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Research Article

Uptake and Translocation of Cesium in Lettuce (*Lactuca sativa* L.) under Hydroponic Conditions

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The uptake of radiocesium (RCs) by plants is key to the assessment of its environmental risk. However, the transfer process of RCs in the water-vegetable system still remains unclear. In this work, the uptake and accumulation processes of Cs^+ (0-10 mM) in lettuce were explored under different conditions by using hydroponics. The results showed that the higher exposure concentration of Cs^+ could lead to a faster uptake rate and would be beneficial to the uptake and accumulation of Cs^+. The uptake of K^+ by roots and leaves was inhibited significantly when Cs^+ concentration increased, but unapparent for Ca^{2+} and Mg^{2+}. It was found that the higher K^+ and Ca^{2+} concentration was, the higher inhibition was found for the uptake of Cs^+ in root. The uptake of Cs^+ leads the decrease of chlorophyll content and brought a negative effect on plant photosynthesis, consequently, a negative effect on lettuce morphology and obvious decrease of biomass and root length. The contents of glutathione (GSH), malondialdehyde (MDA), and root vitality were increasing during the growth following stress of high concentrations of Cs^+, which caused stresses on the antioxidant system of lettuce. The enrichment coefficient for Cs^+ in leaves was in the range of 8-217. Moreover, the transfer factor was in the range of 0.114-0.828, which suggested that the high Cs^+ concentration could enhance the transfer of Cs^+ from lettuce root to leaf. This study provides more information on the transfer of RCs from water to food chain, promoting the understanding of the potential risk of RCs.

1. Introduction

Radiocesium (RCs) is one of the typical and important fission products of uranium in terms of the high fission yield (~10%), with low melting temperature and long half-life. Due to the high radiotoxicity and mobility, RCs is easy to transfer in the environment and accumulate in the food chain, which would possibly induce harm to the whole ecological environment. In the environment, the sources of RCs mainly include the nuclear weapon tests, the leakage of nuclear facility sites, and the nuclear accidents such as Chernobyl and Fukushima. In addition to RCs, the stable cesium also has a certain harm to the environment, mainly originating from the industrial production activities, such as the processes of mining and milling and the production of crushed cesium grenade ore [1]. Moreover, the natural erosion and weathering of rock could also contribute to the accumulation of Cs in water (including ground and surface water) and soil [2].

In the environment, RCs and the stable cesium could enter plants through the roots growing in contaminated water and soil [3]. In general, the translocation of RCs from soil to plants should experience the soil-water, soil-plant, and water-plant interfaces, in which the water-plant interface is extremely important to the migration and translocation of RCs. Plant roots take up Cs^+ from the soil solution firstly and then transported simplistically to the xylem [4]. Due to the similar chemical properties to K^+, there is a relatively high competitive effect between K^+ and Cs^+ at binding sites in proteins [5]. In addition, Cs^+ could inhibit the inward-rectifying potassium channels in the plasma membranes of plant cells, e.g., *AtAKT1* in Arabidopsis (*Arabidopsis thaliana*) [4, 6]. Theoretical

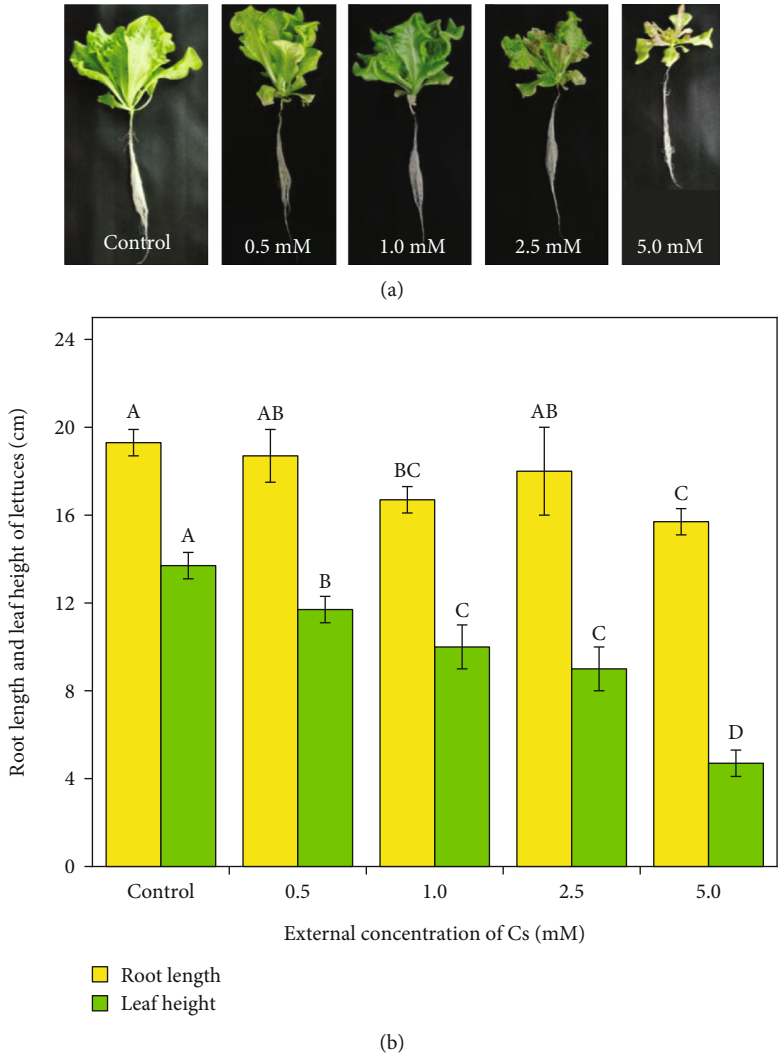

FIGURE 1: Effects of Cs^+ exposure on lettuce root lengths and leaf height. Notes: the different lowercase letters indicate that significant differences ($P < 0.05$) exist between treatment groups with different Cs levels in lettuce (LSD test).

models suggest that, in K-replete plants, the influx of Cs^+ to root cells is predominant through voltage-insensitive cation channels (*VICCs*), with "high-affinity" K1/H1 symporters transporting the remainder [4]. In fact, cesium is not a nutrient element required for the plant growth, and the cells in plant could be damaged due to the radiation of RCs [7]. It is reported that Cs^+ exhibited an obvious phytotoxicity when its concentration was higher than 0.2 mM [4, 8]. Previous studies have confirmed that the accumulation of stable Cs could result in a harmful reaction in plants, which would affect physiological and metabolic processes of plants such as growth, photosynthetic reactions, and genetics [9–12].

Transfer factor (TF) is a macroscopic parameter that integrates soil chemical, biological, hydrological, physical, and plant physiological processes. In a simple model, these transfer parameters represent the ratio of radionuclide concentrations in roots and shoot parts. To determine the radiological impacts, it is essential to understand the uptake and translocation processes and pathways in the soil-plant system. Generally, plants do not discriminate stable and radioactive cesium. Therefore, a high correlation about TFs was frequently observed for ^{133}Cs, ^{134}Cs, and ^{137}Cs [13, 14]. Consequently, the long-term transfer processes of RCs could be predicted well by using the transfer of stable Cs from water and soil to plants. A high distribution correlation between ^{137}Cs and ^{133}Cs in plants showed no significant difference in the uptake of RCs and stable Cs in sunflower. Thus, the uptake patterns of ^{137}Cs and ^{133}Cs are similar in plants [13].

Vegetable is an important medium and a key link for the transmission of mineral elements in the natural environment to humans. Lettuce (*Lactuca sativa* L.) is a popular leafy vegetable and is available worldwide. Lettuce is a good model for identifying determinants controlling cesium accumulation in plant tissues and developing breeding strategies aimed at limiting heavy metal accumulation in edible tissues [15]. In this work, we conducted hydroponic experiments of lettuce by using stable cesium at different treatment conditions. The objective of the cultivation experiment was to elucidate the effects of various factors on Cs^+ uptake and migration, such as Cs^+ concentration, the growth time, and the coexisting ions. Moreover, we attempted to evaluate the

Table 1: Effects of exposure to Cs^+ on biomass of lettuce.

Cs treatment (mM)	Leaf fresh weight (g)	Root fresh weight (g)	Leaf dry weight (g)	Root dry weight (g)
0	42.447 ± 10.96^a	3.247 ± 0.513^a	2.604 ± 0.526^a	0.247 ± 0.066^a
0.005	34.853 ± 2.491^a	2.747 ± 0.264^a	2.318 ± 0.211^a	0.207 ± 0.026^{ab}
0.05	36.100 ± 4.603^a	3.183 ± 0.619^a	2.659 ± 0.055^a	0.239 ± 0.039^a
0.5	37.537 ± 7.342^a	3.227 ± 0.567^a	2.403 ± 0.524^a	0.222 ± 0.037^a
1.0	31.230 ± 0.142^a	2.640 ± 0.529^a	2.062 ± 0.197^b	0.183 ± 0.036^{abc}
5.0	18.710 ± 5.779^b	1.523 ± 0.701^b	1.370 ± 0.423^b	0.118 ± 0.034^c
10.0	16.207 ± 2.199^b	1.490 ± 0.191^b	1.438 ± 0.322^b	0.132 ± 0.026^{bc}

Values are mean ± SD ($n = 3$ individual plants). The same letters and ns indicate no significant difference at the 5% level by Tukey's multiple range test.

potentiality of Cs^+ entering plants by enrichment coefficient (EC) and TF.

In this study, our work enhanced the understanding of the migration of RCs through the environment to food chain. It will have a well prediction to the potential risk of RCs for the human health in the future.

2. Materials and Methods

2.1. Plant Culture and Nutrient Solution. Lettuce seeds were purchased from Mianyang Huaxia Modern Seed Industry Co., Ltd. In this work, lettuce seeds were sterilized with 0.5% NaClO for five minutes and germinated on the filter paper in a suitable temperature, humidity, and avoidance environment in a greenhouse. And then, lettuce seeds were transplanted in the plastic containers ($12 \times 8 \times 10$ cm in length, width, and height) with Hoagland's nutrient solution. The nutrient solution (pH ~6.0) contained 2.0 mM $MgSO_4$, 5.0 mM $Ca(NO_3)_2 \cdot 4H_2O$, 5.0 mM KNO_3, 1.0 mM KH_2PO_4, and micronutrients (i.e., 4.0 μM $MnCl_2 \cdot 4H_2O$, 0.40 nM $Na_2MoO_4 \cdot 2H_2O$, 0.8 nM $ZnSO_4 \cdot 7H_2O$, 45 nM H_3BO_3, 0.3 nM $CuSO_4 \cdot 5H_2O$, and 0.02 mM $C_{10}H_{12}FeN_2NaO_8$). The growth conditions of lettuce were at $25 \pm 2 \circ C$, $50\% \pm 5$ humidity, and photocycle of 12 h light and 12 h dark. The photon flux density during the light period was 1600 $\mu mol\, m^{-2}\, s^{-1}$.

2.2. Hydroponic Experiments

2.2.1. Effects of Cs^+ Dose and Growth Time. Serial culture solutions with different Cs^+ concentrations were prepared in this study, where Cs^+ concentrations were in the range of 0 ~ 10 mM. After lettuce was transferred into nutrient solution after growing to 10 cm in height, the culture solution was replenished every 3 days and maintained at a volume of 0.8 L. At 3, 6, 9, 12, 15, 18, and 21 days after transplanting, lettuce plants were harvested, and then, the roots were rinsed for five times with tap water and deionized water, respectively. The harvested lettuce was separated into leaf and root parts and followed by dried with 48 h in oven at 75°C. Each treatment was carried out with three replicates and four plants per repetition. Taking Cs^+ concentration and growth time as regulation factors, there were 7 treatment groups, respectively, 49 treatment groups in total.

2.2.2. Effects of Na^+, K^+, and Ca^{2+} on Uptake of Cs^+. High (1.0 mM) and low (0.1 mM) Cs^+ concentrations were selected to estimate the effects of Na^+, K^+, and Ca^{2+} on lettuce here. Na^+, K^+, and Ca^{2+} were results from NaCl, KNO_3, and $Ca(NO_3)_2$ solutions. The concentrations of cation were in the range of 0 ~ 10 mM. Lettuces were cultivated in a completely hydroponic solution firstly. When lettuce grew to 10 cm for each seedling, the cultivate solutions were replaced with different concentrations of Na^+, K^+, and Ca^{2+} that contained Cs^+. Lettuce plants were harvested from each group at 21 days after adding cesium.

2.3. Determination of Cs^+ Concentration. In order to determine Cs^+ content in plants, the dried lettuces were incinerated in muffle furnace at 550°C and grounded into powder for further analysis. Approximate 250 mg powder sample was digested in polytetrafluoroethylene tank with a mixed digestion solution (including 2.0 mL HNO_3 and 1.0 mL H_2O_2), and then, the polytetrafluoroethylene tanks were heated for 24 h in baking oven at 195°C. After that, the pH of each sample was set between 3 and 4, and then, the dissolved lettuce samples were diluted to 10 mL. Supernatants were passed through a 0.45 μm filter. The contents of Cs^+ in leaves and roots were determined by using ion chromatography (Thermo Scientific ICS-600).

2.4. Calculation of Enrichment Coefficient and Transfer Factor. Enrichment coefficient (EC) and transfer factor (TF) were calculated using the following formula:

$$\mathrm{EC} = \frac{C_{\text{leave part}}}{C_{\text{culture solution}}}, \tag{1}$$

$$\mathrm{TF} = \frac{C_{\text{leave part}}}{C_{\text{root part}}}, \tag{2}$$

where $C_{\text{leave part}}$ is the concentration ($mg\, g^{-1}$, with respect to dry weight (dw)) of Cs^+ in leave, $C_{\text{culture solution}}$ is the concentration ($mg\, kg^{-1}$) of Cs^+ in culture solution, and $C_{\text{root part}}$ is the concentration ($mg\, g^{-1}$, dw) of Cs^+ in root.

2.5. Statistical Analysis. The data obtained in the experiments were subjected to one-way analysis of variance (ANOVA) with Tukey's multiple range test to determine the significance of the difference between the mean values using SPSS software. Correlation analysis was performed using a bivariate Pearson test, and the differences were considered statistically significant when $P < 0.05$.

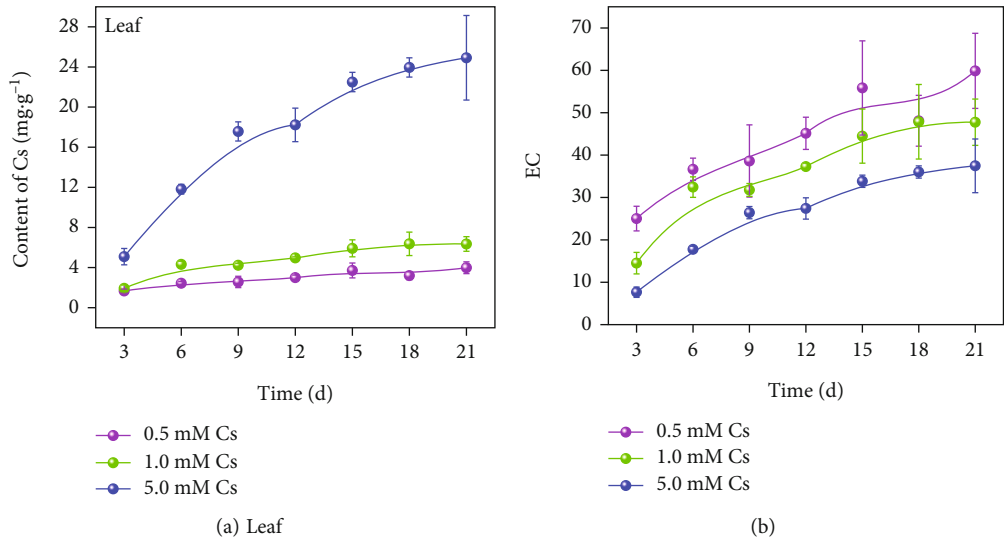

Figure 2: Analysis of the uptake process of cesium in lettuce leaves. (a) was the uptake kinetics of cesium. (b) was the enrichment coefficient of cesium.

3. Results and Discussion

3.1. Effect of Cs^+ Stress on Lettuce Growth. As shown in Figure 1(a), when Cs^+ concentration was higher than 2.5 mM, lettuce leaves appeared withered symptoms and leaf area was significantly reduced. The biomass of lettuces was decreased obviously as revealed in Table 1. Figure 1(b) shows the growth conditions of lettuce root and leaf, and the results indicated that the root length of lettuce was shorter than in the control group and another two groups with 1.0 and 5.0 mM Cs^+, respectively. The leaf height of lettuce was obviously decreasing with the concentration of Cs^+ increased from 0 to 5.0 mM. It could be seen from Section 3.5 that when the concentrations of Cs^+ were greater than 0.5 mM, the chlorophyll content was significantly decreased, which might lead to the inhibition of plant photosynthesis. Therefore, lettuce growth was significantly inhibited under Cs^+ stress, which could be attributed to the disruption of Cs^+ on the enzymatic activity and cellular structure [7]. Previous reports have found that high Cs^+ concentrations could inhibit the growth and the development of *Arabidopsis thaliana*, and the seed germination was reduced with 1.0 mM Cs^+ treatment. Moreover, low Cs^+ concentrations ranged from 500 to 700 μM could cause seedlings to start showing signs of chlorosis [16]. Jung et al. [17] also found that not only chlorosis appeared in specific parts of leaves but also the elongation of primary roots and root hairs was delayed when *Arabidopsis thaliana* was treated with 10 mM CsCl.

As shown in Figure 2(a), the Cs^+ content in leaves treated with 5.0 mM Cs^+ is significantly higher than that in 0.5 mM and 1.0 mM Cs^+. Moreover, the concentration of Cs^+ in leaves obviously increased with the increasing growth time and showed the faster uptake rate at 5.0 mM Cs treatment. It was in accordance with the previous findings that the uptake rate of Cs^+ increased with the increasing biomass of *Napier grass* [18]. As shown in Figure 2(b), the lower Cs^+ level was, the higher EC was observed, and it was more conducive to the enrichment of cesium in lettuce at a long growth time. However, it was noted that the enrichment efficiency of Cs^+ remained a similar level even under various treatment concentrations.

3.2. Evolution of Cs Distribution in Lettuce. As shown in Figures 3(a) and 3(b), the contents of K^+ in lettuce leaf and root obviously decreased with the increase of Cs^+ concentration, while both Mg^{2+} and Ca^{2+} contents did not change significantly. The result indicated that Cs^+ could regulate the uptake of K^+ in terms of the competitive uptake of Cs^+ and K^+. Both Mg^{2+} and Ca^{2+} are alkaline metal elements, and their chemical properties are quite different from Cs^+. In fact, K^+ transport channel has a low affinity to Mg^{2+} and Ca^{2+}; therefore, as expected, there is no obvious influence of Cs^+ and K^+ on the uptake of Mg^{2+} and Ca^{2+} by lettuce. Some previous researches have confirmed that the influx of Cs^+ into root cells was mainly mediated by the alkaline cations, especially for K^+ [4, 19, 20]. Our results confirmed that the stress of Cs^+ could indirectly regulate the uptake of K^+ due to the similar chemical and physical characteristic of Cs^+ and K^+. Sahr et al. [16] found that the transport of K^+ through its transport channels was probably inhibited in the presence of higher Cs^+ levels in leaves, as it was reviewed by [4]. Le Lay et al. [21] observed differences in Cs^+ distribution (1.0 mM) in cells and tissues of plant leaves grown in K-depleted and K-sufficient medium (i.e., 0 and 20.0 mM K^+) and proposed that both elements competed for entry inside plant.

The distribution of Cs^+ in roots and leaves under different culture times is shown in Figures 3(c) and 3(d). The contents of Cs^+ in roots and leaves increased significantly with the increase of culture times under all the Cs^+ treated groups. In general, Cs^+ uptake strongly depends on the plant developmental state, and the interception efficiency of Cs^+ is much higher in mature plants and old leaves [22, 23]. Moreover, it is noted that the content of Cs^+ in roots was much higher than that in leaves at the same culture time in this work (Figures 3(c) and 3(d)), which indicated that more

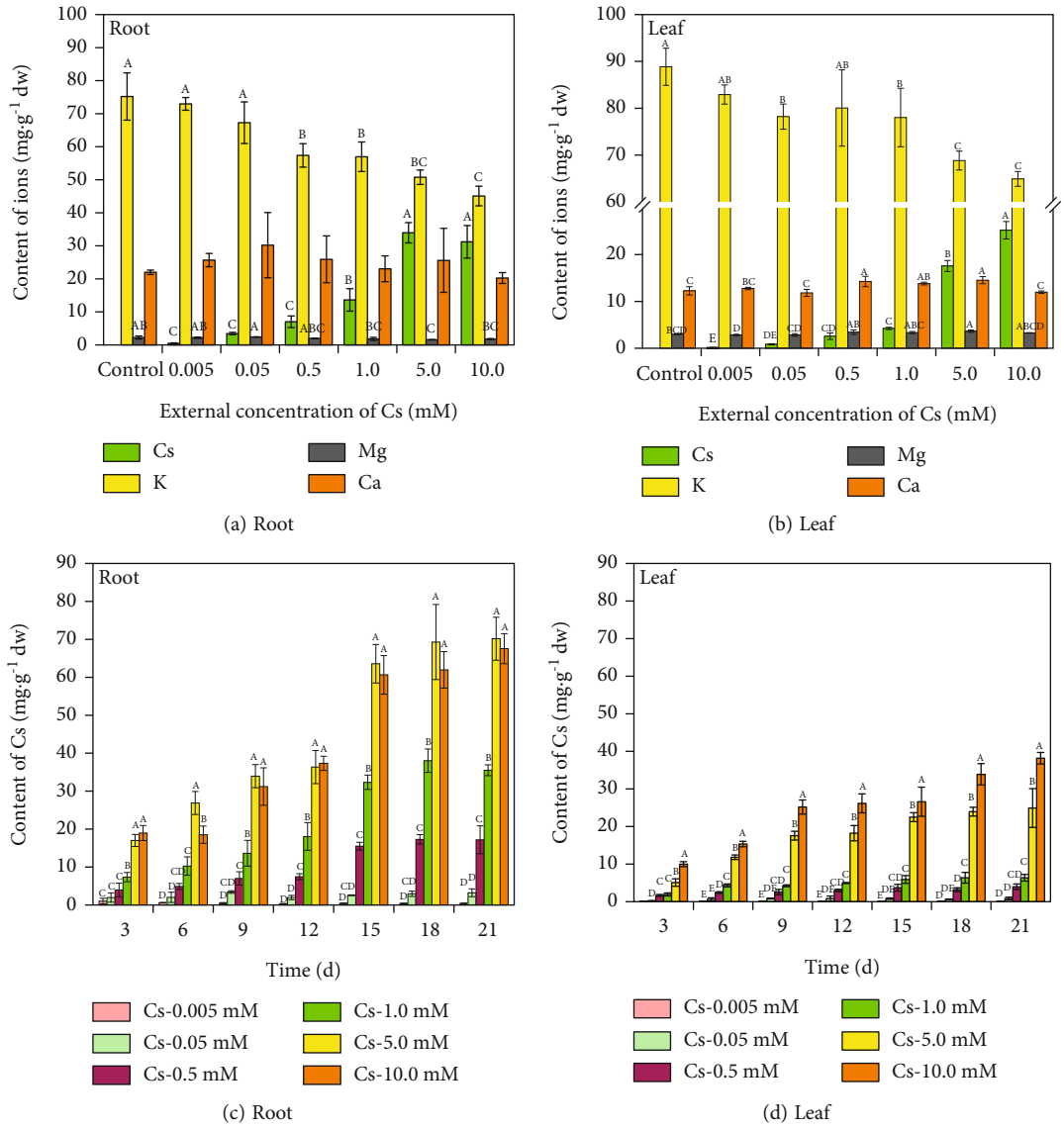

FIGURE 3: Effects of different Cs^+ concentrations and sampling time on the content of each element (Cs, K, Mg, and Ca) in lettuce. (a) and (c) represented changes of element content in root. (b) and (d) represented changes of element content in leaf. Notes: the different lowercase letters indicate that significant differences ($P < 0.05$) exist between treatment groups with different Cs levels in lettuce (LSD test).

Cs^+ would be transferred from root to leaf. An interesting phenomenon was observed that the content of Cs^+ in roots showed a slight decrease when Cs^+ concentration was higher than 5.0 mM (Figures 3(a) and 3(c)). It was possibly due to the fact that high Cs^+ concentration benefits to the accumulation of Cs^+ on/in the root epidermis and cell wall; the Cs^+ concentration in this position is much higher than outer solution, which resulted in the inhibition of Cs^+ uptake. Another possibility was that the water loss and ion channel destruction of root parts further decreased the uptake of Cs^+. However, the content of Cs^+ in leaves still increased even at Cs^+ concentration of 10 mM, possibly because Cs^+ entered in root vascular bundle which was continuing to transport upward under transpiration power in lettuces.

3.3. Regulation of Cations on Cs^+ Uptake and Distribution. Previous researches have reported that K^+, NH_4^+, Ca^{2+}, and Mg^{2+} have an obvious effect on the uptake of plants to RCs [24, 25]. Figure 4 and Figure S1 show the effects of Na^+, K^+, and Ca^{2+} on the uptake and distribution of Cs^+ in lettuce. As shown in Figures 4(a) and 4(b), the contents of Cs^+ in roots and leaves firstly increased in the K^+ concentration range of 0-0.5 mM and then decreased when K^+ concentration was greater than 0.5 mM. The function of uptake and metabolism of K^+ was normal under the low K^+ concentration treatment, so as the K^+ content increased, the uptake of Cs^+ increased. However, when K^+ concentration was too high, there was a competition between K^+ and Cs^+. Moreover, root activities and metabolic functions were inhibited, resulting in a decrease in Cs^+ content. K^+ concentration in the external medium clearly affected the uptake efficiency of Cs^+. The result was consistent with the previous molecular studies indicating the role of the high-affinity K^+ carrier *AtHAK5* in Cs^+ uptake under K-deprivation [26]. In fact, the discrimination of plants to Cs^+

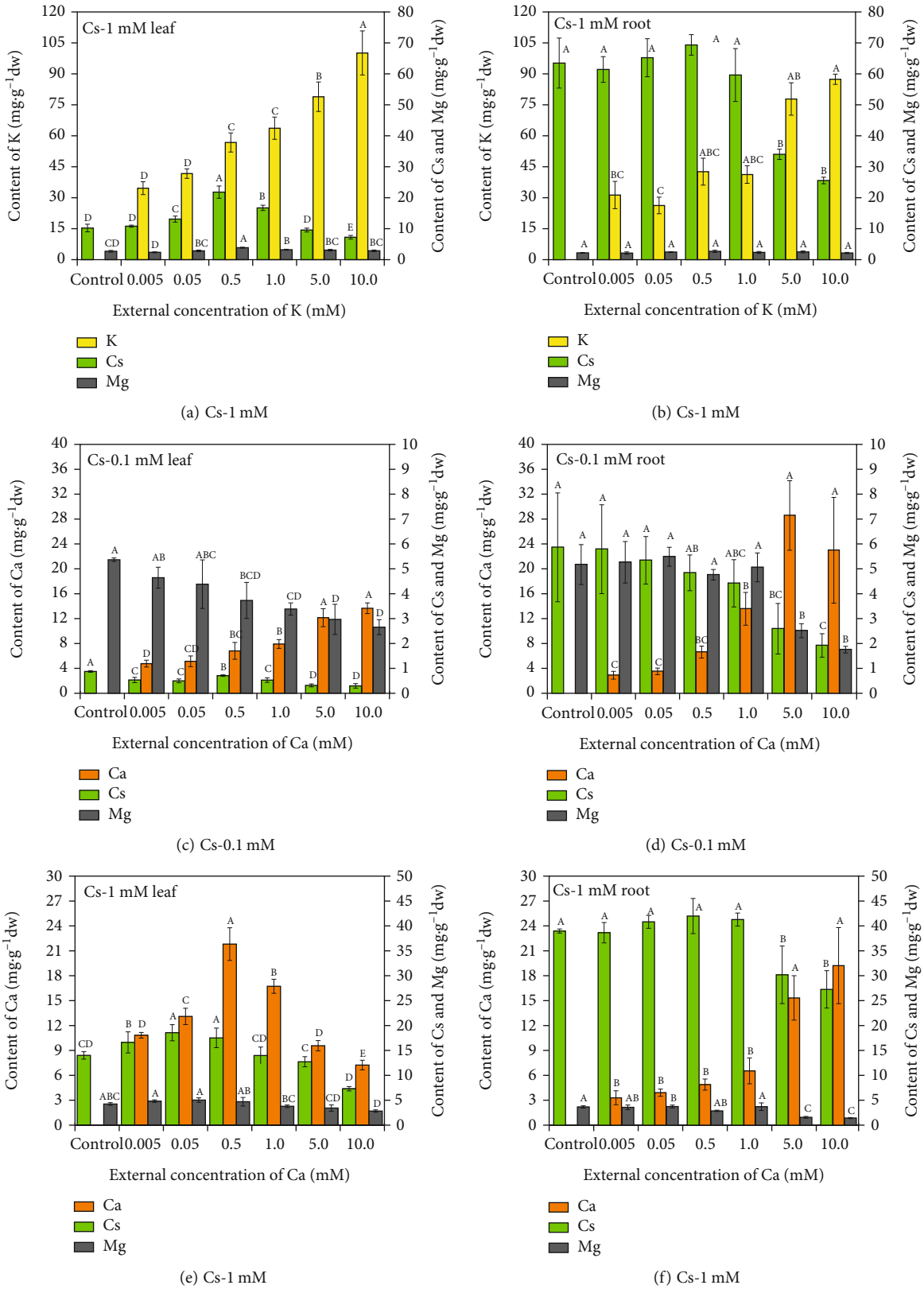

FIGURE 4: The effect of different concentrations of K^+ and Ca^{2+} on the uptake of different ion in lettuces. (a) Cs-1 mM, leaf;and (b) Cs-1 mM, root; were ion contents in the leaves and roots of lettuces treated with K^+ under 1 mM Cs treated. (c) Cs-0.1 mM, leaf; and (d) Cs-0.1 mM, root; were ion contents in the leaves and roots of lettuces treated with Ca^{2+} under 0.1 mM Cs treated. (e) Cs-1 mM, leaf; and (f) Cs-1 mM, root. were ion content in the leaves and roots of lettuces treated with Ca^{2+} under 1 mM Cs treated. Notes: the different lowercase letters indicate that significant differences ($P < 0.05$) exist between treatment groups with different Cs levels in lettuce (LSD test).

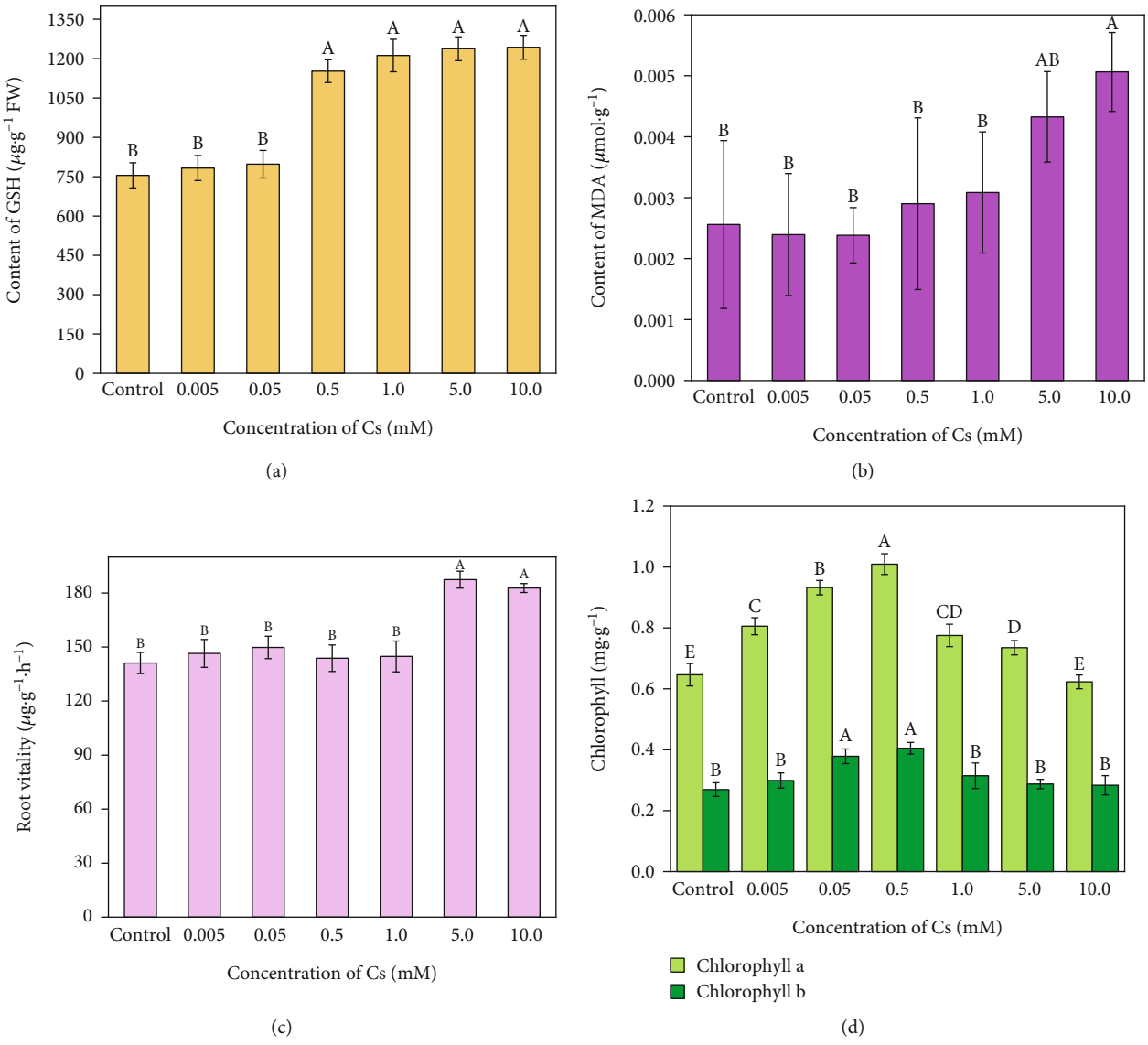

Figure 5: Response of plant physiological indicators to Cs^+ stress. (a–d) The contents of glutathione (GSH), malondialdehyde (MDA), root vitality, and chlorophyll a and chlorophyll b. Notes: the different lowercase letters indicate that significant differences ($P < 0.05$) exist between treatment groups with different Cs levels in lettuce (LSD test).

and K^+ was obviously declining with the decreasing of concentrations of Cs^+ and K^+ due to their similar physiochemical characteristics [27]. Moreover, a large amount of Cs^+ distributed in the cell wall at the low external K^+ concentration, which was also ascribed to the similar adsorption affinity of Cs^+ and K^+ on the root surface [28]. Isaure et al. [29] found that cesium distribution was similar to potassium in *Arabidopsis thaliana* through microfocused synchrotron-based X-ray fluorescence analysis. Both Cs^+ and K^+ were mainly concentrated on the vascular system of stems and leaves, which suggested that Cs^+ could compete with K^+ binding sites in cells [29].

As shown in Figure 4(c), the maximum Cs^+ content in leaves was below 1.0 mg g^{-1} at 0.1 mM Cs^+ treatment group, and Ca^{2+} could slightly inhibit the uptake of Cs^+ in the leaves. However, the content of Cs^+ in roots obviously decreased from ~6.0 mg g^{-1} to ~2.0 mg g^{-1} with the increase of Ca^{2+} concentration in the culture solution (Figure 4(d)). In Figures 4(e) and 4(f), the maximum Cs^+ contents in leaves and roots were below 19 mg g^{-1} and 43 mg g^{-1} at 1.0 mM Cs^+ treatment group, respectively. Simultaneously, the Cs^+ contents in leaves and roots were increased firstly and then decreased with the increase of Ca^{2+} concentration in the culture solution, and the maximum uptake of Cs^+ appeared at 0.5 mM Ca^{2+} treatment (Figures 4(e) and 4(f)). Moreover, the content of Ca^{2+} in leaves gradually decreased from ~22 mg g^{-1} to ~7 mg g^{-1} as the increase of Ca^{2+} concentration from 0.5 to 10 mM (Figure 4(e)). High concentration of Ca^{2+} could lead to excessive salt content in the culture medium and further inhibit the growth and development of roots. Therefore, the uptake of Cs^+ in lettuce was inhibited under the Ca^{2+} stress to some extents. It could be seen from Table S2 that the dry weight biomass slightly decreased to 1.193 g for leaves and 0.130 g for roots in the group at 10.0 mM Ca^{2+}. Due to the competition among coexisting ions in the culture solution, Ca^{2+} indeed

Table 2: Correlation analysis between Cs treatment concentrations and growth parameters and physiological parameters.

Index	Cs concentration	FW_{leaf}	MDA	FW_{root}	GSH	Root vitality	Chl a	Chl b
Cs concentration	1							
Leaf-FW	-0.912**	1						
MDA	0.972**	-0.937**	1					
Root-FW	-0.895**	0.980**	-0.926**	1				
GSH	0.650	-0.734	0.779*	-0.673	1			
Root vitality	0.882**	-0.946**	0.909**	-0.947**	0.602	1		
Chl a	-0.567	0.443	-0.533	0.571	-0.102	-0.454	1	
Chl b	-0.406	0.368	-0.392	0.529	0.006	-0.388	0.952**	1

**At level 0.01 (double-tail), the correlation was significant. *At level 0.05 (double-tail), the correlation was significant.

inhibited the uptake of Mg^{2+} significantly (Figures 4(c)–4(f)). As is well known, porphyrin ring is the main molecular skeleton of chlorophyll, where Mg^{2+} is present in the structure center of porphyrin molecule [30]. The deficiency of Mg^{2+} could significantly inhibit the transformation from coproporphyrinogen III or protoporphyrin IX to chlorophyll [31]. Meanwhile, Mg^{2+} is a synthetic component of many enzymes in plants and an activator of some enzymes [30]. The results clearly showed that high Cs^+ concentrations could cause chlorosis of lettuce leaves (Figure 1(a)) and inhibit the uptake of Mg^{2+}, which indicated that Cs^+ affected the synthesis of chlorophyll and the occurrence of photosynthesis.

No significant change was observed about Cs^+ contents in roots and leaves after lettuce exposed to Na^+ solution (Figure S1C-F). Compared with the K^+- and Ca^{2+}-treated groups, the lowest uptake amount of Cs^+ was observed after Na^+ treated, indicating a stronger inhibition of Na^+ on uptake of Cs^+ by lettuce. The inhibition effect of Na^+ on lettuce growth mainly suppressed the uptake of essential elements and water through the increasing osmotic pressure of root cells [32–36].

As shown in Figure S2A-D, Cs^+ content in roots was much higher than that in leaves, but the accumulation of Cs^+ in leaves was much higher than that in roots, which is due to the fact that the biomass of leaves was much larger than that of roots. Because the leaves of lettuce are the main edible parts, it is deduced that Cs^+ contamination in leaves may bring threats to the safety of food chain and human health.

3.4. Response of Plant Physiological Indicators to Cs^+ Stress. Glutathione (GSH), malondialdehyde (MDA), root vitality, and chlorophyll were determined after a 21-day treatment with Cs^+. The detection methods are shown in the Supplementary Materials (available here). As shown in Figure 5(a), the GSH content significantly increased to ~1200 $\mu g\,g^{-1}{}_{FW}$ from ~800 $\mu g\,g^{-1}{}_{FW}$ when Cs^+ concentration was higher than 0.5 mM. Reactive oxygen was produced due to the oxidative stress when lettuce was subjected to high concentration of Cs^+ stress, which inhibited the normal growth of the plant. To this end, the antioxidant GSH was produced in plant cells to remove the effects of reactive oxygen. And the content of GSH was increased with the increasing of Cs^+ treatment concentration.

In the case of plant tissue aging or under adverse conditions, the membrane lipid peroxidation often occurred, where MDA was one of the final decomposition products of membrane lipid peroxidation [37]. As shown in Figure 5(b), MDA content kept a constant level which was less than 0.003 $\mu mol\,g^{-1}$ when Cs^+ concentration was less than 0.5 mM and then significantly increased to ~0.005 $\mu mol\,g^{-1}$ at 10 mM Cs^+. The results clearly confirmed that the damage of lettuce could be negligible at low dose of Cs^+ due to the low chemical toxicity of stable Cs. However, high Cs^+ concentration could produce certain damage to lettuce tissue. Figure 5(c) shows that the root reactive oxygen species increased significantly in the presence of 5.0 and 10.0 mM Cs^+, and it severely inhibited the growth of plant roots as shown in Figure 1(a). As shown in Table 2, a significant positive correlation was observed among Cs^+ concentration, MDA, and root vitality. Root is the main tissue in which plants absorb water and mineral elements. Root vitality is one of the important parameters to estimate the uptake of nutrients and other substances. Moreover, root vitality could reflect the accumulation of peroxides and free radicals in plants during adversity, which accelerated the oxidation of plant root aging. High Cs^+ level treatment inhibited the growth and the development of lettuce roots, which reduced biomass and influenced the surface area of root part and then further affected the transfer of Cs^+ at the water-root interface.

As shown in Figure 5(d), the contents of chlorophyll a and b increased firstly and then decreased with increasing Cs^+ concentration, and the greatest value occurred at 0.5 mM, which was consistent with the changes in lettuce biomass. Plant physiology began to show obvious symptoms after treated with high Cs^+ concentration. In fact, chlorophyll a could transform light energy into chemical energy by photochemical action in photosynthesis, and chlorophyll b mainly plays a role of absorbing and transferring light energy. The total content of chlorophyll indicates the high sensitivity of lettuce to Cs stress, which affect the photosynthetic efficiency and photosynthetic yield. As shown in Figure 1(a), the leaf color and species of lettuce were changed a lot under different Cs^+ culture solutions, which was

Table 3: Effects of exposure to the different concentrations of Na^+, K^+, and Ca^{2+} on biomass while the lettuces were cultivated in cesium concentration of 1.0 mM.

Treatment	Concentration (mM)	Leaf fresh weight (g)	Root fresh weight (g)	Leaf dry weight (g)	Root dry weight (g)
Na^+	0	17.490 ± 0.879^{ab}	2.110 ± 0.243^{ab}	0.854 ± 0.047^{ab}	0.101 ± 0.009^{bc}
	0.005	21.290 ± 4.312^{a}	2.790 ± 1.012^{a}	1.083 ± 0.227^{a}	0.132 ± 0.027^{ab}
	0.05	8.657 ± 0.761^{c}	0.837 ± 0.163^{c}	0.685 ± 0.048^{b}	0.064 ± 0.007^{c}
	0.5	20.190 ± 4.196^{ab}	2.283 ± 0.660^{ab}	1.147 ± 0.290^{a}	0.157 ± 0.034^{a}
	1.0	18.860 ± 1.380^{ab}	1.933 ± 0.029^{ab}	1.076 ± 0.141^{a}	0.144 ± 0.023^{a}
	5.0	17.390 ± 1.254^{ab}	1.803 ± 0.218^{ab}	0.962 ± 0.078^{ab}	0.133 ± 0.014^{ab}
	10.0	16.090 ± 0.869^{b}	1.317 ± 0.206^{b}	0.875 ± 0.031^{ab}	0.120 ± 0.005^{ab}
	Average	17.14	1.868	0.955	0.122
K^+	0	7.120 ± 1.818^{bc}	0.573 ± 0.204^{bc}	0.670 ± 0.187^{cd}	0.073 ± 0.018^{cd}
	0.005	7.233 ± 1.026^{bc}	0.547 ± 0.083^{bc}	0.726 ± 0.106^{bcd}	0.080 ± 0.010^{bcd}
	0.05	6.920 ± 0.815^{c}	0.450 ± 0.020^{bc}	0.750 ± 0.110^{bcd}	0.088 ± 0.006^{abc}
	0.5	5.210 ± 0.061^{c}	0.330 ± 0.044^{c}	0.534 ± 0.035^{d}	0.056 ± 0.004^{d}
	1.0	9.833 ± 0.822^{b}	0.657 ± 0.081^{b}	0.850 ± 0.069^{abc}	0.087 ± 0.007^{abc}
	5.0	13.317 ± 2.531^{a}	0.980 ± 0.286^{a}	0.944 ± 0.199^{ab}	0.098 ± 0.020^{ab}
	10.0	15.480 ± 1.400^{a}	1.050 ± 0.151^{a}	1.013 ± 0.081^{a}	0.105 ± 0.010^{a}
	Average	9.302	0.655	0.784	0.084
Ca^{2+}	0	9.057 ± 0.663^{c}	1.060 ± 0.098^{ns}	0.684 ± 0.047^{d}	0.065 ± 0.007^{b}
	0.005	9.230 ± 1.297^{c}	1.077 ± 0.395^{ns}	0.731 ± 0.083^{cd}	0.069 ± 0.017^{b}
	0.05	10.053 ± 1.944^{bc}	1.377 ± 0.177^{ns}	0.882 ± 0.121^{bcd}	0.084 ± 0.009^{ab}
	0.5	12.480 ± 1.231^{b}	1.213 ± 0.127^{ns}	0.956 ± 0.066^{ab}	0.090 ± 0.004^{ab}
	1.0	12.330 ± 1.929^{b}	1.040 ± 0.160^{ns}	0.916 ± 0.147^{abc}	0.087 ± 0.018^{ab}
	5.0	17.830 ± 0.807^{a}	1.257 ± 0.260^{ns}	1.110 ± 0.103^{a}	0.108 ± 0.017^{a}
	10.0	16.837 ± 1.990^{a}	1.033 ± 0.199^{ns}	0.994 ± 0.118^{ab}	0.100 ± 0.013^{a}
	Average	12.545	1.151	0.896	0.086

Values are mean ± SD ($n = 3$ individual plants). The same letters and ns indicate no significant difference at the 5% level by Tukey's multiple range test.

possibly related to the lettuce photosynthesis. Kim et al. [38] found that the content of photosynthetic pigments increased or decreased when different varieties of red peppers were irradiated by radioactive elements and believed that this phenomenon was not directly related to the increase in early growth, but related to the varieties of pepper. Therefore, it is speculated that the increase of chlorophyll content is related to the variety of lettuce itself and stimulation of low concentration of Cs on lettuce growth. Previous researchers have found that photosynthesis was inhibited in *A. thaliana* under a wide Cs^+ concentration range from 0.5 to 10 mM [16, 17, 21]. Kamel et al. [39] observed a decrease of chlorophyll content in *Epipremnum aureum* by the addition of RCs to nutrient solution. The concentration of chlorophyll a and b was also significantly decreased in *Phytolacca americana* and *Amaranthus cruentus* with increasing ^{134}Cs concentration in soil [40]. Stable Cs could lead to abnormal expression of genes related to photosynthesis pathway and then block the electron transport process from plastoquinone-QA to plastoquinone-QB, which resulted in abnormal photosynthesis and growth of *B. juncea* [41].

3.5. Effect of Cs^+ Application on Lettuce Biomass. As shown in Table 1 and Table S1, the fresh weight of leaves and roots decreased with the increasing Cs^+ concentration within 6 days for all groups. However, the biomass increased and then decreased when sampling time was longer than 9 days, which was similar to chlorophyll content. The largest biomass was either at 0.05 or 0.5 mM Cs^+ level, and the smaller biomass was either at 5.0 or 10.0 mM Cs^+ level. As shown in Table 2, a significant negative correlation was found between Cs^+ concentration and fresh weight of leaves and roots. It is obvious that high Cs^+ concentration can inhibit significantly the growth of lettuce. In similarity, low concentrations of RCs stimulated the growth of *Lepidium sativum* cultivated in hydroponics with a radiation dose of 0.7 mGy [42]. Moreover, Kim et al. [38] confirmed that the low doses of RCs radiations (2-8 Gy) could enhance the seed germination and early seedling growth of *red pepper*, which was attributed to the activation of plant enzymes promoting plant metabolism as well as growth processes [43].

In Table 3 and Table S2, the average biomass of lettuce was the greatest under regulation of different Ca^{2+} concentrations, but the smallest one was related to K^+ regulation at 0.1 mM Cs^+ concentration. In case of 1.0 mM Cs^+ level, the largest biomass was related to Na^+ treatment, and the lowest one corresponds to the K^+ treatment group. Although the biomass of roots and leaves could be regulated by K^+, Ca^{2+}, and Na^+ ions, however, K^+ and Ca^{2+} could produce more significant effect on lettuce biomass. Such phenomena mainly correspond to the variation tendency of Cs^+ content in root and leaf when lettuces were treated with K^+ and

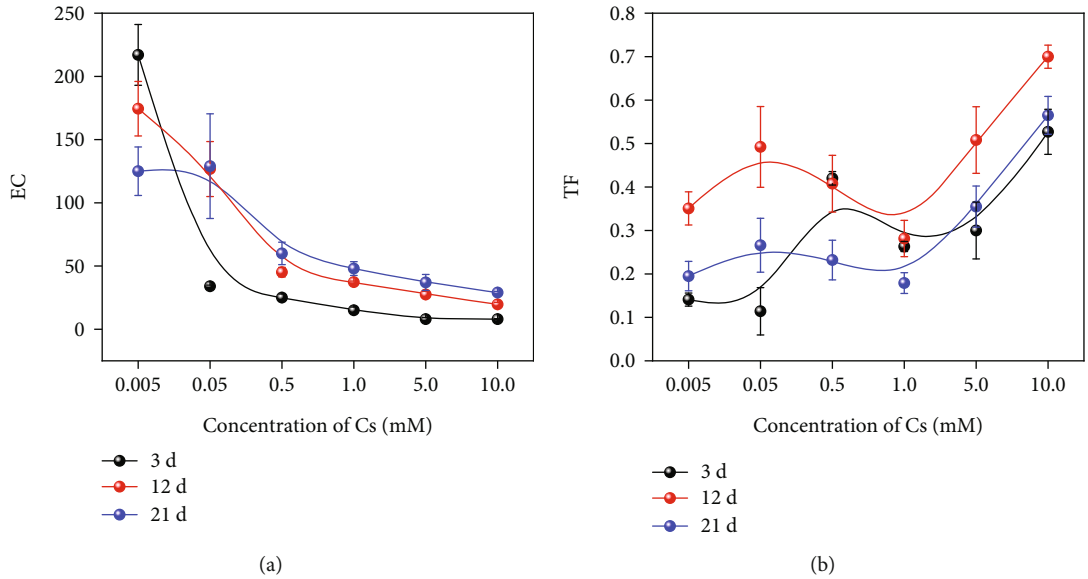

FIGURE 6: Comparison of enrichment coefficient (EC) and transfer factors (TF) at six different Cs^+ concentrations and sampling days ($n = 3$ individual plants).

Ca^{2+}. It suggests that K^+ and Ca^{2+} were main regulation substance on Cs^+ uptake by lettuce in the environment. According to previous views, more Cs^+ will be accumulated in lettuce tissues at the maximum biomass, so it is easily misleading and producing potentially harmful on human health [22, 23].

3.6. Analysis of TF and EC. As shown in Figure 6(a) and Table S3, EC was found to be in the range of 8-217. There was a notable phenomenon that EC increased with the decrease of Cs^+ concentration and the increase of growth time (except for the 5.0 μM Cs^+ treatment group). It indicates that RCs is more likely to enter the plant at low concentrations or trace level. However, there was much higher amount of Cs^+ in leaves when lettuce grew at an exposure of high Cs^+ level for long days (Table S3), which suggests that the edible portion of the plant accumulates more Cs^+, and the chances of entering the human body increase greatly. From Figure 6(b) and Table S3, TF was ranged from 0.114 to 0.828 under the influence of different Cs^+ concentration and sampling time. The transfer factors showed a trend of increasing with the increasing of Cs treatment concentration at first, then gradually decreasing little by little, but increasing at last. At high Cs^+ concentration, TF was much higher than that at low Cs^+ concentration, which indicates that more Cs^+ transferred from roots to edible partial leaves. The TF of stable Cs and RCs become influenced by the presence of other elements. It is therefore very important to consider type and nutritional status of the soil or culture solution.

4. Conclusion

This work presents the distribution and accumulation of Cs^+ in roots and leaves of the lettuce under different hydroponic conditions. The results clearly showed that lettuce growth and development were significantly inhibited at high Cs^+ level treatment, where lettuce biomass and root length significantly decreased. The content of Cs^+ in roots and leaves increased with the increase of Cs^+ concentration and growth time, and it was noticed that the content of Cs^+ in roots was much higher than that in leaves. The external K^+ concentration was negatively correlated with Cs^+ content in lettuce. K^+ was the main factor controlling the uptake of Cs^+ in lettuce. Under the Cs^+ stress, the contents of glutathione and malondialdehyde and the root viability of lettuce were significantly increasing as the Cs^+ concentration increased. The oxidative stress reaction in plant cells after Cs^+ stress caused damage to the antioxidant system in the roots and leaves of lettuce. However, the chlorophyll content decreased at high Cs^+ concentration treatment, which indicates that the stress of Cs^+ could inhibit photosynthesis reaction and results in an abnormal biological activity for lettuce. The lower concentration of Cs^+ treatment was, the higher EC in leaf was determined. Higher concentration of Cs^+ was treated, and more Cs^+ ions were transferred from roots to leaves. The solution-plant system used in this study ignores other factors, such as organic matter, clay minerals, and water content. Further consideration of the process in soil may provide a more comprehensive understanding of the factors affecting the migration of Cs^+ to plants. The findings in this work will be useful for understanding the contamination of vegetable plants in radioactive contaminated areas.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors have no conflict of interest to disclose.

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Supplementary Materials

Figure S1: the effect of K^+ and Na^+ on the uptake of ions in lettuces. Figure S2: the comparison of mean value of the content, accumulation, EC, and TF of Cs under the influence of K^+, Ca^{2+}, Na^+, and two level of Cs. Table S1: effects of exposure to Cs^+ on biomass of lettuce. Table S2: effects of exposure to the different concentrations of Na^+, K^+, and Ca^{2+} on biomass while the lettuces were cultivated in cesium concentration of 0.1 mM. Table S3: cesium concentration, enrichment coefficient (EC), and transfer factor (TF) in lettuce leaves and roots after treatment with different cesium concentrations. *(Supplementary Materials)*

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