Seven Remaining Heavy Metal Elements of Paddy Soil

Before the experiment, soil sampling and related analyses were performed on the paddy soil. The results showed no exceedances for all seven elements except Cd. The content of the remaining seven heavy metal elements in the three experimental groups is detailed in Table 3. As presented in the table, relative to the initial content of heavy metal elements in soil without experimental treatment, the contents of Cr, Ni, Cu, Zn, As, Hg, and Pb in the soil of the T1, T2, and T3 experimental groups all decreased, with a significant reduction ($p < 0.05$) of Cr, Ni, and Cu. In accordance with GB 15618-2018 [23], it can be argued that after the experimental treatment, the content of seven heavy metal elements in the soil of each experimental group also meets the national standard.

The experimental results clearly indicate that the content of other heavy metal elements in the soil will decrease correspondingly when the GT is selected for the remediation of Cd-contaminated paddy field. Based on the above-mentioned results, it can be preliminarily speculated that under the action of a direct current electric field, some heavy metal elements in the paddy soil will also have directional migration and accumulation along with Cd, and then will be collected through the adsorbent materials around the electrodes, thus reducing the content of heavy metal elements in the soil. Therefore, the GT is anticipated to show a certain potential in the remediation and treatment of composite-contaminated soils with multiple heavy metal elements.

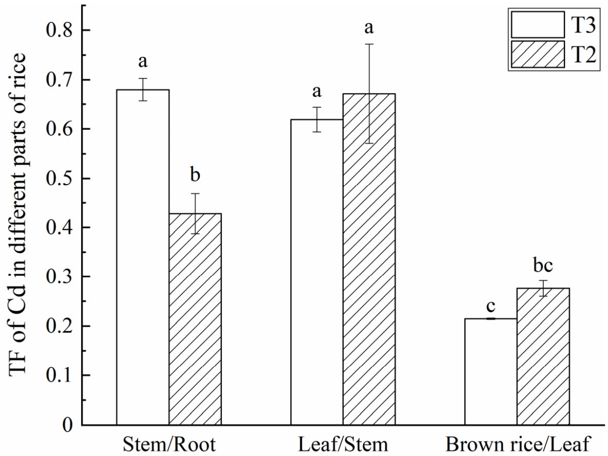

Figure 6. Variation in Cd translocation factor in various tissues and organs of rice. The T3 group was the control group, and the T2 group used the geo-electrochemical technology. Different letters above the error lines indicate significant differences ($p < 0.05$).

Table 3. The content of the remaining seven heavy metal elements of paddy soil in the Agricultural Science Institute experiment site.

Element	Cr	Ni	Cu	Zn	As	Hg	Pb
Initial value	53.59 ± 1.20 a	19.58 ± 0.41 a	31.99 ± 1.31 a	85.60 ± 4.52 a	20.97 ± 1.45 a	0.16 ± 0.01 a	63.25 ± 2.70 a
T1	47.37 ± 0.23 b	18.44 ± 0.26 b	25.35 ± 2.09 c	77.37 ± 2.57 a	17.45 ± 1.44 a	0.16 ± 0.01 a	57.75 ± 3.22 a
T2	45.78 ± 0.85 bc	18.49 ± 0.26 b	29.14 ± 1.13 ab	81.59 ± 1.76 a	20.46 ± 1.70 a	0.14 ± 0.00 a	60.97 ± 2.27 a
T3	44.45 ± 0.71 c	18.32 ± 0.29 b	27.72 ± 0.37 bc	79.86 ± 1.46 a	20.44 ± 0.38 a	0.15 ± 0.00 a	61.03 ± 2.52 a
Legal limit	250	70	50	200	30	0.5	100

Note: Units are mg/kg. The results are displayed as mean ± standard deviation. Different letters after the value indicate significant differences ($p < 0.05$). The legal limits are derived from Chinese national standards (GB 15618-2018).

5. Conclusions

(1) The experiment findings were that the GT was effective in removing the Cd element from paddy soil, particularly when it was applied directly to the soil. Therefore, it is suggested that in situ treatment of Cd-contaminated paddy fields should be carried out by the GT during the rice fallow period so as to ensure the safe use of the paddy fields.

(2) The GT effectively reduced the Cd element content in various parts of the rice plants by reducing the accumulation of Cd in soil by various tissues and organs such as rice roots, stems, leaves, and grains. Furthermore, the implementation of the GT affected the process of the rice plants to transport Cd from the underground parts to the aboveground parts; specifically, it affected the process of the rice root system to transport Cd, thereby ensuring the safe production of the rice.

(3) The results showed a good application prospect for the GT to reduce the content of the Cd element in the paddy soil. At the same time, the GT is also expected to show a certain potential in the remediation and treatment of composite-contaminated soils with multiple heavy metal elements.

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