

Boron decreased cadmium accumulation in water spinach by enhancing cadmium chelation of covalently bound pectin in the root cell wall

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Research Article

Keywords: boron, cadmium, root cell wall (RCW), covalently bound pectin (CSP), water spinach (*Ipomoea aquatica*)

Posted Date: August 2nd, 2023

DOI: <https://doi.org/10.21203/rs.3.rs-3133086/v1>

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Version of Record: A version of this preprint was published at Environmental Science and Pollution Research on August 30th, 2023. See the published version at <https://doi.org/10.1007/s11356-023-29447-z>.

Abstract

Cadmium (Cd) contamination and boron (B) deficiency are two major challenges associated with the farmland soils in Southern China. Therefore, this study was undertaken to examine the impacts of B supply on Cd accumulation in water spinach (*Ipomoea aquatica*) by using cultivar (T308) with high Cd concentration. The study further investigated the physiological mechanism behind the changes in Cd accumulation due to B supply. The findings revealed that B supply substantially reduced the Cd concentration in the leaves of water spinach by 41.20% and 37.16% under the Cd stress of 10 μM and 25 μM , respectively. Subcellular distribution of Cd showed that the Cd content as well as its proportion in root cell wall (RCW) increased significantly after B supply. Fourier transform infrared spectroscopy showed a significant enrichment of negative charged groups (such as -OH, -COOH, and -NH₂) in the RCW after B supply. Overall, B supply also enhanced covalently bound pectin (CSP) content as well as the Cd content linked with CSP under Cd stress. These observations revealed that B regulated the Cd chelation in RCW, thereby reducing the amassment of Cd in water spinach.

1. Introduction

Cadmium (Cd) is a biologically toxic metallic element, which is difficult to eliminate from the environment. Consequently, it can accumulate persistently in soil (Rizwan et al. 2017). Moreover, the Cd accumulated in soil can be up taken by the crops, thus entering the food chain and causing health risks for animals and humans (Lei et al. 2015; Lu et al. 2015; Zhang et al. 2015; Zhao et al. 2015). Leafy vegetables are one of the key sources of Cd ingestion by human (Huang et al. 2017). Therefore, it is necessary to take measures for reducing the amassment of Cd in crops and vegetables.

In recent years, environmental pollution caused by cadmium has attracted widespread attention. Previous studies have shown that exogenous nutrients supplied during soil fertilization were able to decrease the Cd amassment in crops (Wu et al. 2021). Among these nutrients, boron (B) is a vital trace element for plants, which is associated with cell wall functions and integrity (Hua et al. 2016; Shireen et al. 2018). B supply has already been proved effective for decreasing the Cd accumulation in oilseed rape (*Brassica napus*), rice (*Oryza sativa*), and hot pepper (*Capsicum annuum*) (Huang et al. 2021a; Huang et al. 2022; Riaz et al. 2021; Wu et al. 2020; Xin et al. 2023). However, a considerable portion of cropland soils in China is struggling with not only Cd pollution, but also B deficiency, thereby affecting the crop growth and yield.

Cell wall is an important component of plant cells, which is crucial for maintaining the cell structure and shape, regulating the entry and exit of macromolecules, and providing resistance against adverse conditions in the external environments (Yan et al. 2021; Yang et al. 2011). During exposure to high Cd concentrations, the root cell wall (RCW) acts as the chief defense block to protect the plant cells from Cd stress. However, the high concentration of Cd may alter the structure and composition of RCW (Li et al. 2015). The negatively charged groups (i.e., -COOH, -OH, and -NH₂) are highly prevalent in cell wall polysaccharides such as pectin. This groups can bind to Cd²⁺ and promote the retention of Cd in plant

cells (Loix et al. 2017; Yu et al. 2020). Due to the high affinity between the carboxyl groups of pectin and metal ions, pectin has been regarded as the main binding site for metal ions (Jia et al. 2019). Especially, the catalytic action of pectin methylesterase can produce the free carboxyl groups, which can form bonds with the metal ions such as Cd^{2+} (Willats et al. 2006). Moreover, It has been reported that pectin content, especially low-methyl esterified pectin, may influence the ability of cell walls to bind with metals (Krzesłowska 2011).

Water spinach (*Ipomoea aquatica*) is one of the major leafy vegetables grown in Southern China. Water spinach is highly susceptible to Cd absorption, especially during cultivation in Cd-contaminated soils (Wang et al. 2009). As a dicotyledon, water spinach is also highly sensitive to B deficiency during its growth. Therefore, the present study has been undertaken to simultaneously address the issue of Cd pollution and B shortage in the cropland soils in China. A water spinach cultivar (T308) with high content of Cd was selected as the research object to assess the impacts of B supply on Cd amassment in water spinach. Moreover, the possible mechanisms regarding the alteration in Cd accumulation in RCW by B were also elucidated. The study would be beneficial for developing appropriate control and prevention measures for high Cd amassment in crops.

2. Materials and methods

2.1 Research object and methods

A high Cd accumulation cultivar (T308) of water spinach was employed to conduct this research. The seeds were soaked in 2% H_2O_2 for 15 minutes for disinfection and then washed thrice with ultrapure water. Afterwards, the seeds were spread in sterilized sand to sprout. One week later, the seedlings were collected and transferred to a tissue culture bottle with surface shading. Half strength Hoagland nutrient solution was employed for growing the seedlings through hydroponics, and the nutrition was changed every three days. Three weeks later, the grown seedlings were subjected to different B and Cd treatments. Three Cd concentrations were used: 0 μM , 10 μM , and 25 μM , denoted as Cd0, Cd1, and Cd2, respectively. The B treatment was carried out in two forms - no B addition and B addition in concentration of 2 mg B L^{-1} , denoted as B0 and B1, respectively. Each treatment was conducted with three replicates. After 5 days of treatment, the root, stem, and leaf samples of cultivated water spinach were collected.

2.2 Determination of Cd concentration

The collected root samples were soaked in 0.05 mM calcium chloride for 30 minutes to clean the heavy metals present on the surface. After calcium chloride treatment, roots were washed with ultrapure water. After washing, the moisture was removed by heating the root, stem, and leaf samples at 70 °C to achieve stable weight. Subsequently, the samples were digested by using HNO_3 and H_2O_2 solution (v/v, 5:1) at 180 °C. The accumulated Cd content in the samples was measured by using flame atomic absorption spectroscopy (Hitachi Z-5300, Japan).

2.3 Subcellular distribution of Cd

The subcellular components of the plant cells were dissociated as per the process described by Huang et al. (2021a). Approximately 0.5 g of fresh sample (root, stem, and leaf) were ground into powder with the liquid nitrogen in a mortar pestle. Eight milliliters of pre-cooled buffer (pH 7.5) consisting of 250 mM sucrose, 1 mM dithiothreitol, and 50 mM Tris HCl was added to the powdered samples and the solution was homogenized on ice. The homogenized samples were filtered through nylon membrane of 80 μ m pore size to obtain the cell wall component (F1) in the form of filtered residue. The filtrate was centrifuged (4 °C, 20000 g, 45 min) and the soluble component (F2) of cells containing vacuoles and cytoplasm was obtained as the supernatant, while the precipitate contained the cell organelles (F3). The Cd concentration in the subcellular components were assessed as per the description given in section 2.2.

2.4 Determination of antioxidant enzyme activity

Superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT) activities were assessed by using the superoxide dismutase kit (SOD-2-Y), catalase kit (CAT-2-Y) and peroxidase kit (POD-2-Y), respectively, according to the protocol provided by the manufacturer. All reagent kits used for determination of enzyme activities were procured from Suzhou Comin Biotechnology Co., Ltd., China.

2.5 Fourier transform infrared spectroscopy of RCW

Extraction of RCW was done as described by Wang et al. (2020), with some minor variations. Fresh root sample was grounded with liquid nitrogen by using a mortar and pestle. RCW was extracted from the grounded sample using 75% ice ethanol. After standing for 20 min on ice bath, the mixture was centrifuged (4 °C, 5000 g, 10 min) and the obtained precipitate was sequentially washed with acetone, methanol trichloromethane mixture (v/v, 1:1), and methanol solution. During each washing step, the precipitate was kept in the solution for 10 mins and then the suspension was centrifuged at 4 °C and 5000 g for 10 min. The precipitate obtained after last washing was freeze-dried to obtain RCW.

Fourier transform infrared spectroscopy (FTIR) spectroscopy (IRAffinity-1S, Shimadzu, Japan) was employed to analyze the changes in the functional groups of RCW after B supply. Two micrograms of RCW were thoroughly ground with 200 mg KBr in an agate mortar and then pressed to prepare thin pellets. The pellets were placed into FTIR spectrophotometer and the absorbance spectrum was recorded from 4000 to 400 cm^{-1} wavenumber (Huang et al. 2023a).

2.6 Determination of the pectin content

The covalently bound pectin (CSP), water-soluble pectin (WSP), and ion-bound pectin (ISP) contents in the RCW of water spinach were measured by using the quantification kits of respective pectin contents (Suzhou Comin, China). The protocols provided by the kit manufacturer were followed to measure the pectin contents. Subsequently, the extracted CSP, ISP, and WSP were digested in the solution of HNO_3 and H_2O_2 (v/v, 5:1) at 180 °C. The digested content was used to measure the concentration of Cd in these three types of pectin through inductively coupled plasma mass spectrometry (ICAP-RQ, Thermofisher, USA).

2.7 Statistical analysis

In order to carry out the statistical analysis and draw the graphs, SPSS 21.0 and Excel 2019 were employed. The Cd translocation factors (TFs) were calculated according to the following formula:

$$TF_{\text{stem/root}} = \text{stem Cd content} / \text{root Cd content}$$

$$TF_{\text{leaf/stem}} = \text{leaf Cd content} / \text{stem Cd content}$$

One-way analysis of variance (ANOVA) was conducted to analyze the significance of variations. Correlation analysis was performed using Pearson's coefficient analysis to determine the correlation of RCW Cd concentration with CSP content and CSP Cd concentration.

3. Results

3.1 Effects of B on the growth status and root antioxidant enzyme activities of water spinach under Cd stress

The growth indicators of water spinach under various treatment conditions are shown in Figure S1. For Cd0 (without Cd), Cd1 (10 μM) and Cd2 (25 μM) groups, B supply showed no noteworthy impact on the height of plants, length of roots, and fresh weight of stems and roots of water spinach ($p > 0.05$). The effects of B supply on the root antioxidant enzyme activities under Cd treatment have been shown in Fig. 1. In Cd0 group, B supply resulted in an increase in SOD activity and decrease in POD activity ($p < 0.05$). In Cd1 and Cd2 group, B supply did not show any significant effect on the activities of SOD, CAT, and POD ($p > 0.05$). Overall, no significant impacts of B supply were observed on the growth and antioxidant enzyme activities of water spinach under Cd treatment.

3.2 Effect of B on Cd accumulation and translocation in water spinach

With the increase in Cd stress, the Cd concentration in roots, leaves, and stems of water spinach also increased (Fig. 2). However, the effects of B supply were different for the Cd1 and Cd2 treatments. Under Cd1 (10 μM) treatment, B supply had no significant effects on the Cd concentration in root and stem of water spinach. However, the Cd concentration in leaf significantly decreased (41.20%) from 25.68 mg/kg to 15.10 mg/kg ($p < 0.05$). Moreover, no significant effects of B supply were observed in Cd1 group on Cd TF for root to stem and stem to leaf ($p > 0.05$; Fig. 3). Under Cd2 (25 μM) treatment, B supply resulted in 31.97%, 24.69%, and 37.16% decrease in the Cd content accumulated in the roots, stems and leaves of water spinach, respectively ($p < 0.05$). No significant effects of B supply were observed in Cd2 group on the Cd TF for root to stem. However, the Cd TF for stem to leaves under Cd2 treatment significantly decreased after B supply ($p < 0.05$).

3.3 Effects of B on subcellular distribution of Cd water spinach

Under Cd1 treatment, B supply resulted in reduced Cd concentration in F2 and F3 components from 7.21 to 4.32 mg/kg and 1.55 to 0.73 mg/kg, respectively. On the contrary, Cd concentration in F1 component increased from 5.51 to 7.23 mg/kg ($p < 0.05$, Fig. 4). Under Cd2 treatment, the Cd concentration in F1 component increased from 13.26 to 15.57 mg/kg after B supply, while Cd content in F2 component decreased from 14.41 to 10.02 mg/kg ($p < 0.05$). No substantial impact of B supply was noticed on the Cd concentration in F3 component under Cd2 treatment. Without B supply, the subcellular distribution of Cd in the F1, F2 and F3 components under Cd1 treatment were 38.57%, 50.46%, and 10.97% respectively. However, after B supply, subcellular Cd distribution in these three components increased to 59.09%, 35.01%, and 5.90%, respectively. Similarly, in absence of B supply, the subcellular portions of Cd in F1, F2, and F3 components in Cd2 treatment were 44.61%, 48.36%, and 7.02% respectively. However, the respective Cd proportions in three components changed to 57.30%, 36.89%, and 5.81%, respectively, after B supply. Regardless of the Cd treatment (10 μ M or 25 μ M), B supply significantly increased the Cd concentration as well as the subcellular portion of Cd in RCW of water spinach.

Under Cd1 treatment, Cd concentrations in F1 and F3 components of stem reduced by 33.64% and 35.97%, respectively after B supply ($p < 0.05$, Figure S2). However, no substantial impact of B supply was witnessed on the Cd concentration in F2 component. On the contrary, Cd concentrations decreased in all three components after B supply under Cd2 treatment and decrease was found to be 22.99%, 30.62%, and 22.26% in F1, F2, and F3, respectively. For both Cd1 and Cd2 treatment, B supply did not exhibit any remarkable impact on the subcellular distribution of Cd in the stem cells of water spinach.

In the leaves of water spinach, B supply resulted in 32.16% and 48.81% decrease in Cd concentrations of F1 and F3 components respectively under Cd1 treatment ($p < 0.05$, Figure S3). However, no substantial impact of B supply was noticed on the Cd concentration in F2 component under Cd1 treatment. Under Cd2 treatment, B supply led to 27.67%, 31.81%, and 28.43% decrease in the Cd concentrations of F1, F2, and F3 components of leaf, respectively. Without B supply, the subcellular proportions of Cd in F1, F2, and F3 components were 41.75%, 38.48%, and 19.77%, respectively under Cd1 treatment. After B supply, the subcellular proportions of Cd in F1, F2, and F3 components were found to be 33.65%, 54.57%, and 11.78% in leaf cells. Moreover, proportion of Cd in leaves vacuoles of water spinach was also higher due to B supply under Cd1 treatment. On the contrary, subcellular allocation of Cd remained unchanged after B supply in the leaves of water spinach under the stressing Cd2 concentrations.

3.4 FTIR analysis of RCW

To investigate the mechanism of B induced improved Cd²⁺ binding ability of RCW, the variations in the functional groups of RCW between Cd2 treatments with and without B supply were compared using FTIR spectroscopy (Fig. 5). The most prominent peaks were observed at 3408, 1653 and 1056 cm^{-1} . Comparatively less prominent absorbance peaks also appeared in the FTIR spectra at 2927, 1734, 1520, 1375, 1325, 1242 and 1152 cm^{-1} . Peaks at 3408 cm^{-1} and 2927 cm^{-1} corresponded to hydroxyl group ($-\text{OH}$), amino group ($-\text{NH}$), and C-H bond of lignin, pectin, and cellulose in the RCW (Huang et al. 2023a). The absorption peak at 1734 cm^{-1} corresponded to the C = O in the ester carbonyl groups ($-\text{COOR}$). These

ester carbonyl groups are commonly found in the highly methylated pectin (Nie et al. 2017). The peak at 1653 cm^{-1} was associated with the protein amide I band (C = O vibration) (Meyer et al. 2015). Presence of this peak confirmed the changes in RCW due to B supply under Cd2 treatment. The peak at 1375 cm^{-1} corresponded to the -COOH groups in pectin (Wang et al. 2020; Xu et al. 2015). The peaks observed at 1520 , 1325 , and 1242 cm^{-1} were found to be associated with the sinapyl (S-) and guaiacyl (G-) aromatic rings of lignin (Guo et al. 2021; Huang et al. 2023a; Shen et al. 2023). Peaks at 1152 and 1056 cm^{-1} was related to the C-O-C, C-C, and C-OH bonds in cellulose and hemicellulose (Ren et al. 2020). FTIR analysis revealed that the intensities of peaks corresponding to the functional groups of pectin, lignin, cellulose, and hemicellulose were higher for the Cd2 treatment with B supply, as compared to Cd2 without B supply. For Cd2 treatment without B supply, the most significant peak was observed at 1653 cm^{-1} . However, in the presence of B, the most significant peak was shifted to 3408 cm^{-1} . This indicated that the B supply affected the distribution and composition the functional groups in RCWs.

3.5 Root pectin content and Cd concentration in pectin

Under Cd2 treatment, B application had no remarkable influence on the WSP and ISP contents in the RCW of water spinach. However, the CSP content in RCW increased significantly in Cd2 treatment with B supply ($p < 0.05$, Fig. 6). In addition, the Cd content in the CSP also increased significantly in RCW ($p < 0.05$). Both the CSP content and CSP Cd concentration were found to be positively linked with the measured Cd content in RCW ($p < 0.05$).

4. Discussion

4.1 Effect of B on Cd amassment and translocation in water spinach

Boron is crucial for the growth and development of plants, owing to its involvement in the functions and structural integrity of cell walls (Camacho Cristóbal et al., 2008). It has been previously reported that B not only decrease the Cd accumulation in wheat, rice, rapeseed, and hot pepper, but also alleviated the toxic effects of Cd (Chen et al. 2019; Huang et al. 2021a; Huang et al. 2022; Qin et al. 2020; Wu et al. 2020). In this study, B supply led to substantial decline in the Cd concentration in leaves of water spinach, both under low ($10\text{ }\mu\text{M}$) and high ($25\text{ }\mu\text{M}$) Cd stress. In addition, B supply reduced the translocation of Cd from stems to leaves in water spinach to a significant extent under Cd2 treatment. These results suggest that it is reasonable to use B as exogenous nutrient to mitigate the possibilities of Cd amassment in water spinach grown in Cd polluted areas.

Boron supply has been reported to alleviate the oxidative damages induced by Cd in rice roots by increasing the antioxidant enzyme activities, thereby promoting the growth of rice plants in the presence of high Cd concentration (Huang et al., 2021; Riaz et al., 2021a). In this study, B and Cd did not have significant effects on the growth and antioxidant enzyme (SOD, CAT, and POD) activities of water spinach

overall. This may be because the study was conducted on a water spinach variety with high Cd accumulation, which had a strong tolerance for Cd stress.

4.2 B increased the chelation ability of RCW in water spinach

In order to survive under the conditions of Cd stress, plants tend to alleviate the toxic effects of Cd by decreasing the metabolic activities through several biological processes including cell wall fixation, vacuolar compartmentalization, and chelation (Ni et al., 2003; Iori et al., 2012; Peng et al., 2014). To face the Cd stress, subcellular level allocation of Cd is crucial for plants (Li et al., 2010). During high Cd concentrations, plants either hold the Cd in cell walls by chelating Cd to the cell wall or allocate Cd into the vacuoles to reduce the Cd concentration in the cytoplasm, thereby preventing the Cd to induce any cell damage (Wang et al., 2020). In this study, the overall Cd concentration as well as the subcellular share of Cd was much higher in the cell wall components and soluble components of roots, stems, and leaves, as compared to the organelle components. This is helpful in alleviating the harmful impacts of Cd in the cell organelles. The allocation of Cd in the RCW and vacuoles results in limited transportation of Cd from roots to stems and leaves (Huang et al. 2021b). In this study, B supply resulted in higher Cd content and share of Cd in RCW of water spinach, under Cd1 and Cd2 treatment. This suggested that RCW played important roles in B induced translocation and amassment of Cd in water spinach. Similar phenomenon has also been reported in crops, including rice, hot pepper and rapeseed (Wu et al., 2020; Huang et al., 2021a; Huang et al., 2022).

RCW is the chief protection block of the cells to face the Cd stress, which regulates the entry of molecules into the cells. RCW prevents the Cd-induced cell damage by decreasing the entry of Cd into the cell protoplasm (Wang et al. 2020). The ability of RCW to chelate with Cd^{2+} can be primarily attributed to the negatively charged functional groups, such as $-\text{COOH}$, $-\text{OH}$, and $-\text{NH}_2$ (Xiao et al. 2020). FTIR revealed the substantial rise in the intensities of peaks corresponding to functional groups of pectin, lignin, and cellulose, after B supply under Cd2 treatment. These results indicated that B supply led to higher availability of Cd^{2+} binding sites in the RCW of water spinach. This increase in Cd^{2+} binding sites can be attributed to the higher Cd content in water spinach and higher Cd proportion in the RCW after B supply. Previously, B supply has also been reported to enrich the $-\text{COOH}$ and $-\text{OH}$ groups in RCW of oilseed rape under Cd stress (Wu et al., 2020).

4.3 B increased Cd chelation by CSP of RCW in water spinach.

Pectin has been reported to serve as the main binding site in the plant cell walls for the metal ions, and positive correlations have been observed between the pectin content and heavy metal amassment in the cell walls (Wang et al. 2018; Wang et al. 2020; Xiong et al. 2009). Approximately 50 and 79% of the Cd in RCW of soybean (*Glycine max*) and pakchoi (*Brassica chinensis*) were deposited in the pectin of the cell walls (Wang et al., 2018; Wang et al., 2020). Increased pectin content in the cell walls has been observed

as an adaptive measure in plants to survive during Cd stress, as the excess Cd binds to the increased binding sites in the pectin of cell wall (Li et al., 2015; Meyer et al., 2015; Wang et al., 2020; Wu et al., 2020). The non-hyper accumulative ecotype of *Sedum alfredii* contains higher pectin content in RCW, as compared to the hyper accumulative ecotype, thus leading to higher retention of Cd in RCW via increased number of Cd binding sites (Li et al., 2015).

Pectin is mainly composed of CSP, ISP, and WSP. Among these components, CSP and ISP are considered more important for retaining the Cd^{2+} , as these components contain higher number of partially esterified homogalacturonan (low methylated), which have more Cd binding sites (Deng et al. 2018; Szatanik-Kloc et al. 2017; Wu et al. 2020). In this study, the CSP content as well as the Cd concentration in CSP of RCW significantly increased after B supply under Cd² treatment. This indicated that the Cd binding capacity of RCW in water spinach improved after B supply, owing to the increased CSP content and higher availability of Cd binding sites. This inference can be supported by the facts that both the CSP content and Cd concentration in CSP were found to be significantly correlated with Cd concentration in the cell wall component. Our previous study on the cultivar-based Cd assessment in water spinach also showed that CSP content in RCW was negatively correlated to the Cd TF from root to stem (Huang et al. 2023b).

5. Conclusions

This study examined the impacts of B supply on the Cd accumulation in water spinach. Based on the observations, three key findings conclusions can be drawn. Firstly, Cd concentration in water spinach significantly decreased due to B supply, both under the Cd concentration of 10 and 25 μM . Secondly, Cd chelation with RCW improved due to the increased number of -COOH and -OH groups after B supply, which resulted in higher Cd retention in RCW. Thirdly, B supply increased CSP content in RCW, thus improving the Cd chelation with CSP. This led to the increased Cd concentration in RCW. Consequently, Cd assessment in water spinach declined after B supply. Thus, the present research confirmed the key roles of RCW in B-induced reduction of Cd accumulation in water spinach. These results would be helpful in constructing the prevention and control measures for Cd accumulation in crops through B fertilizer application.

Declarations

Author contribution

A total of ten authors participated in this work, including Ying-Ying Huang, Chuang Shen, Xue-Song Wang, Hui-Ling Fu, Bai-Fei Huang, Yi Li, Hui Wen, Yun-fan Wang, Wen-Jing Zhou, Jun-Liang Xin. Conception and design of study: Jun-Liang Xin, Ying-Ying Huang, Chuang Shen; Acquisition of data: Ying-Ying Huang, Xue-Song Wang, Hui-Ling Fu, Bai-Fei Huang, Yun-fan Wang, Wen-Jing Zhou; Analysis and/or interpretation of data: Ying-Ying Huang, Yi Li, Hui Wen, Jun-Liang Xin; Drafting the manuscript: Ying-Ying Huang; Revising the manuscript critically for important intellectual content: Chuang Shen, Ying-Ying Huang, Jun-Liang Xin.

Funding

This study was supported by National Natural Science Foundation of China (Grant No. 42107039), Scientific Research Foundation of Hunan Provincial Education Department (Grant No. 20B164), the Science and Technology Project of Guangdong Province (2021B0909050002), and the College Students Research Learning and Innovative Experiment Project of Hunan Province (Grant NO. S202311528024).

Data availability

Not applicable

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent to publish

Not applicable

Competing interests

The authors declare no competing financial interest.

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Figures

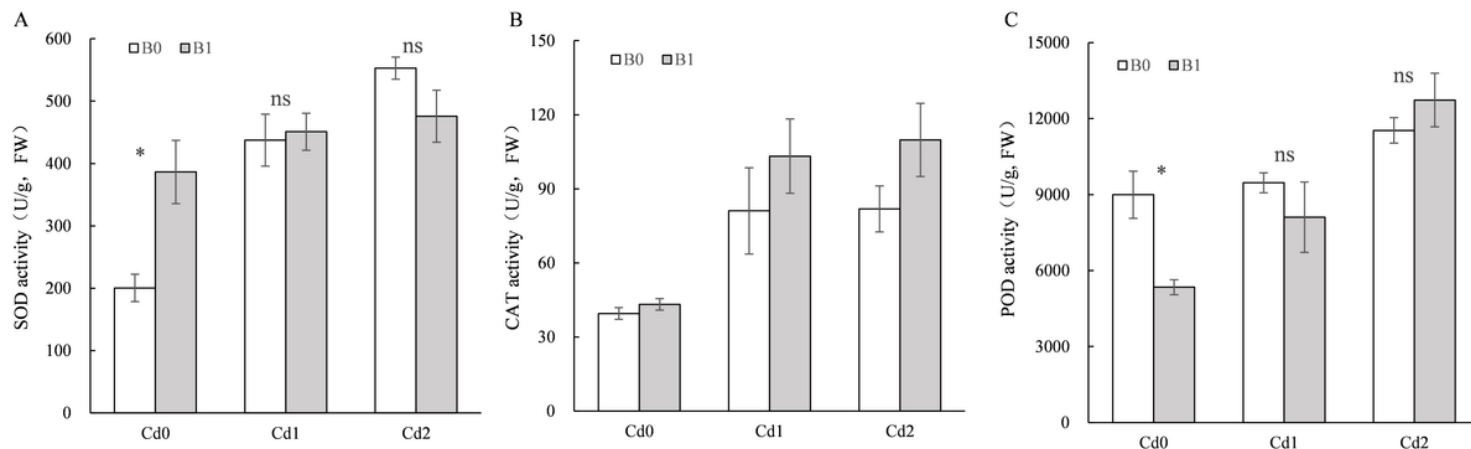


Figure 1

(A) SOD, (B) CAT, and (C) POD activities in water spinach. Here, ns represents no significant variations, while * represents significant variations with $p < 0.05$.



Figure 2

Cd content in (A) root, (B) stem, and (C) leaf of water spinach. Here, ns represents no significant variations, while * represents significant variations with $p < 0.05$.

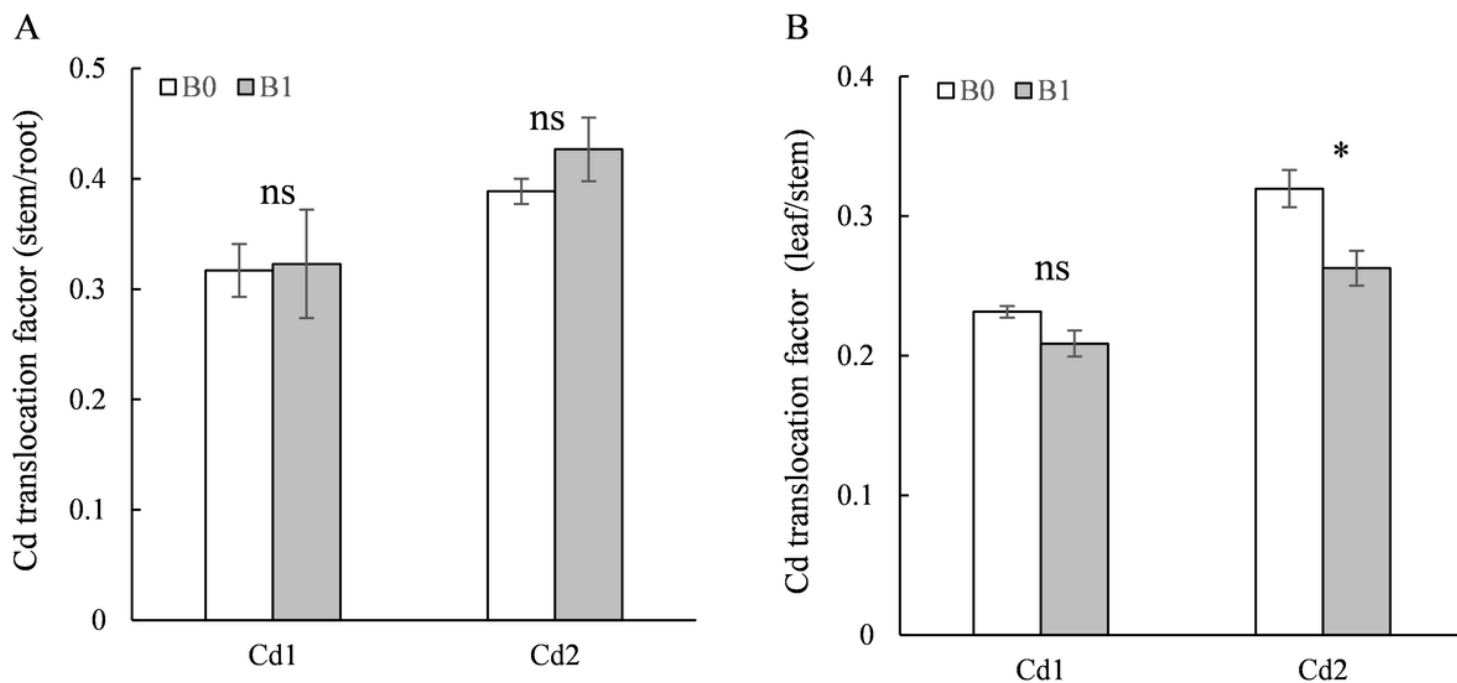


Figure 3

Cd translocation factor for (A) root to stem and (B) stem to leaf. Here, ns represents no significant variations, while * represents significant variations with p 0.05.

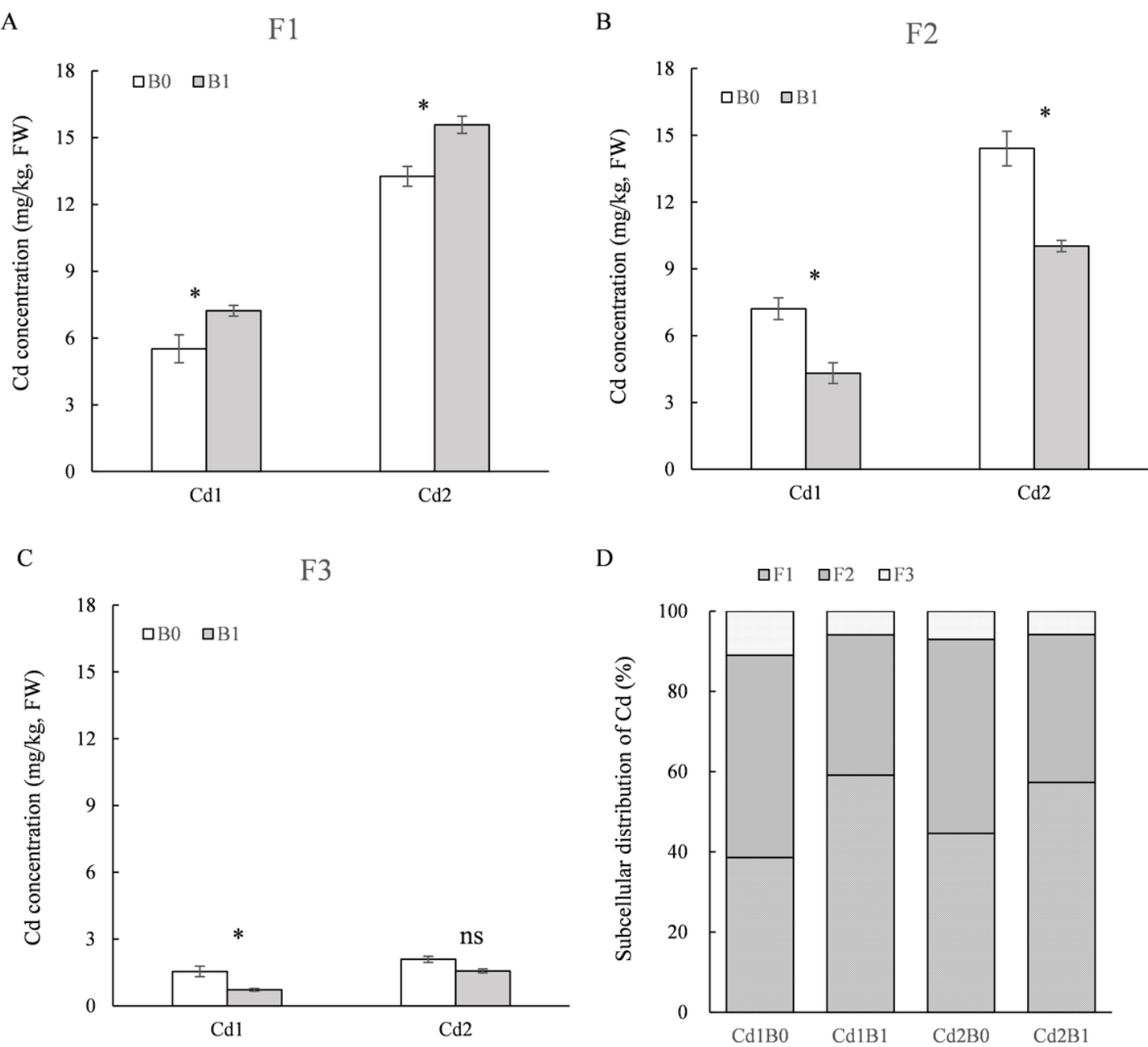


Figure 4

Cd content in (A) F1 component, (B) F2 component, and (C) F3 component of water spinach root; (D) distribution of Cd proportion in water spinach root at subcellular level. Here, ns represents no significant variations, while * represents significant variations with p 0.05.

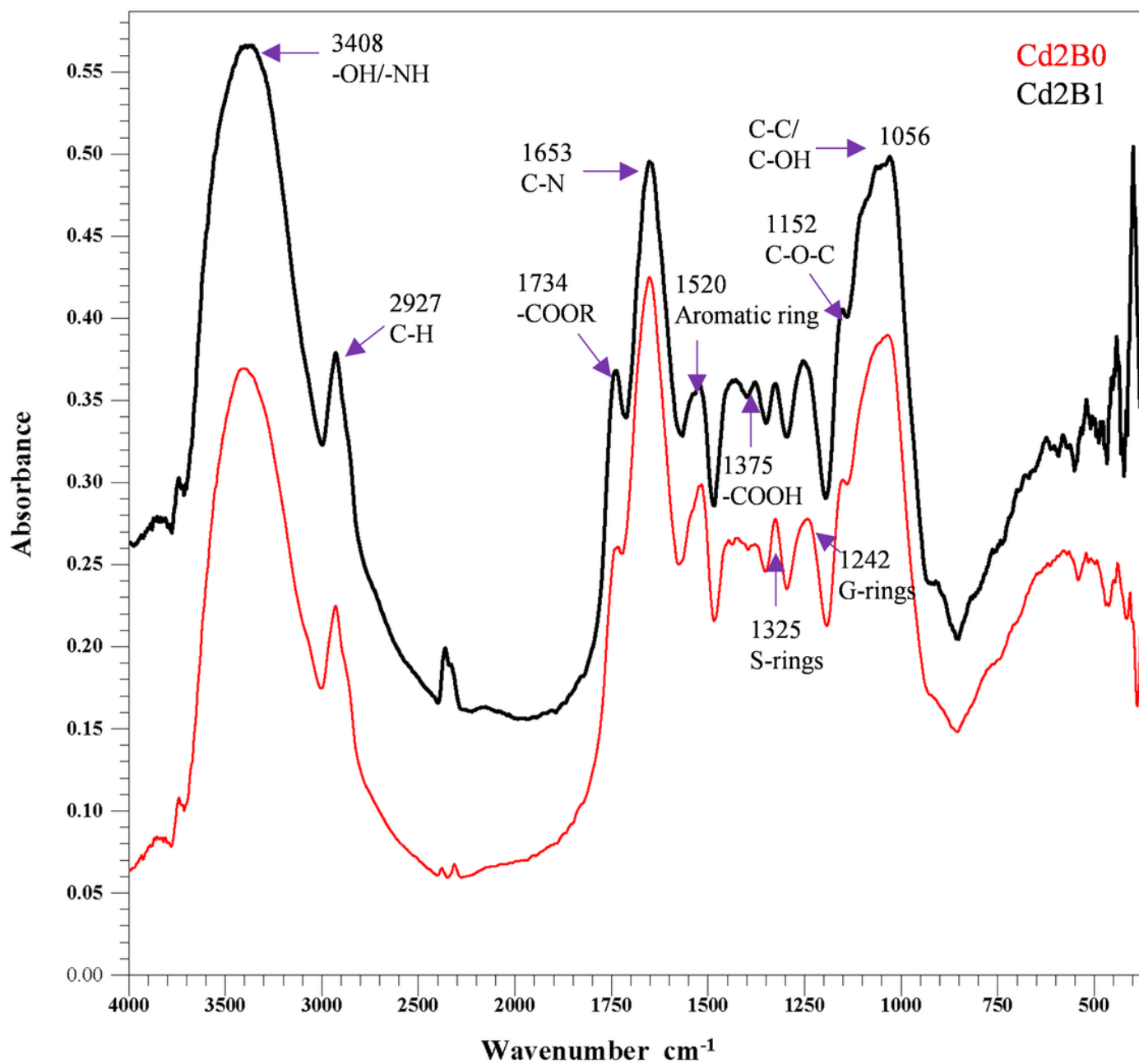


Figure 5

FTIR spectra of root cell walls in water spinach under Cd2B0 and Cd2B1.

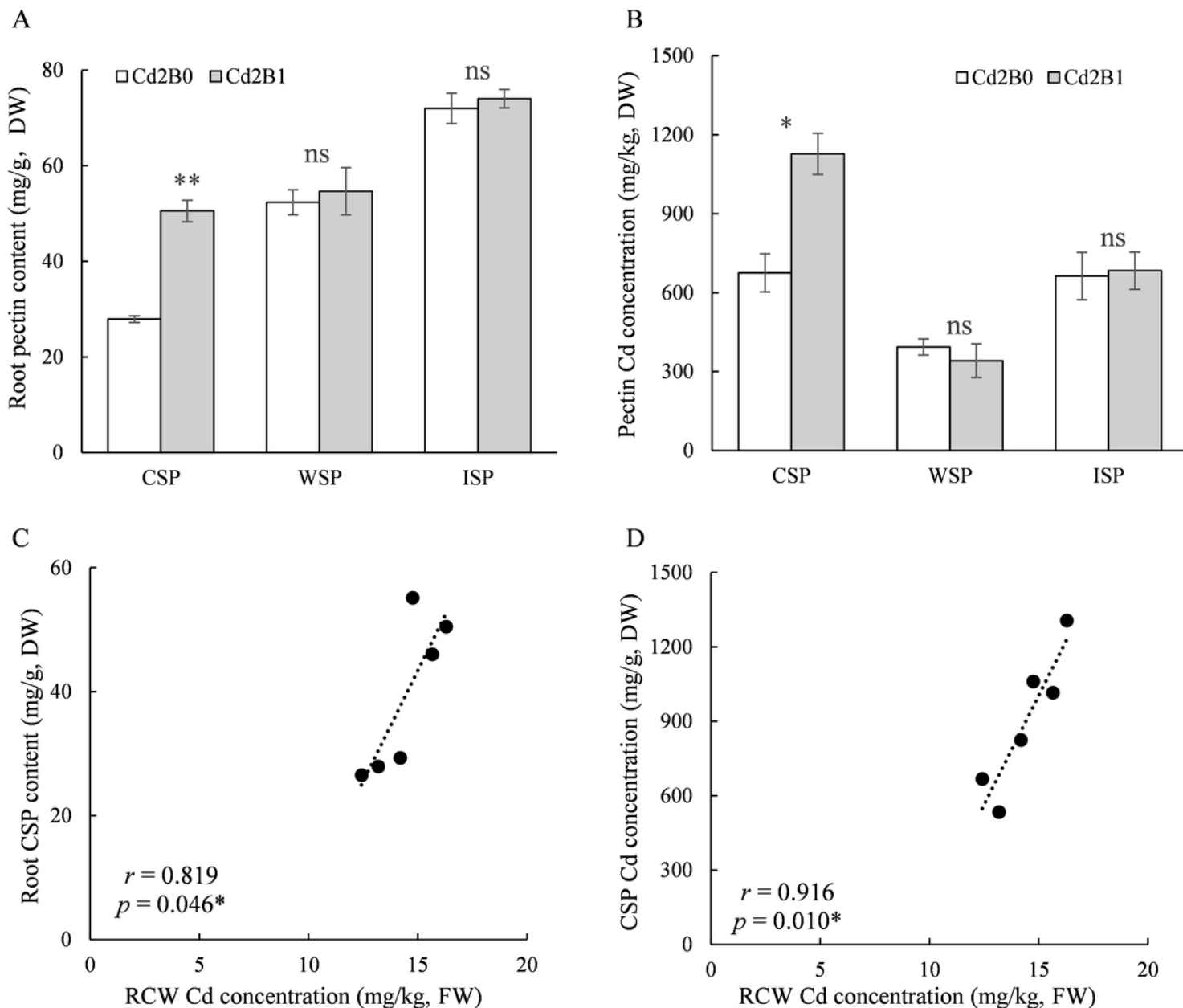


Figure 6

(A) Pectin content in root, (B) Cd concentration in pectin, (C) correlation analysis of CSP content and Cd content in RCW, and (D) correlation analysis of CSP Cd concentration and Cd content in RCW.

Supplementary Files

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