Comparing the Effects of Calcium and Magnesium Ions on Accumulation and Translocation of Cadmium in Rice

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Abstract

Rice is one of China's most important food crops, and it is considered the primary source of human exposure to cadmium (Cd) pollution. A hydroponic experiment was performed to investigate the effect of calcium (Ca) and magnesium (Mg) on the absorption, distribution, and translocation of Cd in rice. Under the concentration gradient of Ca, Mg, and Cd, the concentrations of Cd in rice tissues were determined. The results revealed that the existence of Ca and Mg in the environment could benefit rice growth and limit the accumulation and translocation of Cd in plants. Cd concentrations in rice plants were as orders: roots > stems > leaves ≈ panicles ≈ husks > grains. While Cd content in rice grains decreased significantly under high Ca and Mg concentrations, this pattern was not observed under low and medium concentrations. Ca^{2+} and Mg^{2+} ions significantly influenced the translocation of Cd in the environment-rice system. Under the Ca (Mg)-deficient and Ca (Mg)-rich conditions, the husk and panicle played an essential role in hindering Cd transport to the rice grain, respectively. At the same concentration, the effect of Ca on the decrease of Cd bioconcentration was greater than that of Mg. An apparent antagonism was observed between Cd and Ca (Mg) in different parts of the rice plant. Altogether, the results of this study indicate that it was possible to plant and grow rice in Cd-polluted soil and that the accumulation and translocation of Cd in rice plants could be reduced by optimizing soil nutrient elements.

1. Introduction

Cadmium (Cd), a toxic heavy metal, has recently gained more attention due to various human activities, such as mining, smelting, sewage sludge, chemical fertilizers, and pesticides (Bin et al. 2013, Römkens et al. 2009). Cd is present in many foods, as it can be absorbed by grain crops, accumulate in the edible parts, and then enter the food chain (Liu et al. 2015). Rice is a staple food in China, especially in the south, and it is the primary exposure source of Cd in humans due to the ingestion of contaminated rice grown in high Cd soils (Feng et al. 2010). Long-term consumption of Cd-polluted rice may cause serious health problems, such as anemia, cancer, heart attack, proteinuria, lung disorder, emphysema, and osteoporosis (Mei et al. 2017). In recent years, the occurrence of notorious itai-itai disease in Japan was connected to the intake of Cd-contaminated rice (Järup &Åkesson 2009).

Given its Karst topography, the Guizhou province has a high Cd content in the soil related to the high local geochemical background (Chen et al. 2015). According to China National Environmental Monitoring Centre (CNEMC 1990), the background content of Cd in Guizhou is 1.244 mg/kg, the highest concentration in China. Cd is mainly sourced from the weathering and pedogenesis of carbonate rocks with high Cd and Calcium (Ca) content (Li et al. 2020). Pu et al. (2015) and Fang et al. (2007) found that most soil samples in Guizhou Province were rich in Ca^{2+}, Mg^{2+}, $CO_3{}^{2-}/HCO^{3-}$, and soil solutions contained an abundance of Ca^{2+} Mg^{2+} ions.

Given that calcium oxide (CaO) mainly controls soil pH, researchers found that the Ca^{2+} ions in soil were responsible for its increased pH (Hamid et al. 2020). Some studies have suggested that calcium ion channels may allow Cd to enter into plant cells (Liu et al. 2020, Perfus-Barbeoch et al. 2002). Ca plays an essential role in plant growth as a significant nutrient element. Meanwhile, studies have shown considerable competition between Ca and Cd at the transport sites of plant cell membranes (Qin et al. 2020). It is believed that Ca alleviates the toxicity of Cd in plants through three processes: First, Ca alleviates the accumulation of Cd in plants by regulating plant growth; Secondly, Ca increases the activity of antioxidant enzymes in plants to relieve oxidative stress caused by Cd; Thirdly, Ca enhances photosynthetic, physiological, and metabolic activities in plants to regulate the signaling pathways that depend on calcium transmission (Guo et al. 2018, Huang et al. 2017, Khan et al. 2020, Rahman et al. 2016). However, some studies have shown that calcium can also increase the absorption of Cd by *Sesbania sesban* and *Brassica juncea*

(Franziska &Hans 2015, Suzuki 2005). Therefore, whether Ca^{2+} ions decrease Cd accumulation in rice plants requires further study.

Magnesium (Mg), a component of the chlorophyll molecule, significantly influences the synthesis of nucleic acids and proteins for photosynthetic energy (Chen et al. 2017b, Ismail et al. 2008). Mg is the fourth essential nutrient element for plant growth and coexists with Ca, potassium (K), sodium (Na), and other elements in the soil. All of these elements inhibit the uptake of Cd in plants. Mg competes with heavy metal ions during uptake by the roots and affects the accumulation and transport of Cd in the plant. Applying Mg fertilizer to Cd-polluted land inhibits the availability of Cd in the soil. Studies found that Mg-deficiency increased the absorption and accumulation of Cd in rice seedlings while adding Mg^{2+} ions alleviated the Cd stress of rice seedlings. Mg deficiency can influence the physiological metabolism of rice, leading to the increased expression of Cd transporter OsiRT1, Oszip1, and Oszip3 in the plant, inducing increased Cd uptake and translocation by the roots (Chou et al. 2011).

External environmental factors (such as soil pH, Eh, and organic matter) can also impact the uptake of Cd in rice and its translocation processes (Chen et al. 2017a, Honma et al. 2016, Liu et al. 2013). As a result, soil remediations often focus on reducing the availability of heavy metals in the soil by increasing its pH. Calcium magnesium phosphate can promote the development of iron plaque on the root surface, thereby decreasing the Cd concentration and increasing the free amino acid concentration in grains, thus significantly limiting the accumulation of Cd in rice root protoplasts (Cai et al. 2021, Zhao et al. 2020). However, the potential influence of Ca^{2+} and Mg^{2+} ions under the same concentration conditions, which have a more significant blocking effect on cadmium, remains unclear. We conducted a hydroponic experiment to investigate: (i) the uptake, translocation, and accumulation of Cd in rice plants; (ii) the effect of Ca^{2+} and Mg^{2+} ions on the absorption, distribution, and translocation of Cd in rice; and (iii) the effect difference between Ca and Mg on Cd in rice.

2. Materials And Methods

2.1 Plant material and experimental design

The rice cultivars, C Liangyouhuazhan, were obtained from the Rice Research Institute, Guizhou Academy of Agricultural Sciences. Sterilized (with 5% NaCl for 15 min) healthy seeds were cleaned with deionized water and placed on moist filter paper for germination in the dark conditions of 25 ± 1°C. The germinated seeds were sown in the seedbed at Rice Research Institute of Guizhou Academy of Agricultural Sciences on May 1, 2020.

When the fourth leaf appeared, healthy seedlings were transplanted to hydroponic pots containing 1/4 Hoagland's nutrient solution and treating solution. The pH was adjusted to pH 5.5-6.0 using 1 M HCl or NaOH. The hydroponic pots were placed into a controlled plant growth chamber. The growing conditions were: 16 h of light and 8 h of darkness per day, a daytime temperature of 26°C, and a nighttime temperature of 20°C, while the relative humidity was 60%.

The treating solutions were: (1) only Cd treatments: including 0.2, 0.8 and 2.0 mg/L $CdCl_2$ solution, regarded as Cd1, Cd2 and Cd3, respectively; (2) Cd + Ca treatments: combined 0.2, 0.8 and 2.0 mg/L $CdCl_2$ solution with 0.1, 0.25 and 0.5 g/L $CaCl_2$ solution in pairs, for a total of nine groups, regarded as Cd1Ca1, Cd1Ca2, Cd1Ca3, Cd2Ca1, Cd2Ca2, Cd2Ca3, Cd2Ca1, Cd2Ca2 and Cd3Ca3, respectively; (3) Cd + Mg treatments: combined 0.2, 0.8 and 2.0 mg/L $CdCl_2$ solution with 0.1, 0.25 and 0.5 g/L $MgCl_2$ solution in pairs, for a total of 9 groups, regarded as Cd1Mg1, Cd1Mg2, Cd1Mg3, Cd2Mg1, Cd2Mg2, Cd2Mg3, Cd2Mg1, Cd2Mg2 and Cd3Mg3, respectively. The hydroponic experiment was completely randomized with three replicates. The solution was replaced every three days during the whole rice cultivation.

2.2 Sample collection and preparation

The rice samples were collected in the tillering stage (July 30), filling stage (September 14), and mature location (October 7). The roots were soaked in EDTA (10mM) solution for 15 min to remove the adhering Cd. The whole plants were washed with tap water first and then washed with deionized water three times. The roots, stems, leaves, panicles, husks, and grains samples were separated independently, these parts were also oven-dried to a constant weight at 75°C. All parts were weighed, ground into a powder, and passed through a 100-mesh screen before further analysis.

2.3 Chemical analysis

To determine Ca, Mg, and Cd contents, over-dried (0.1 g) samples were immersed in 4 mL nitric acid and 3 mL hydrofluoric acid per sample and dissolved within a high-pressure reactor at 180 °C for 20 h. After digestion, 1 mL perchloric acid was added to it, and the digestion tank was placed at the electric hot plate to dispel the redundant acid until the white smoke stopped. The transparent liquid was filtered and diluted to 10 mL. Ca, Mg, and Cd contents were analyzed using an inductively coupled plasma optical emission spectrometer(ICP-OES, Thermo Fisher 7400). Certified reference material for rice (GBW10044) provided by National Standard Materials Center was used for quality control; the recovery rates of Cd in the plant samples were 91.3%-108.8%.

3. Data Analysis

3.1 Translocation factor and bioconcentration factor

The translocation factor (TF) was defined as the ratio of the Cd concentration in the upper parts of the rice plant to that in the lower regions at a mature stage. The TF was used to evaluate the capacity of plants to translocate Cd (Wang et al. 2021, Yasmin Khan et al. 2017). The TFs of Cd from; the solution to the roots, roots to stems, stems to leaves, leaves to panicles, panicles to husks, and from husks to grains was estimated. The Cd bioconcentration factor (BCF) was defined as the ratio of Cd concentration in rice grains to the total Cd concentration in the nutrient solution. This factor was used to evaluate the ability of plants to accumulate Cd (Jin et al. 2016, Yang et al. 2020).

3.2 Statistical analysis

The statistical relationship among all data was analyzed using one–way analysis of variance (ANOVA), and the least significant difference (LSD) was utilized to determine if significant differences existed between the mean values ($P < 0.05$) with SPSS 19.0. All data were expressed as the mean ± SD (n = 3). All of the figures were generated utilizing Origin 9.2 and CorelDRAW X8 software.

4. Results And Discussion

4.1 Cd distribution in rice plant

Cd distribution in the rice plants of different treatments was determined as roots > stems > leaves ≈ panicles ≈ husks > grains (Fig. 1). The Cd content in the roots, stems, leaves, panicles, husks and grains ranged from 0.08 to 2.43, 0.02–2.21, 0.04–1.55, 0.09–0.95, 0.12–0.53 and 0.07-0.41mg/kg, respectively, and their mean values were 0.92 ± 0.63, 0.62 ± 0.54, 0.37 ± 0.37, 0.30 ± 0.20, 0.26 ± 0.11, 0.17 ± 0.09 mg/kg, respectively. The majority of Cd was present in the roots, which was 2.16, 6.73, and 3.08 times higher than that in grains for Cd1, Cd2, and Cd3 treatments, respectively.

4.2 Effect of Ca and Mg on Cd absorption of rice at different stages

At the tillering stage, the Cd concentration of all rice tissues decreased with the application of Ca^{2+} and Mg^{2+} ions, except for those grown in the Cd1Ca1 treatment (Fig. 2). Cd1Ca1 treatment slightly increased Cd concentration in the root, but the effect was not significant. It is possible that the Cd^{2+} ions were aggressively antagonistic to Ca and Mg ions. Under excessive Cd stress, the addition of Ca^{2+} and Mg^{2+} ions reduced the absorption of Cd in rice during the tillering stage, and the inhibiting effects of Ca^{2+} and Mg^{2+} ions on Cd^{2+} were enhanced with the continued increase of Cd concentrations in the rice plant.

During the filling stage, the Cd concentrations in the roots, stems, panicles, and brown rice ranged from 0.16–2.43, 0.02–2.21, 0.09–0.95, and 0.03–0.49 mg/kg, respectively, and their average values were 1.08 ± 0.71, 0.78 ± 0.65, 0.38 ± 0.22 and 0.20 ± 0.14 mg/kg, respectively. The absorption of Cd in the roots, stems, panicles, and brown rice was also affected by Ca^{2+} and Mg^{2+} ions application. Under the applications of Ca1, Ca2, and Ca3, the Cd concentration of these tissues decreased significantly as compared to the Ca0 treatment. However, in the relatively lower concentrations of Cd, the effects of Ca treatment were not significant. These results suggest that exogenous Ca and Mg influence Cd distribution because they decrease the absorption and translocation of Cd to the aerial parts, protecting them from toxicity.

At the mature stage, the Cd levels in the roots, stems, leaves, panicles, husks, and grains were increased in Ca1 treatments, but their concentrations were reduced by 3.07–61.70%, 7.70-85.47%, 34.41–86.19%, 23.89–62.68%, -2.32-56.36 and 0.80–78.60%, respectively, for Ca2 and Ca3 treatments. This phenomenon was also observed in the Mg treatment. However, the increase of Mg^{2+} ions significantly raised the Cd concentration of all tissues in Cd1Mg1 treatment, especially for the roots and husks. These results suggest that Ca and Mg improve Cd accumulation in rice at low concentrations. In Cd3, Cd3Ca1, Cd3Mg1, and Cd3Mg2 treatments, the Cd concentrations of rice grains reached 0.346, 0.411, 0.303, and 0.214 mg/kg, respectively, which exceed the Chinese maximum permissible concentration for Cd in rice.

4.3 Effect of Ca and Mg on Cd translocation of rice

The translocation factors among tissues in rice plants were significantly different (Table 1). The mean $TF_{solution-root}$ value was higher than most other tissues, suggesting that roots were the main translocation channel of Cd in rice plants with hydroponic culture conditions. A similar trend was found in previous research, Khaliq et al. (2019) found that translocation factors from soil to root were much higher (> 14 times) than those for the other parts. Additionally, the $TF_{panicle-husk}$ (mean value 1.27) was much higher than $TF_{husk-grain}$ (mean value 0.66), indicating that the husk played an important role in hindering Cd transport to the rice grain.

Table 1
Translocation factor of rice plant in different treatments

Cd level	Ca(Mg) level	$TF_{solution-root}$	$TF_{root-stem}$	$TF_{stem-leaf}$	$TF_{leaf-panicle}$	$TF_{panicle-husk}$	$TF_{husk-grain}$	BCF
Cd1	Ca0	1.38	0.83	0.78	0.75	1.22	0.83	0.68
	Ca1	2	0.29	3.07	0.38	1.92	0.43	0.54
	Ca2	1.34	0.49	0.89	0.83	1.71	0.69	0.58
	Ca3	0.78	0.75	0.43	2.01	1.2	1.11	0.67
Cd2	Ca0	1.73	0.54	0.75	0.43	0.99	0.69	0.2
	Ca1	1.4	0.62	0.44	1.38	0.84	0.71	0.31
	Ca2	1.03	0.31	0.87	0.53	2.1	0.52	0.16
	Ca3	0.71	0.19	1.3	1.19	0.99	0.51	0.11
Cd3	Ca0	1.04	0.59	0.99	0.39	0.88	0.82	0.17
	Ca1	0.88	1.12	0.67	0.38	1.03	0.78	0.21
	Ca2	0.58	0.95	0.38	0.62	1.31	0.41	0.07
	Ca3	0.4	0.82	0.26	1.06	1.03	0.4	0.04
Cd1	Mg0	1.38	0.83	0.78	0.75	1.22	0.83	0.68
	Mg1	1.86	0.65	0.76	1.24	1.22	0.47	0.64
	Mg2	1.07	0.81	0.74	1.13	1.53	0.64	0.71
	Mg3	0.77	0.95	0.52	1.36	1.77	0.76	0.7
Cd2	Mg0	1.73	0.54	0.75	0.43	0.99	0.69	0.2
	Mg1	1.34	0.26	0.81	0.81	1.57	0.76	0.28
	Mg2	0.98	0.29	0.45	1.6	1.23	0.5	0.13
	Mg3	0.65	0.3	0.57	1.49	0.92	1.02	0.15
Cd3	Mg0	1.04	0.59	0.99	0.39	0.88	0.82	0.17
	Mg1	0.8	0.73	0.71	0.83	0.64	0.69	0.15
	Mg2	0.61	0.53	0.86	0.35	1.79	0.6	0.11
	Mg3	0.38	0.48	1.04	0.28	1.79	0.73	0.07

The $TF_{solution-root}$ had a similar changing trend between Ca and Mg treatments; concentrations were lower in Mg treatments than in Ca treatments, but the difference was not significant (Fig. 3). Significant negative correlations were observed between Ca content and $TF_{solution-root}$ ($R^2 = 0.69$; $p < 0.05$ for Ca; $R^2 = 0.73$; $p < 0.01$ for Mg), indicating that exogenous Ca and Mg inhibited the absorption and translocation of Cd from solution to rice roots.

Under the Cd1 treatment, the application of Ca and Mg initially induced a decrease in $TF_{root-stem}$, before $TF_{root-stem}$ then increased with their contents growing from 0.1 mg/kg to 0.5mg/kg. These results suggest that Ca and Mg can promote Cd translocation from the roots to stems under low Cd concentrations. Interestingly, the change of $TF_{root-stem}$ in Cd2 was opposite to that in Cd1. $Tf_{root-stem}$ in Cd3 presented a decreasing trend, indicating that Ca^{2+} and Mg^{2+} ions reduced the translocation of Cd from roots to stems when Cd concentration reached a threshold value. Still, the exact threshold at which Ca (Mg) aggravated Cd accumulation required further investigation.

There was no clear trend in the change of $TF_{stem-leaf}$, and the correlation analysis revealed that Ca and Mg had no significant impact on $TF_{stem-leaf}$. $TF_{leaf-panicle}$ was highly and positively correlated with the Ca concentration (R^2 = 0.67; $p < 0.01$), suggesting Ca^{2+} ions promote Cd translocation. The panicles may accumulate more Cd, which is entirely different from other tissues of rice plants.

When Ca (Mg) increased from 0 to 0.25 mg/kg, the $TF_{leaf-panicle}$ and $TF_{panicle-husk}$ had an upward trend, and $TF_{husk-grain}$ had a downward trend, indicating that with the addition of Ca (Mg) from 0 to 0.25 mg/kg, more Cd was translocated from leaves to panicles and then to husks; meanwhile, it reduced Cd translocation from husks to grains. Therefore, in the range of Ca (Mg) concentrations from 0 to 0.25 mg/kg, the husks play an important role in protecting grains from Cd accumulation. We also found that when Ca (Mg) increased from 0.25 to 0.5 mg/kg, $TF_{leaf-panicle}$ and $TF_{husk-grain}$ increased slightly. At the same time, $TF_{panicle-husk}$ decreased, indicating that panicles reduced Cd translocation to the husks and sequentially reduced the Cd accumulation in grains.

As shown in Fig. 4, both the Ca and Mg treatments resulted in the same trend under the Cd1 levels, with the BCF rapidly decreasing in Ca1 and Mg1 treatments before slowly increasing in Ca2, Mg2, Ca3, and Mg3 treatments. However, Ca treatments' rangeability was bigger than Mg treatments, suggesting that Ca^{2+} ions had a more significant effect on the reduction of BCF than Mg^{2+} ions. In Cd2 treatments, the BCF increased first and then decreased with the addition of $Ca2^{+}$ ions, while Mg treatments had a lower BCF than Ca treatments under the low and middle doses condition. Yet these results were reversed when the Ca^{2+} and Mg^{2+} ions contents reached 0.5 g/L. In Cd3 treatments, the addition of Mg^{2+} ions decreased the BCF persistently; Ca treatments showed a trend of increasing first and then decreasing. The decreasing effect of Ca treatments was stronger than that of Mg treatments under the middle and high doses conditions, the minimum BCF in rice was found in Cd3Ca3 treatment. These results indicate an antagonistic effect between Cd and Ca (Mg) that was more robust under the high concentration environmental conditions. Additionally, at the intermediate and high Ca and Mg concentrations, the BCF in Ca treatments was lower than that in Mg treatments, suggesting that the inhibiting effect of Ca to Cd was more significant than Mg.

4.4 The interaction between Cd and Ca (Mg) in rice plant

Ca, Mg, and Cd concentrations among different parts of rice were significantly and positively correlated at the maturity stage (Fig. 5). Here, an apparent antagonism was observed between Cd and Ca (Mg) in other parts of the rice plant, as Cd content was negatively correlated with Ca and Mg concentration, with exceptions in the comparison of Leaves-Cd to Grains-Ca, Panicles-Ca to Grains-Cd, Grains-Cd to Grains-Ca, Stems-Cd to Panicles-Mg and Leaves-Cd to Panicles-Mg. The Cd concentration in grains was significantly and negatively correlated with Ca content in panicles and grains, with the coefficients being − 0.586* and − 0.631*, respectively. We concluded that Ca content in the rice panicle and grain have a blocking effect on Cd accumulation in grain.

5. Discussion

An increasing number of reports has indicated that Cd toxic accumulation in rice is alleviated by Ca and Mg by reducing its uptake and accumulation. The Cd distribution in the rice plant of our study is consistent with previous research (Khaliq et al. 2019). Cd is poorly translocated to aerial tissues and generally accumulated in its roots. The roots are in direct contact with the external environment and may act as an effective barrier to reduce the uptake and translocation of Cd due to the unique structure of the Casparian strip of the endothelial layer in roots cells (Guo et al. 2021, Wu et al. 2018). Previous studies found that Cd concentrations in rice roots were more than ten times greater than in the aerial tissues, and Cd was localized in the cell walls, indicating that the cell walls of root effectively reduced the transport of Cd to the aerial organs (Liu et al. 2016, Yu et al. 2020).

In this study, Cd contents in all tissues decreased substantially with Ca, suggesting an interference between Ca^{2+} and Cd^{2+} ions. Cd is a nonessential and toxic element for rice plants, and it is believed to use Ca transporters to enter the cells due to the chemical similarity (Tian et al. 2016, Ye et al. 2020). Through the specific translocation channels, Ca^{2+} ions restrict the uptake and translocation of Cd^{2+} ions by root and consequently influence the plant Cd contents (Kanu et al. 2019). A previous study found while the plant was under Cd stress, the concentration of Ca in the cytoplasm rose sharply, and the signal was transmitted rapidly among cells, allowing plants to respond quickly to Cd stress (Guo et al. 2018). Ye et al. (2020) found that cCd stress increased the abundance of amino groups, hydroxyl groups, cellulose, and epoxide in rice, inducing structural damage to the plasma membrane and cell wall, but that Ca treatments reduced this adverse effect.

Exposure to Cd results in structural changes in chlorophyll, mainly by replacing divalent Mg^{2+} ions, resulting in the decomposition of chlorophyll molecules (Kanu et al. 2019). Khaliq et al. (2019) found that Mg contents negatively correlated with Cd contents in upland rice, but no significant correlation was found between Cd and Mg concentration in the leaves. The difference between our studies may be the distinctions of planting patterns and rice cultivars. Reports showed the content of Cd in the shoots and roots of rice seedlings under the Mg-deficiency condition was higher than that of normal growth rice seedlings (Chou et al. 2011). KASHEM andKAWAI (2007) suggest using Mg-containing materials as soil conditioners to improve the imbalance between exchangeable Ca and Mg in the Japanese agricultural soil. The addition of Mg in nutrient solution could promote plants' growth in a Cd-contaminate environment, reduce the Cd concentration, and detoxify the physiological Cd toxicity in plants.

Previous reports found Ca significantly decreased the concentration of Cd in rice roots. Yet, the addition of Ca at different concentration gradients significantly increased the translocation of Cd from roots to shoots in rice plants (Ye et al. 2020, Zhang et al. 2020). The present study was different from these, as we documented Ca applications that decreased Cd concentrations in both roots and stems, and the $TF_{root-stem}$ differed in different Cd levels. With the Ca (Mg) concentration raised from 0 to 0.25mg/kg, $TF_{leaf-panicle}$ and $TF_{panicle-husk}$ increased simultaneously; meanwhile, $TF_{husk-grain}$ decreased, and rice grains accumulated a little Cd. These results suggest that the deficiency of Ca and Mg actually enhanced the Cd translocation from leaves to panicles and then to the husks. In contrast, the husks represented a barrier to prevent Cd from translocating to the grains. Another interesting finding was that when Ca (Mg) concentration reached 0.5 mg/kg, $TF_{panicle-husk}$ decreased. At the same time, $TF_{husk-grain}$ concurrently increased, suggesting that panicles could accumulate more Cd and reduce Cd translocation to husks and then to grains. Therefore, panicles likely play a protective role in preventing Cd from translocating to edible parts in the high-Ca (Mg) environment. In sum, in both Ca (Mg)-deficient and Ca (Mg)-rich conditions, there was were tissues that reduce Cd translocation to the grains. This result may be the internal physiological regulation of the rice plant, and the mechanism remains to be studied in the future.

Comparing the bioconcentration factors, the addition of Ca could reduce BCF to a greater extent than that of Mg. The difference may be the nutritional requirement of Ca was greater than that of Mg in rice, and Ca was involved in more metabolism regulation processes. Through the transport channels competition and other ways, Ca influenced Cd accumulation more than Mg.

6. Conclusion

This study identified that the existence of Ca^{2+} and Mg^{2+} ions in the environment could have a beneficial effect on rice plants' growth by limiting the accumulation and translocation of Cd in plants. Cd distributions in rice plants were as follows: roots > stems > leaves ≈ panicles ≈ husks > grains. Cd content in rice grains decreased significantly under high Ca and Mg concentrations, but the effect was not evident under low and medium concentrations. Ca and Mg ions significantly influenced the migration of Cd in the environment-rice system. Under the Ca (Mg)-deficient and Ca (Mg)-rich conditions, the husk and panicle played an essential role in hindering Cd transport to the rice grain, respectively. At the same concentration, the effect of Ca on Cd bioconcentration was greater than that of Mg. An apparent antagonism was observed between Cd and Ca (Mg) in different parts of the rice plant.

In this hydroponic experiment, the effects of Ca^{2+} and Mg^{2+} ions on the absorption, accumulation, and translocation of Cd in rice plants were analyzed from the aspect of Cd concentrations. In future studies, molecular biology, genomics, and other methods should be used further to study the internal physiological regulation of rice plants. Under the Ca (Mg)-deficient and Ca (Mg)-rich conditions, the changes of Cd translocation in panicles and husks are also a focal point for research in the future.

7. Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

All data generated or analyzed during this study are included in this published article and its supplementary information files.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Xiangying Li: Conceptualization, Methodology, Visualization, Software, Writing-original draft. Lang Teng: Investigation, Resources, Formal analysis, Data Curation. Tianling Fu: Validation, Investigation. Tengbing He: Writing–review&editing, Supervision, Validation. Pan Wu: Writing–review&editing, Project administration, Funding acquisition.

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Figures

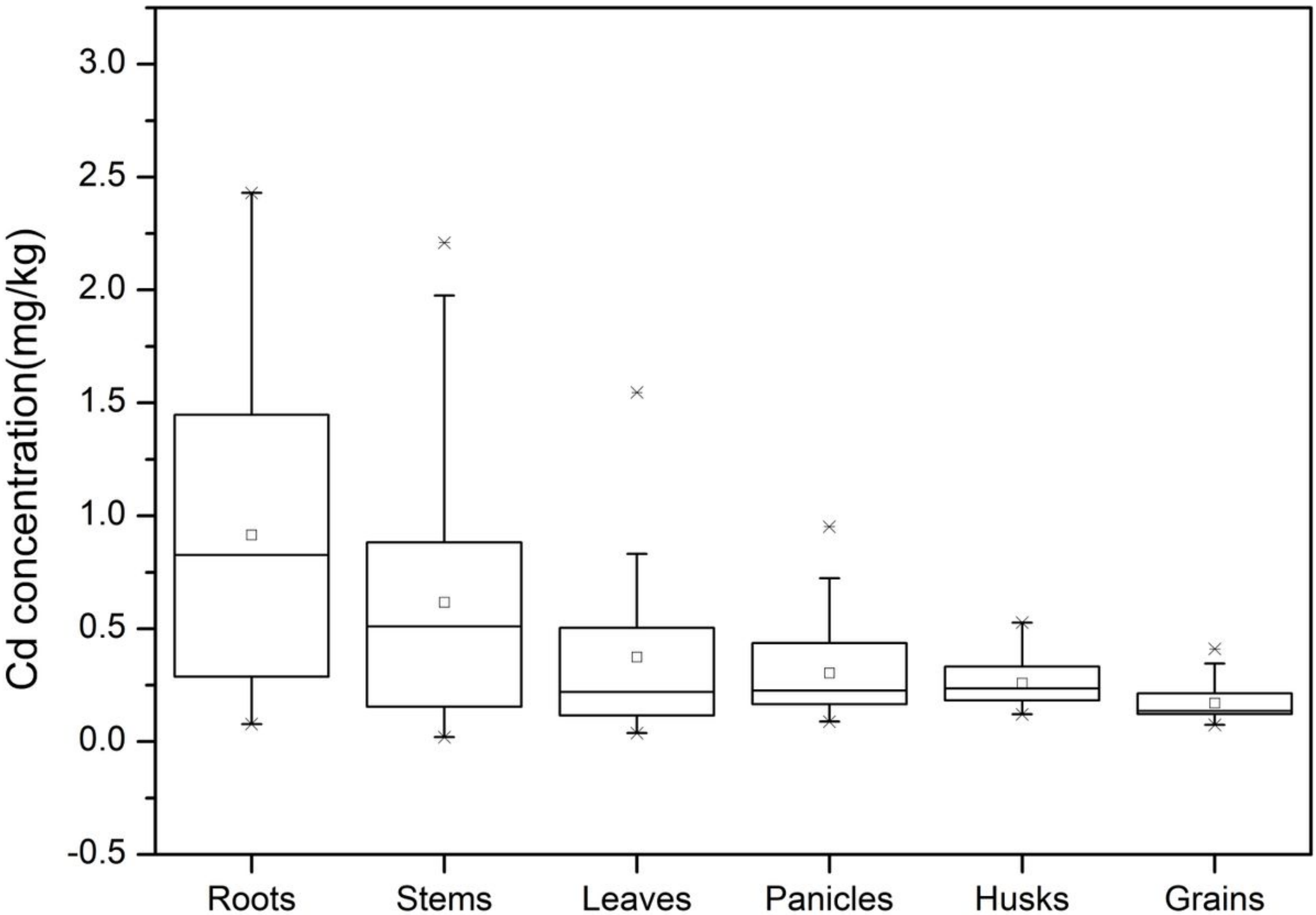

Figure 1

The Cd distribution in different parts of rice.

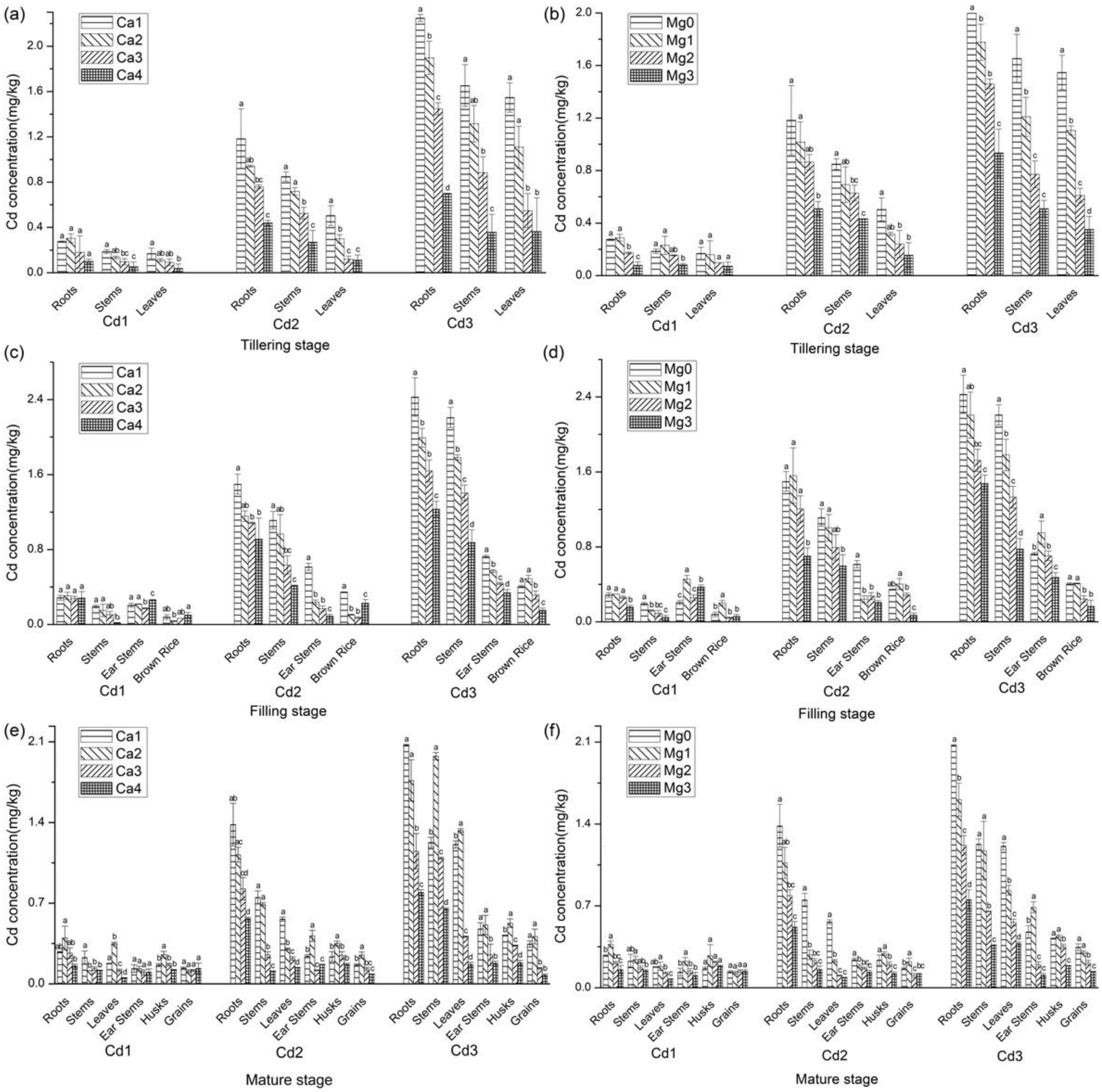

Figure 2

Effect of Ca (a,c,e) and Mg (b,d,f) on Cd distribution at different stages (Error bars represent standard deviation). Different letters above the bars indicate a significant difference ($p < 0.05$) among Ca (Mg) treatments within the same Cd levels.

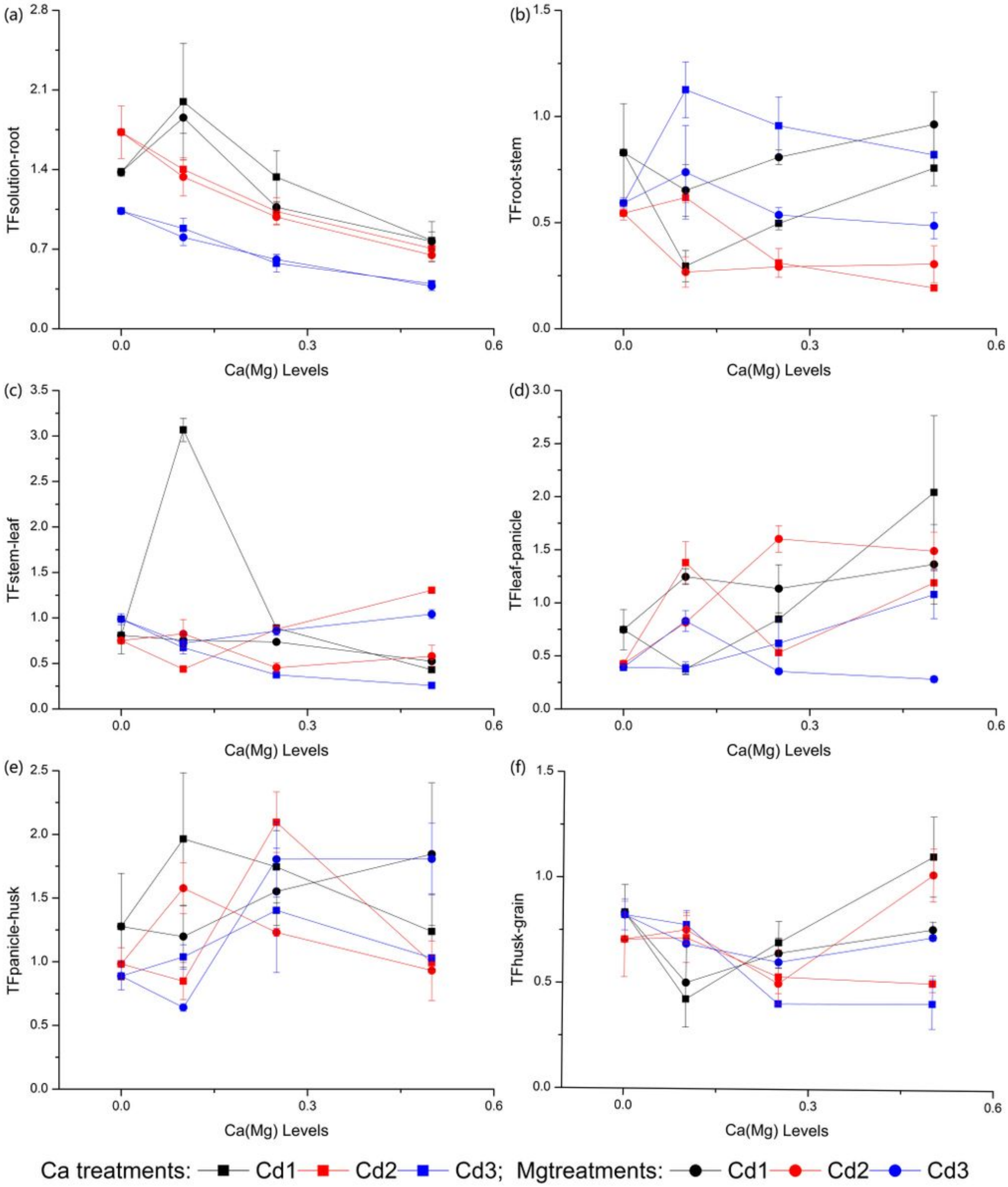

Figure 3

Effect of Ca and Mg on translocation factor of rice plant. a TFsolution-root; b TFroot-stem; c TFstem-leaf; d TFleaf-panicle; e TFpanicle-husk; f TFhusk-grain. Error bars indicate standard deviation.

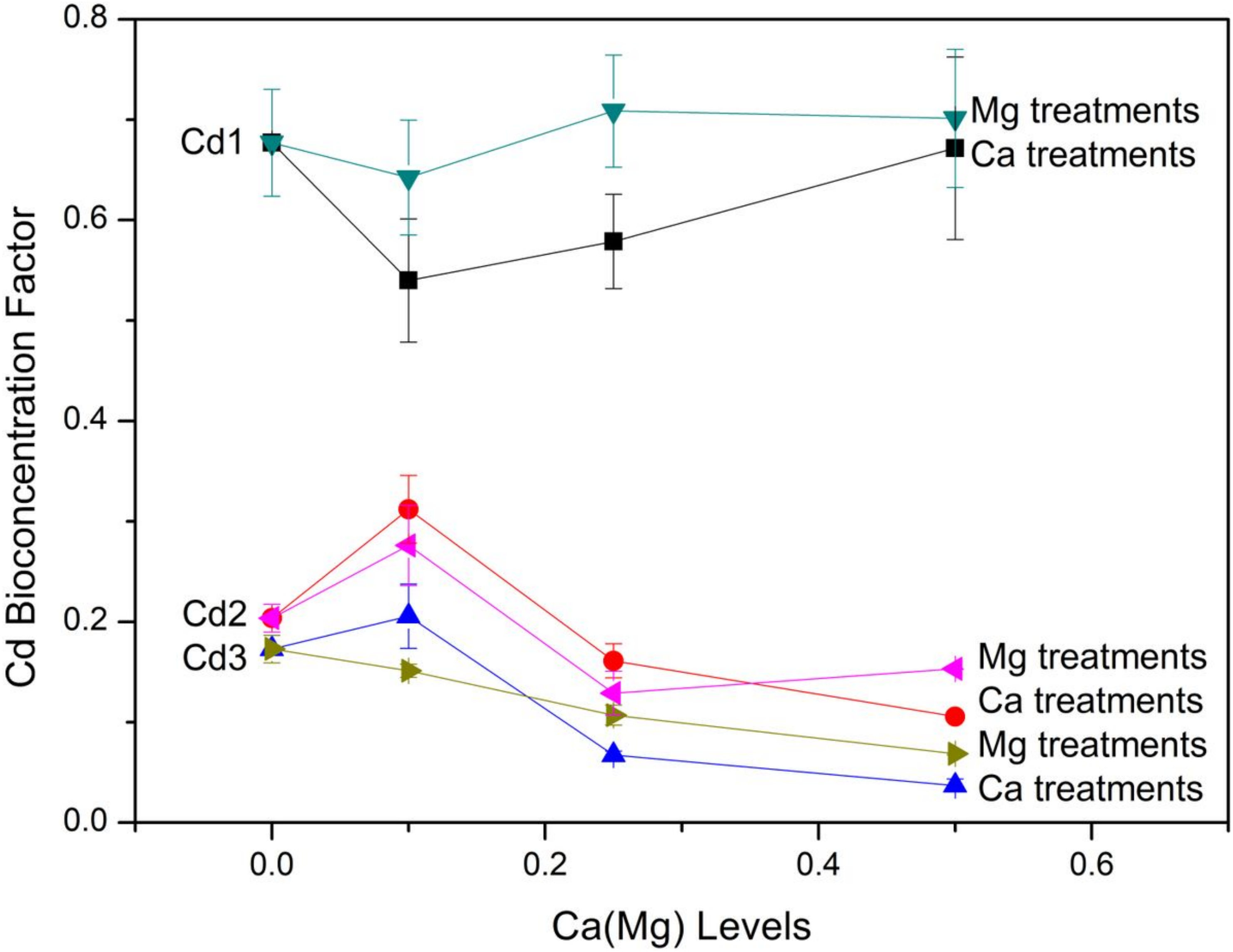

Figure 4

Comparation of bioconcentration factor between Ca and Mg treatments.

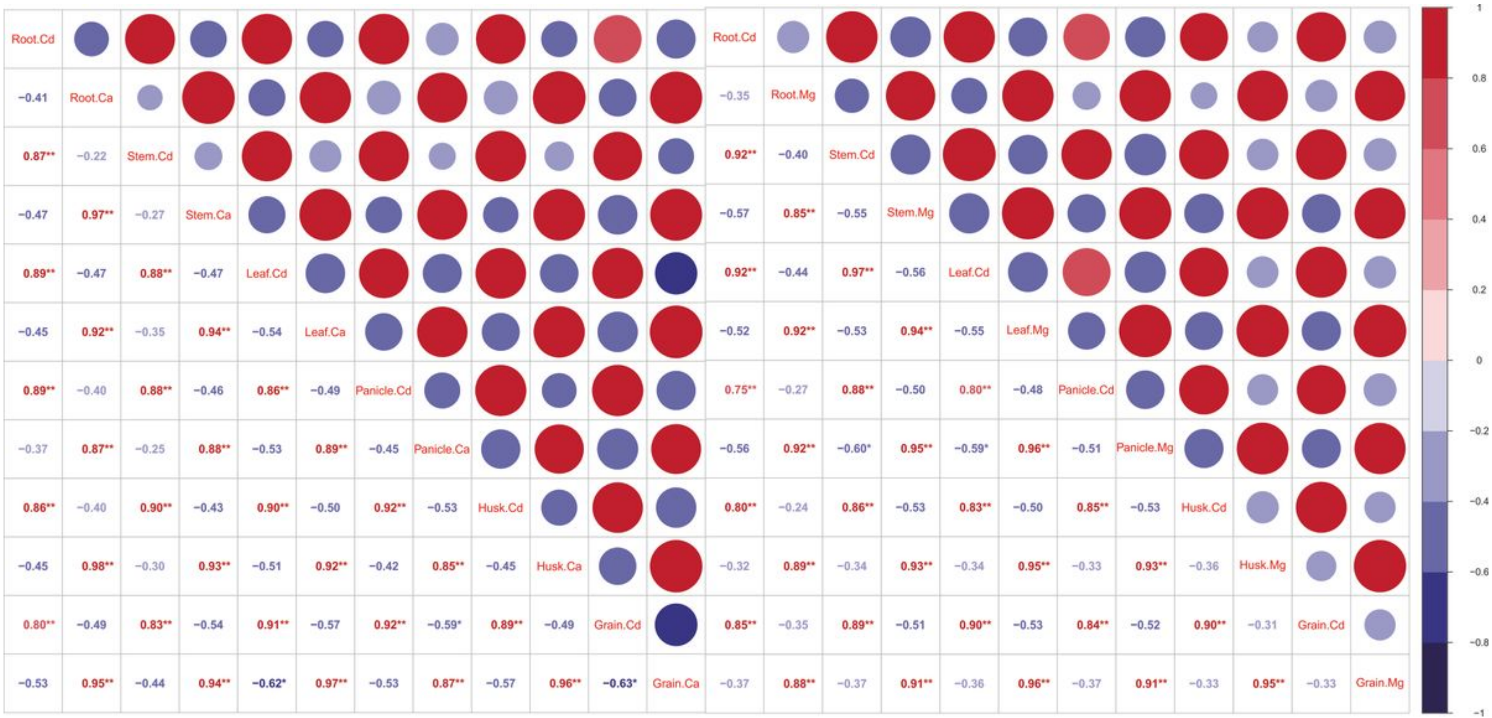

Figure 5

Correlation analysis of Cd and Ca (Mg) content in rice at a mature stage.