

Application of sodium chloride improves quinoa (*Chenopodium quinoa* Willd.) growth and cesium absorption under cesium stress

katsunori Isobe

isobe.katsunori@nihon-u.ac.jp

Nihon University: Nihon Daigaku <https://orcid.org/0000-0001-6821-1312>

Yuta Oku

Nihon University: Nihon Daigaku

Masao Higo

Nihon University: Nihon Daigaku

Research Article

Keywords: Cesium, Epidermal bladder cells, Quinoa (*Chenopodium quinoa* Willd.), Sodium chloride

Posted Date: December 8th, 2025

DOI: <https://doi.org/10.21203/rs.3.rs-8202702/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

Quinoa contains epidermal bladder cells (leaf EBCs) on its surface that increase salt tolerance and facilitate the accumulation of unwanted substances. Additionally, cesium levels in the leaf EBCs are higher than in the leaf cells. Therefore, leaf EBCs are considered key for Cs absorption in quinoa. This study investigated whether, under Cs stress conditions 1) applying NaCl could restore quinoa growth and improve Cs absorption and 2) leaf EBCs maintained their Cs absorption capacity. K content in the leaf cells did not decrease upon CsCl treatment; therefore, CsCl-induced growth inhibition cannot be attributed to K deficiency. CsCl inhibited growth and this effect was rescued upon concomitant NaCl treatment. Cs content in the leaf cells was similar to or even higher than that when only CsCl was applied, suggesting that accumulated Cs in the leaf cells no longer inhibited growth or that Na had a growth-promoting effect. Phytoremediation of Cs can be achieved by applying NaCl, even when high soil Cs levels inhibit plant growth. Compared to leaf cells, Cs and K contents were higher in the leaf EBCs, regardless of CsCl treatment, indicating leaf EBC accumulation of these elements. Conversely, NaCl treatment led to higher Na content in the leaf cells than in the leaf EBCs, suggesting that when the internal Na content increases, quinoa does not actively transfer Na from the leaf cells to leaf EBCs. Therefore, leaf EBCs do not play a major role in salt tolerance in quinoa.

Introduction

In Japan, a large amount of radiocesium (Cs-137) was released into the environment after the Fukushima Daiichi Nuclear Power Plant accident on March 11, 2011 (Chino et al. 2011; Fujii et al. 2014; Saravanan et al. 2025). Cesium does not easily diffuse into soil, and the half-life of Cs-137 is approximately 30 years; therefore, it remains in the soil for many years (Almgren and Isaksson 2006; Cao et al. 2022). The accumulation of Cs-137 in soil has long-term effects on human society, agriculture, and natural ecosystems (Ammar et al. 2024; Saravanan et al. 2025). Additionally, Cs is the most toxic element among the group I alkali metals (Sheahan et al. 1993; Adams et al. 2018; Hampton et al. 2004); even non-radioactive Cs, when accumulated in large amounts, can inhibit plant and organism growth. In Fukushima, the soil surface layer was removed to eliminate the Cs-137 accumulated due to the nuclear accident; however, this process is extremely costly and labor-intensive (Ito et al. 2012). Therefore, phytoremediation is considered an efficient method for extracting Cs from soil. However, phytoremediation of Cs is not yet practical because plants have a low capacity to absorb Cs (Tamaoki et al. 2016). Recent studies on the identification of proteins involved in Cs absorption and transport in plants have achieved significant progress in this area (Rai and Kawabata 2020). Phytoremediation becomes a sustainable solution for mitigating Cs contamination, notably for soil restoration and agricultural sustainability (Nurliati et al. 2024; Phang et al. 2024). Thus, we believe that plant-based Cs removal from soil will soon become a feasible technology.

Quinoa (*Chenopodium quinoa* Willd.) is a pseudo-cereal native to South America with a high capacity for Cs absorption (Broadley et al. 1999; Isobe et al. 2019). Some quinoa cultivars grow to approximately 2 m tall and produce significant biomass among annual plants (Ali et al. 2020); furthermore, quinoa is a

halophyte (Hussin et al. 2023). Applying an appropriate amount of NaCl enhances aboveground growth and increases Cs absorption (Isobe et al. 2019; Wada et al., Isobe et al. 2024). Quinoa contains epidermal bladder cells (leaf EBCs) on its surface, which are believed to increase salt tolerance and facilitate the accumulation of unwanted substances (Wada et al. 2020; Isobe et al. 2024; Palacios et al. 2024). Among the leaves, stems, and panicles, the leaves exhibit the highest Cs content, which remains stable after seed filling (Wada et al. 2020). Additionally, Cs levels in leaf EBCs are higher than those in leaf cells (Isobe et al. 2024). Therefore, leaf EBCs are considered key sites of Cs absorption in quinoa. However, excessive Cs accumulation in the soil may inhibit plant growth and Cs uptake due to toxicity. This study investigated whether applying NaCl could restore quinoa growth and enhance Cs absorption under Cs stress conditions. We also examined whether the leaf EBCs maintained their Cs absorption capacity under such stress.

Materials and Methods

Pot experiments were conducted in 2023 using the quinoa variety CICA-127. All experiments were performed in Wagner pots (1/5000a; diameter: 16 cm; height: 25 cm) filled with 2.5 kg of air-dried field soil (Andosol) of experimental field in Nihon University (Fujisawa-city, Kanagawa, Japan), 1.0 g of ammonium sulfate ((NH₄)₂SO₄; TORAY Ind., Tokyo, Japan), and 1.0 g of superphosphate (Katakura & Co-op Agri Corporation). In all experiments, samples of each pot served as one replicate, and a total of six replicates were prepared in experiments 1 and 3, and of five replicates were prepared in experiments 2 and 4.

Experiment 1: Effects of the application of CsCl on the growth of above ground parts

For the analysis of the effects of CsCl on the growth of the above-ground parts, five plots were prepared with different CsCl application rates. Overall, 0.3, 0.5, 0.7, and 1.0 g of CsCl (Wako Pure Chemical Industries, Tokyo, Japan) were applied, respectively; the control plot did not have CsCl. (NH₄)₂SO₄ and superphosphate were mixed equally with 2.5 kg of soil (Andosol), and CsCl was added to the top 5 cm of the soil; six pots were prepared per plot. Ten quinoa seeds per pot were sown on June 7, 2023, and after sowing, pots from all plots were placed randomly and independently in an artificial light-type air-conditioned room (KG-206, KOITO ELECTRIC INDUSTRIES LTD., Shizuoka, Japan). Day and night were set at 12 h each temperature was of 25 and 20 C, respectively. The seedlings were thinned to three plants per pot during the third leaf expansion stage. Weeds and diseases were controlled during the cultivation. Irrigation was performed upon observation of surface soil drying.

On July 15, 2023, the plant height (length from the soil surface to the top) of quinoa plants in all plots was measured using a ruler, and the aboveground parts (stems and leaves) were cut at the soil surface. The fresh weights of the aboveground parts were measured using an electronic balance scale (GX-3000R, A&D Manufacturing Company Ltd., Ibaraki, Japan), and leaf areas were measured using a leaf area meter (LO-310, LO-COR Inc., Lincoln, NE, USA). The dry weight of above-ground parts was measured

after oven drying the fresh samples at 80°C for 48 h. Dry leaf was ground to a powder using a blender (Force Mill FM-1, Osaka Chemical Co. Ltd., Osaka, Japan). To measure Cs content, 0.5 g of ground material was digested in 20.0 mL HClO₄ (Kanto Chemical Co., Inc., Tokyo, Japan) for 3 h at 100°C using an acid digestion system, and Cs content was determined by atomic absorption spectrophotometry (iCE 3300 AAS Thermo Fisher Scientific, Waltham, MA, USA).

The top 5 cm of the surface soil of each plot at sowing was air-dried to measure the total Cs content. After air-drying, the soil samples were sieved through a 2 mm mesh sieve for Cs analysis. Then, 1.0 g of soil samples was digested in 20.0 mL HClO₄ for 3 h at 100°C using an acid digestion system, and Cs content was determined by atomic absorption spectrophotometry.

Experiment 2: Effects of the application of CsCl on the Cs content of leaf cells and leaf EBCs

For the analysis of the effects of CsCl application on the Cs content of leaf cells and leaf EBCs, three plots were prepared with different CsCl application rates. Overall, 0.3 and 0.6 g of CsCl were applied; the control plot did not have CsCl. (NH₄)₂SO₄ and superphosphate were mixed equally with 2.5 kg of soil (Andosol), and CsCl was added to the top 5 cm of the soil. A total of 50 pots were prepared per plot. Ten quinoa seeds per pot were sown on July 28, 2023, and after sowing, pots from all plots were placed randomly and independently in unheated vinyl (roof) and net (side) houses from sowing to sampling of the aboveground parts.

On September 8, 2023, five pots from each plot were randomly selected for analysis of the growth of the aboveground parts. Plant height, fresh weight of aboveground parts, leaf area, and dry weight of aboveground parts were measured using the same method as previously described.

The leaf EBCs on the leaves were collected from plants in 45 pots using a brush (Isobe et al. 2024). After leaf EBCs removal, leaf cells and leaf EBCs were dried at 80 °C for 48 h in a drying oven to analyze Cs and potassium (K) content. The dried leaf cells were ground into powder using a blender. To measure Cs and K content, 0.5 g of ground leaf and 0.2 g of dried leaf EBCs were digested in 20.0 mL HClO₄ for 3 h at 100 °C using an acid digestion system, and Cs and K content was determined by atomic absorption spectrophotometry. The total Cs content of the soil at sowing was measured using the same method as previously described in Experiment 1.

Experiment 3: Effects of the application of NaCl on the growth of above ground parts under Cs stress conditions

For the analysis of the effects of NaCl application on the growth of above-ground parts under Cs stress conditions, six plots were prepared with different application rates of CsCl and NaCl. Overall, 0.5 g Cs/20 g Na and 0.7 g Cs/20 g Na were applied; the control plot did not have CsCl and NaCl. (NH₄)₂SO₄, superphosphate, and NaCl were mixed equally with 2.5 kg of soil (Andosol), and CsCl was added to the top 5 cm of the soil. Six pots were prepared for each plot. Ten quinoa seeds per pot were sown on July 21, 2023, and after sowing, pots from all plots were placed randomly and independently in an artificial

light-type air-conditioned room. The day length and day and night temperatures were set at 12 h and 25 and 20°C, respectively. The seedlings were thinned to three plants per pot during the third leaf expansion stage. Weeds and diseases were controlled during the cultivation. Irrigation was performed upon observation of surface soil drying.

On August 31, 2023, the aboveground parts were cut at the soil surface. Plant height, fresh weight of aboveground parts, leaf area, dry weight of aboveground parts, and Cs content of dried leaf cells were analyzed using the same methods as previously described. The Cs and Na contents of the soil at sowing were also analyzed using the same method as previously described.

Experiment 4: Effects of the application of NaCl on the Cs content of leaf cells and leaf EBCs under Cs stress conditions

For the analysis of the effects of NaCl application on the Cs content of leaf cells and leaf EBCs under Cs stress conditions, three plots were prepared with different application rates of CsCl and NaCl. Overall, 0.6 g Cs/20 g Na were applied; the control plot did not have CsCl and NaCl. $(\text{NH}_4)_2\text{SO}_4$ and superphosphate were mixed equally with 2.5 kg of soil (Andosol) and CsCl was added to the top 5 cm of the soil (Andosol). In all the plots, 100 pots were prepared. Ten quinoa seeds per pot were sown on September 2, 2023, and after sowing, pots from all plots were placed randomly and independently in unheated vinyl (roof) and net (side) houses from sowing to sampling of the aboveground parts. On October 31 and November 13, 2023, five pots from each plot was randomly selected for analysis of the growth of the aboveground parts. Plant height, fresh weight of aboveground parts, leaf area, and dry weight of aboveground parts were measured using the same methods as previously described. The leaf EBCs on the leaves were collected from plants in 45 pots using a brush on November 1 and 14, 2023. The Cs, Na, and K contents of the dried leaf cells and leaf EBCs were analyzed using the same methods as previously described. The Cs and Na contents of the soil at sowing were also analyzed using the same methods as previously described.

Statistical analysis

All values are expressed as averages and standard errors. Data were statistically analyzed, and significant differences at the 5% level among the plots were determined by multiple means test using Kaleida Graph ver. 4.0 software.

Results

Effects of CsCl application on the growth of the above ground parts

The soil Cs content at sowing increased with the CsCl application rates; a significant difference was observed between all CsCl application plots and the control (Figs. 1 and 2). Conversely, plant height, leaf area, and the fresh and dry weights of the aboveground parts decreased with increasing CsCl application rates. A significant difference was observed in plant height at 0.5, 0.7, and 1.0 g Cs plots and the control. Regarding leaf area and fresh and dry weight of the aboveground parts, a significant difference was

observed between 1.0 g Cs plots and the control (Table 1). A significant difference was observed in plant height, fresh and dry weights of the aboveground parts between the 0.6 g Cs plots and control (Table 2 and Fig. 3). In the 1.0 g Cs plot, it was not possible to collect a sufficient number of leaves required for Cs content analysis; In the 0.5 and 0.7 g Cs plots, the Cs content of the leaf cells significantly increased with the CsCl application rates compared with that of the control (Table 1).

Effects of CsCl application on the Cs content of leaf cells and leaf EBCs

The Cs content of the leaf cells and leaf EBCs increased with the CsCl application rates. A significant difference was observed in the Cs content of leaf cells and leaf EBCs between the 0.3 and 0.6 g Cs plots and that of the control. Cs content was significantly higher in leaf EBCs than that in leaf cells in all plots (Fig. 4). The K content of the leaf cells and leaf EBCs did not increase with increasing applications of CsCl, and it was significantly higher in leaf EBCs than that in leaf cells in all plots (Fig. 4).

Effects of NaCl application on the growth of above ground parts under Cs stress conditions

With only CsCl application, the Cs content of soil increased with the CsCl application rates; however, with the concomitant CsCl and NaCl application, the Cs content of soil did not increase. Soil Na content at sowing increased with NaCl applications. A significant difference was observed in the Na content of soil between all NaCl application plots and that of the control (Fig. 5). Moreover, a significant difference was observed in Na content of soil between the Cs 0.6g/Na 20g plot and that of the control and 0.6 g Cs plots (Fig. 6). Plant height, leaf area, and fresh and dry weights of the aboveground parts decreased only after CsCl application. A significant difference was observed in plant height between the 0.7 g Cs plots and that of the control. Conversely, plant height, leaf area, and the fresh and dry weights of the aboveground parts increased only with NaCl application. A significant difference was observed in leaf area and fresh weight of the aboveground parts between the 20 g Na plots and those of the control. Plant height, leaf area, and fresh and dry weights of the aboveground parts were increased by CsCl and NaCl application. A significant difference was observed in the fresh weight of above ground part between the 0.7 g Cs/20 g Na plots and that of the control. Even when CsCl was applied, the suppression of aboveground growth was not observed with the concomitant NaCl application. A significant difference was observed in plant height, leaf area, and fresh and dry weights of above ground parts between the Cs 0.7 g Cs/20 g Na plots and those of the 0.7 g Cs plot. A significant difference was observed in leaf area and fresh weight of the aboveground parts between the Cs 0.5 g Cs/20 g Na plots and the 0.5 g Cs plot (Table 3). The leaf Cs content increased with the application of CsCl. A significant difference was observed in the Cs content of leaf cells between all the CsCl application plots and that of control and 20 g Na plots (Table 3). The Na content of the leaf cells increased with NaCl application. A significant difference was observed in the Na content of the leaf cells between all NaCl application plots and that of control and no NaCl plots. The K content of leaf cells did not change with the application of CsCl or NaCl (Table 3).

The growth of the aboveground parts was inhibited only by CsCl application. A significant difference was observed in leaf area and fresh and dry weights of the aboveground parts between the Cs 0.6 g Cs plots

and those of the control. Even when CsCl was applied, the suppression of aboveground growth was not observed with the concomitant NaCl application. There were no significant differences in plant height, leaf area, and fresh and dry weights of above ground parts between the control and those of the Cs 0.6 g Cs/20 g Na plot. The growth of the aboveground parts was inhibited by CsCl application. A significant difference was observed in plant height and fresh and dry weights of above ground part between the 0.6g Cs plots and those of the control. Even when CsCl was applied, the aboveground growth was promoted by NaCl application. There were significant differences in leaf area and fresh weight of the aboveground parts between the control and those of the 0.6 g Cs and 0.6 g Cs/20 g Na plots (Table 4 and Fig. 7).

Effects of NaCl application on the Cs content of leaf cells and leaf EBCs under Cs stress conditions

The Cs content of the leaf cells and leaf EBCs increased with the CsCl application. Moreover, the Cs content in the leaf cells and leaf EBCs increased due to the application of NaCl. The Cs content of leaf EBCs was significantly higher than that of the leaf cells. Likewise, the Na content in the leaf cells and leaf EBCs increased with the NaCl application. There were significant differences in the Na content of leaf cells and leaf EBCs between those of the control and Cs 0.6 g Cs and 0.6 g Cs/20 g Na plots. the Na content of leaf EBCs was significantly higher than that of the leaf cells in the control and 0.6 g Cs plots. However, in the Cs 0.6 g Cs/20 g Na plot, the Na content of the leaf cells was significantly higher than that of the leaf EBCs. Moreover, the K content of the leaf cells increased with the CsCl application, unlike that of the leaf EBCs, which decreased with the CsCl application. There were significant differences in the K content of the leaf cells between the control and that of 0.6 g Cs and the 0.6 g Cs/20 g Na plots. The K content of leaf EBCs was significantly higher than that of the leaf cells (Table 5).

Discussion

Applying 0.5–0.6 g or more of CsCl (Fig. 1, 2, 5, 6) to a 5000/a pot inhibited the above-ground growth of quinoa (Tables 1–4, Figs. 3 and 7). Plant growth inhibition results from a reduction in K absorption caused by Cs uptake (Adams et al. 2019). However, the inhibition of plant growth upon Cs uptake is not solely due to K deficiency, but also involves complex factors such as interference with K binding in proteins and disruption of the Cs/K ratio balance (Hampton et al. 2004; Le Lay et al. 2006; Adams et al. 2015; Adams et al. 2017). In this study, the K content in the leaf cells did not decrease even when CsCl was applied (Fig. 4b, Tables 3 and 5). Thus, we suggest that the inhibition of quinoa growth caused by CsCl application is not due to K deficiency. Other possible factors for the inhibited growth of quinoa found in this study include Cs and Cl toxicity and increased osmotic pressure (Machado and Serralheiro 2017; Munns et al. 2019; Dubois and Inzé 2020; Lui et al. 2024). However, if Cs toxicity or increased osmotic pressure were the cause, quinoa growth would have been more severely inhibited when a large amount of NaCl was applied. As quinoa growth was not inhibited even when 20 g of NaCl per pot was applied (Tables 3 and 4, Fig. 5, 6, 7), we believe that the growth inhibition of quinoa observed with the application of CsCl was not due to Cl or increased osmotic pressure. Thus, Cs primarily inhibited quinoa growth when CsCl was applied.

The application of CsCl alone (Fig. 1, 2, 5, and 6) inhibited the growth of aboveground parts (Tables 1–4), which is thought to result from Cs absorbed into the plant (Fig. 4a, Tables 1, 3, and 5). However, the growth inhibition caused by CsCl was suppressed when NaCl was applied (Tables 3 and 4; Fig. 7). Therefore, the leaf CsCl content was expected to decrease when CsCl and NaCl were concomitantly applied (Figs. 5 and 7). However, the Cs content in the leaf cells was similar to or even higher than that when only CsCl was applied (Fig. 6, Table 5). Hence, although the leaf cells accumulated sufficient Cs to inhibit growth, the simultaneous application of NaCl prevented Cs-induced growth inhibition. This suggests that either the accumulated Cs in the leaf cells no longer inhibited growth or that Na had a growth-promoting effect. Previous studies on halophytes similar to quinoa, such as ice plants and *Arabidopsis thaliana*, have also reported that NaCl application promotes growth (Nakano and Watanabe 2018; Hongqiao et al. 2021; Eoh et al. 2024). Eoh et al. (2024) suggested that the reason for growth promotion in ice plants by NaCl was an increase in the accumulation of antioxidants, flavonoids, polyphenols, d-pinitol, and other substances. Hongqiao et al. (2021) also suggested that NaCl promotes sulfur absorption and the uptake of elements, such as Cl, Zn, and Cu in *Arabidopsis thaliana*, which in turn enhances photosynthesis and promotes plant growth. Furthermore, Subbarao et al. (2003) showed that when K is deficient, Na partially replaces the functions of K, such as osmotic pressure regulation in cells and enzyme activity. Since no K fertilizer was applied in any of the experiments in this study, it is possible that the increased quinoa growth with NaCl (Tables 3 and 4) was due to Na partially fulfilling the functions of K. However, the function of the absorbed NaCl within the quinoa plants remained unclear in the present study. Currently, the area of salt-accumulating land is expanding worldwide (Higashiyama et al. 2020), rendering the cultivation of halophytes essential for future food production. Quinoa, with its high salt tolerance, can be cultivated even in saline-alkali areas. Thus, it is necessary to clarify the mechanism by which NaCl application promotes quinoa growth. Additionally, it is believed that Cs phytoremediation using quinoa can be achieved by applying NaCl, even under conditions in which high soil Cs content inhibits plant growth.

The leaf EBCs in quinoa are thought to accumulate waste products and growth-inhibiting substances to maintain the physiological functions of leaf cells and stems (Shabala et al. 2014; Kiani-Pouya et al. 2017). This study revealed that the accumulation of elements in leaf cells and leaf EBCs differed depending on the type. For example, the Cs and K contents were higher in the leaf EBCs than those in the leaf cells, regardless of the application of CsCl, indicating that these elements were actively accumulated in the leaf EBCs rather than in the leaf cells (Figs. 5, 6, Table 5). In contrast, the NaCl content was higher in leaf EBCs in the control condition and when only CsCl was applied. However, when NaCl was applied, Na content was higher in the leaf cells than in the leaf EBCs (Table 5). This result suggests that even when the internal Na content increases, quinoa does not actively transfer Na from the leaf cells to leaf EBCs. Moog et al. (2022) demonstrated that quinoa accumulates only trace amounts of Na in leaf EBCs, indicating that these cells do not play a major role in salt tolerance. Palacios et al. (2024) also reported that leaf EBCs do not accumulate to sequester excess Na from metabolically active cells. As mentioned, quinoa is a halophyte (Adolf et al. 2012; Kobayashi et al. 2025), and its growth is promoted by the application of Cs and NaCl (Saleem et al. 2017; Isobe et al. 2019). In the

present study, the leaf area and shoot fresh weights were significantly higher in the NaCl-only plots than those in the control plots. Based on these findings, we believe that when quinoa absorbs large amounts of Na, it is retained in somatic cells and used to promote growth. In particular, because no K fertilizer was applied in this study, the absorbed Na may function similarly to K (Subbarao et al. 2003), thus promoting growth. In the present study, the NaCl application rate was set at 20 g per pot. It remains unclear whether the application of more NaCl induces stress and inhibits quinoa growth (Isobe et al., 2014; Isobe et al. 2019; Kobayashi et al. 2025). Therefore, future studies should clarify whether Na is actively transferred from leaf cells to leaf EBCs under Na-stress conditions.

Conclusion

The inhibition of quinoa growth by CsCl application was attributable to Cs rather than K deficiency. The growth inhibition caused by CsCl was suppressed when NaCl was applied. In addition, the Cs content in the leaf cells was similar to or even higher than that when only CsCl was applied. This suggests that either the accumulated Cs in the leaf cells no longer inhibited growth or that Na had a growth-promoting effect. It is believed that Cs phytoremediation in quinoa can be achieved by applying NaCl, even under conditions in which high Cs content in the soil inhibits plant growth. When NaCl was applied, Na content was higher in the leaf cells than in the leaf EBCs. This result suggests that even when the internal Na content increases, quinoa does not actively transfer Na from the leaf cells to leaf EBCs. Therefore, leaf EBCs do not play a major role in salt tolerance.

Declarations

Statements & Declarations

Acknowledgements

This research was supported by Ichimura Foundation for New Technology and College of Bioresource Sciences, Nihon University.

Funding

This research was conducted with the support of Ichimura Foundation for New Technology. We express our gratitude to the Ichimura Foundation.

Author Contributions

K. Isobe: Total coordination of the experiment. Y. Oku: Conducting the experiments 1 to 4. M. Higo: Statistical analysis.

Ethical Approval

This is not applicable

Consent to Participate

This is not applicable

Consent to Publish

This is not applicable

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Data Availability Statement

Data available on request due to privacy/ethical restrictions.

References

1. Adams E, Chaban V, Khandeliah H, Shin R (2015) Selective chemical binding enhances cesium tolerance in plants through inhibition of cesium uptake. *Sci Rep* 5:8842
2. Adams E, Miyazaki T, Hayaishi-Satoh A, Han M, Kusano M, Khandeliah H, Saito K, Shin R (2017) A novel role for methyl cysteinylglycine, a cysteine derivative, in cesium accumulation in *Arabidopsis thaliana*. *Sci Rep* 7:43170
3. Adams E, Miyazaki T, Saito S, Uozumi N, Shin R (2019) Cesium inhibits plant growth primarily through reduction of potassium influx and accumulation in *Arabidopsis*. *Plant Cell Physiol* 60(1):63–76
4. Adolf VI, Shabala S, Andersen M N, Razzaghi F, Jacobsen S-E (2012) Varietal differences of quinoa's tolerance to saline conditions. *Plant Soil* 357:177 – 129
5. Ali S, Chattha MU, Hassan MU, Khan I, Chattha MB, Iqbal B, Rehman M, Nawaz M, Amin MZ (2020) Growth, biomass production, and yield potential of quinoa (*Chenopodium quinoa* Willd.) as affected by planting techniques under irrigated conditions. *Int J Plant Prod* 14:427–441
6. Almgren S, Isaksson M (2006) Vertical migration studies of ¹³⁷Cs from nuclear weapons fallout and the chernobyl accident. *J Environ Radioact* 91:90–102
7. Ammar A, Nour A, Zineb El, Mouridi ZE, Boughribil S (2024) Recent trends in the phytoremediation of radionuclide contamination of soil by cesium and strontium: Sources, mechanisms and methods: A comprehensive review. *Chemosphere* 359:142273
8. Broadley MR, Willey NJ, Mead A (1999) A method to assess taxonomic variation in shoot caesium content among flowering plants. *Environ Pollut* 106:341–349
9. Cao Y, Zhou L, Ren H, Zou H (2022) Determination, separation and application of ¹³⁷Cs: A review. *Int J Environ Res Public Health* 19:10183

10. Chino M, Nakayama H, Nagai H, Terada H, Katata G, and Yamazaki H (2011) Preliminary estimation of release amounts of ¹³¹I and ¹³⁷Cs accidentally discharged from the Fukushima Daiichi nuclear power plant into the atmosphere. *J Nucl Sci Technol* 48:1129–1134
11. Dubois M, Inzé D (2020) Plant growth under suboptimal water conditions: early responses and methods to study them. *J Exp Bot* 71(5):1706–1722
12. Eoh G, Kim C, Bae J, Park J (2024) Evaluation of sodium chloride contents on growth and phytochemical production of *Mesembryanthemum crystallinum* L. *Horticulturae* 10:1304 <https://doi.org/10.3390/horticulturae10121304>
13. Fujii K, Ikeda S, Akama A, Komatsu M, Takahashi M, Kaneko S (2014) Vertical migration of radiocesium and clay mineral composition in five forest soils contaminated by the Fukushima nuclear accident. *Soil Sci Plant Nutr* 60:751–764
14. Hampton CR, Bowen HC, Broadley MR, Hammond JP, Mead A, Payne KA, Pritchard J, White PJ (2004) Cesium toxicity in *Arabidopsis*. *Plant Physiol* 136:3824–3837
15. Hongqiao L, Suyama A, Mitani-Ueno N, Hell R, Maruyama-Nakashita A (2021) A low level of NaCl stimulates plant growth by improving carbon and sulfur assimilation in *Arabidopsis thaliana*. *Plants* 10: 2138 <https://doi.org/10.3390/plants10102138>
16. Higashiyama K, Yoshikawa S, Kanae S (2020) Salinization potential risk due to irrigation on a global scale. *J Jpn Soc Civil Eng Ser B1* 76(2): 115–120
17. Hussin SA, Ali SH, Lotfy ME, El-Samad EHA, Eid MA, Abd-Elkader AM, Eisa SS (2023) Morpho-physiological mechanisms of two different quinoa ecotypes to resist salt stress. *BMC Plant Biol* 23:374
18. Isobe K, Ogishima E, Sato R, Sugiyama H, Higo M, Torigoe Y (2014) Varietal and specific differences in salinity tolerance of quinoa (*Chenopodium quinoa* Willd.) for germination and initial growth. *Jpn J Crop Science* 83: 9–14
19. Isobe K, Nakajima E, Morita M, Kawakura S, Higo M (2019) Effects of NaCl on growth and cesium absorption in quinoa (*Chenopodium quinoa* Willd.). *Water Air Soil Pollut* 230:66
20. Isobe K, Wada K, Oishi S, Higo M (2024) Effects of NaCl application on cesium content, number, and size of epidermal bladder cells in quinoa plants. *Discov Appl Sci* 6:75
21. Ito K, Miyahara H, Ujiie T, Takeshima T, Yokoyama S, Nakata K, Nagano T, Sato T, Hatta T, Yamada H (2012) Practical Approach to decontamination of radioactive cesium- contaminated matter in agricultural region by improved wet classification and use of geomaterials. *Trans At Energy Soc Jpn* 11:255–271
22. Kiani-Pouya A, Roessner U, Jayasinghe NS, Lutz A, Rupasinghe T, Bazihizina N, Bohm J, Alharbi S, Hedrich R, Shabala S (2017) Epidermal bladder cells confer salinity stress tolerance in the halophyte quinoa and *Atriplex* species. *Plant Cell and Environ* 40:1900–1915
23. Kobayashi Y, Sugita R, Fujita M, Yasui Y, Murata Y, Ogata T, Nagatoshi Y, Fujita Y (2025) CqHKT1 and CqSOS1 mediate genotype-dependent Na⁺ exclusion under high salinity conditions in quinoa. *Front Plant Sci* 16:1597647

24. Le Lay P, Isaure MP, Sarry JE, Kuhn L, Fayard B, Le Bail JL, Bastien O, Garin J, Roby C, Bourguignonet J (2006) Metabolomic, proteomic and biophysical analyses of *Arabidopsis thaliana* cells exposed to a caesium stress. Influence of potassium supply. *Biochimie* 88:1533–1547
25. Lui L, Li X, Wang C, Ni Y, Liu X (2024) The role of chloride channels in plant responses to NaCl. *Int J Mol Sci* 25:19 <https://doi.org/10.3390/ijms25010019>
26. Machado RMA, Serralheiro RP (2017) Soil salinity: Effect on vegetable crop growth. Management practices to prevent and mitigate soil salinization. *Horticulturae* 3(30):doi:10.3390
27. Moog MW, Trinh MDL, Nerrevang AF, Bendtsen AK, Wang C, Østerberg JT, Shabala S, Hedrich R, Wendt T, Palmgren M (2022) The epidermal bladder cell-free mutant of the salt-tolerant quinoa challenges our understanding of halophyte crop salinity tolerance. *New Phytol* 236:1409–1421
28. Munns R, Passioura JB, Colmer TD, Byrt CS (2019) Osmotic adjustment and energy limitations to plant growth in saline soil. *New Phytol* 225:1091–1096
29. Nakano T, Watanabe K (2018) Effects of the ratio of ammonium nitrogen to nitrate nitrogen and adding sodium chloride in nutrient solution on growth and mineral uptake of ice plants. *Bull Teikyo Univ Sci* 14:59–64
30. Nurliati G, Romli M, Hikmat MCC, Sriwahyuni H, Hidayati THN, Suryantoro S, Wisnubroto D S, Putero SH, Iskandar D, Syarbaini S, Nirwani L, Sumarbagiono R, Setiawan B, Pratama HA, Ekaningrum NE, Mirawaty M, Winarni ID, Muziawati A, Setiawan A, Setiawan A, Yusuf M (2024) Literature survey and analysis of phytoremediation strategies for Cs-137 decontamination. *Nuclear Engineering and Design* 427:113414
31. Palacios MB, Rizzo AJ, Heredia TB, Roqueiro G, Maldonado S, Murgida DH, Burrieza HP (2024) Structure, ultrastructure and cation accumulation in quinoa epidermal bladder cell complex under high saline stress. *Protoplasma* 261:655–669
32. Phang LY, Mingyuan L, Mohammadi M, Tee C-S, Yuswan MH, Cheng W-H, Lai K-S (2024) Phytoremediation as a viable ecological and socioeconomic management strategy. *Environmental Science and Pollution Research* 31:50126–50141
33. Rai H, Kawabata M (2020) The dynamic of radio-caesium in soils and mechanism of cesium uptake into higher plants: Newly elucidated mechanism of cesium uptake into rice plants. *Plant Sci* 11: <https://doi.org/10.3389/fpls.2020.00528>
34. Saleem MA, Basra SMA, Afzal I, ur-Raman H, Iqbal S, Saddiq MS, Naz S (2017) Exploring the potential of quinoa accessions for salt tolerance in soilless culture. *Int J Agric Biol* 19:233–240
35. Saravanan P, Anjan DK, Vharshini S, Sowmya B, López-Maldonado EA, Saravanan V, Kannan RR, Rajasimman M, Venkatkumar S (2025) A comprehensive review of eco toxicity of Cesium 137 deterioration of radionuclides pollution. *Environmental Science and Pollution Research* 32: 15518–15545
36. Shabala S, Bose J, Hedrich R (2014). Salt bladders: do they matter? *Trends Plant Sci* 19:687–691
37. Sheahan JJ, Ribeiro-Neto L, Sussman MR (1993). Cesium-insensitive mutants of *Arabidopsis thaliana*. *The Plant Journal* 3(5):647–656

38. Subbarao GV, Ito O, Berry WL, Wheeler RM (2003) Sodium-A functional plant nutrient. Crit Rev Plant Sci 22:391–416

39. Tamaoki M, Yabe T, Furukawa J, Watanabe M, Ikeda K, Yasutani I, Nishizawa T (2016) Comparison of potentials of higher plants for phytoremediation of radioactive cesium from contaminated soil. Environ Control Biol 54:65–69

40. Wada K, Takagi R, Horikoshi M, Higo M, Isobe K (2020) Effects of NaCl application on cesium accumulation in the aboveground parts of quinoa (*Chenopodium quinoa* Willd.). Water Air Soil Pollut 231:552

Tables

Tables are available in the Supplementary Files section.

Figures

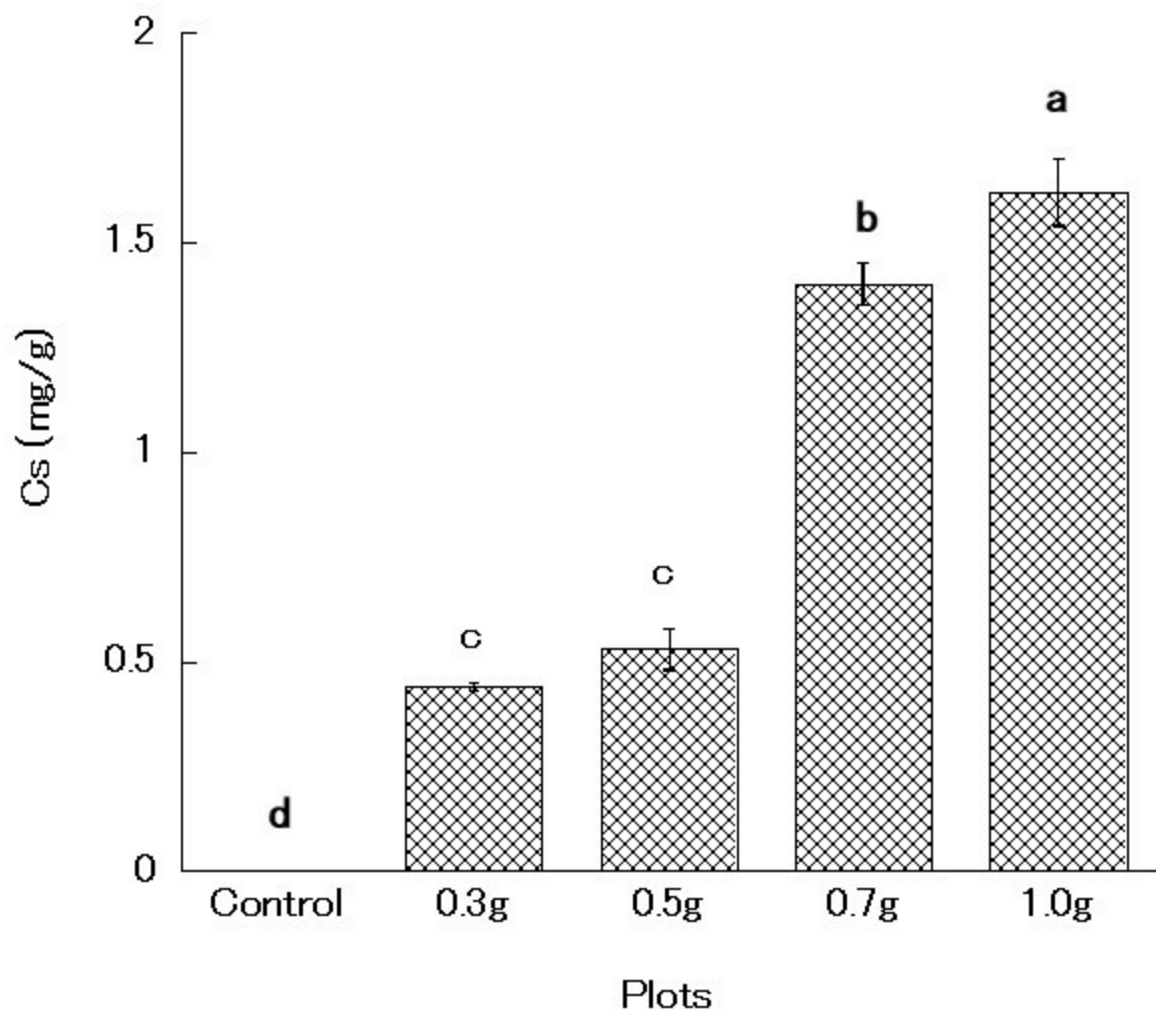


Figure 1

Total Cs content in the soil of each plot at sowing time.

Values followed by different letters are significantly different at $P < 0.05$, as determined by Tukey's multiple range test

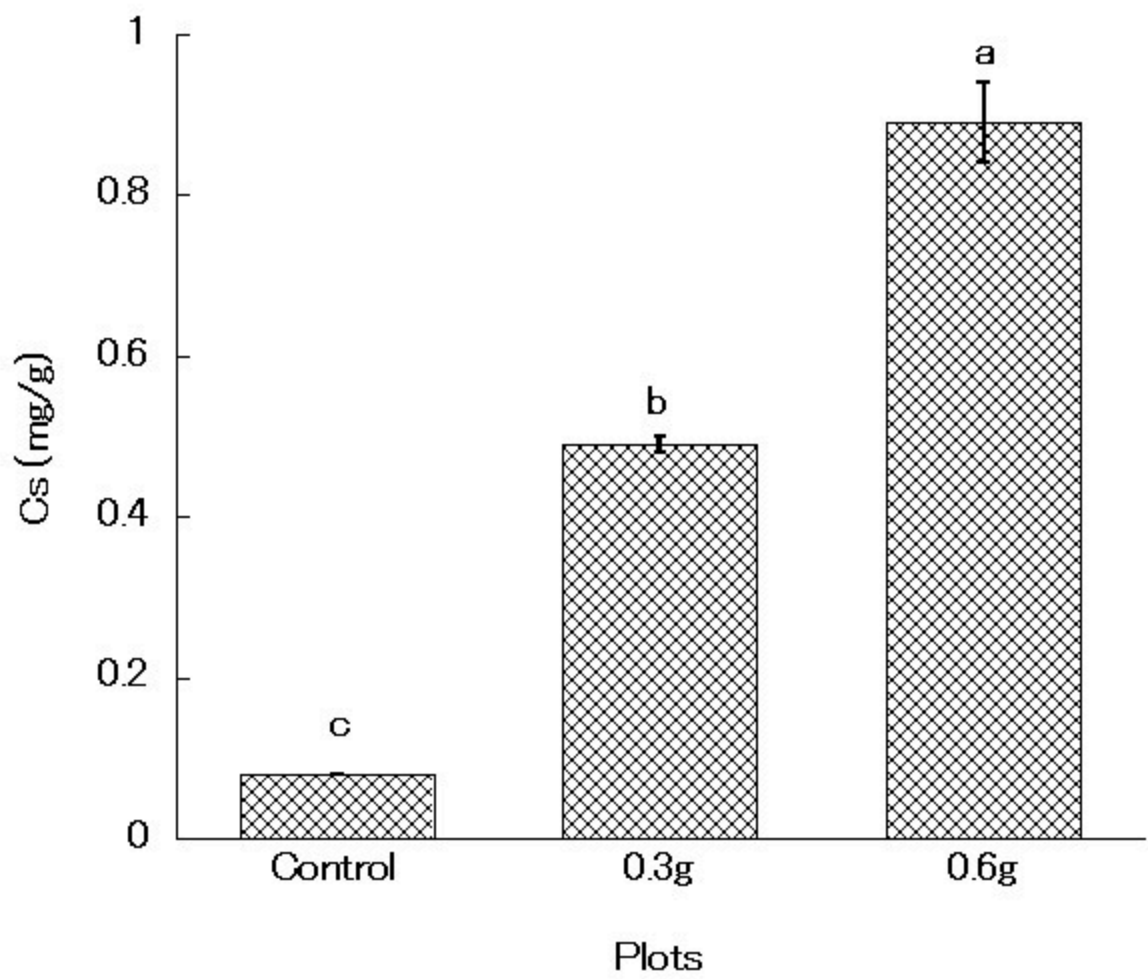


Figure 2

Total Cs content in the soil of each plot at sowing time.

Values followed by different letters are significantly different at $P < 0.05$, as determined by Tukey's multiple range test



Control

Cs 0.3g

Cs 0.6g

Figure 3

Quinoa growth of each plot

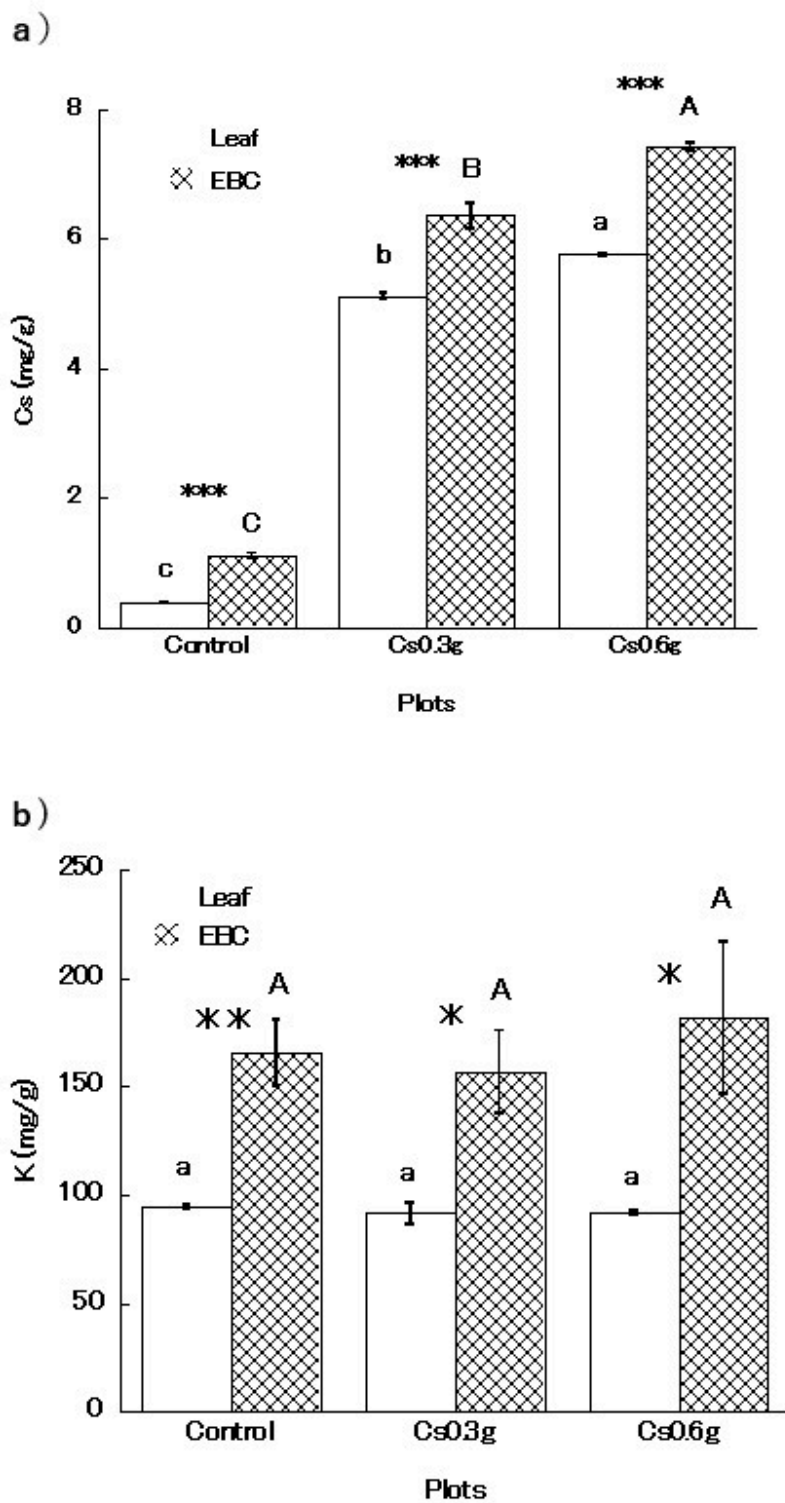


Figure 4

Total Cs (a) and K (b) contents in leaf cells and epidermal bladder cells.

Values followed by different letters are significantly different at $P < 0.05$, as determined by Tukey's multiple range test. **, *, Statistically significant at $P \leq 0.01$, and 0.05 by t-test, respectively

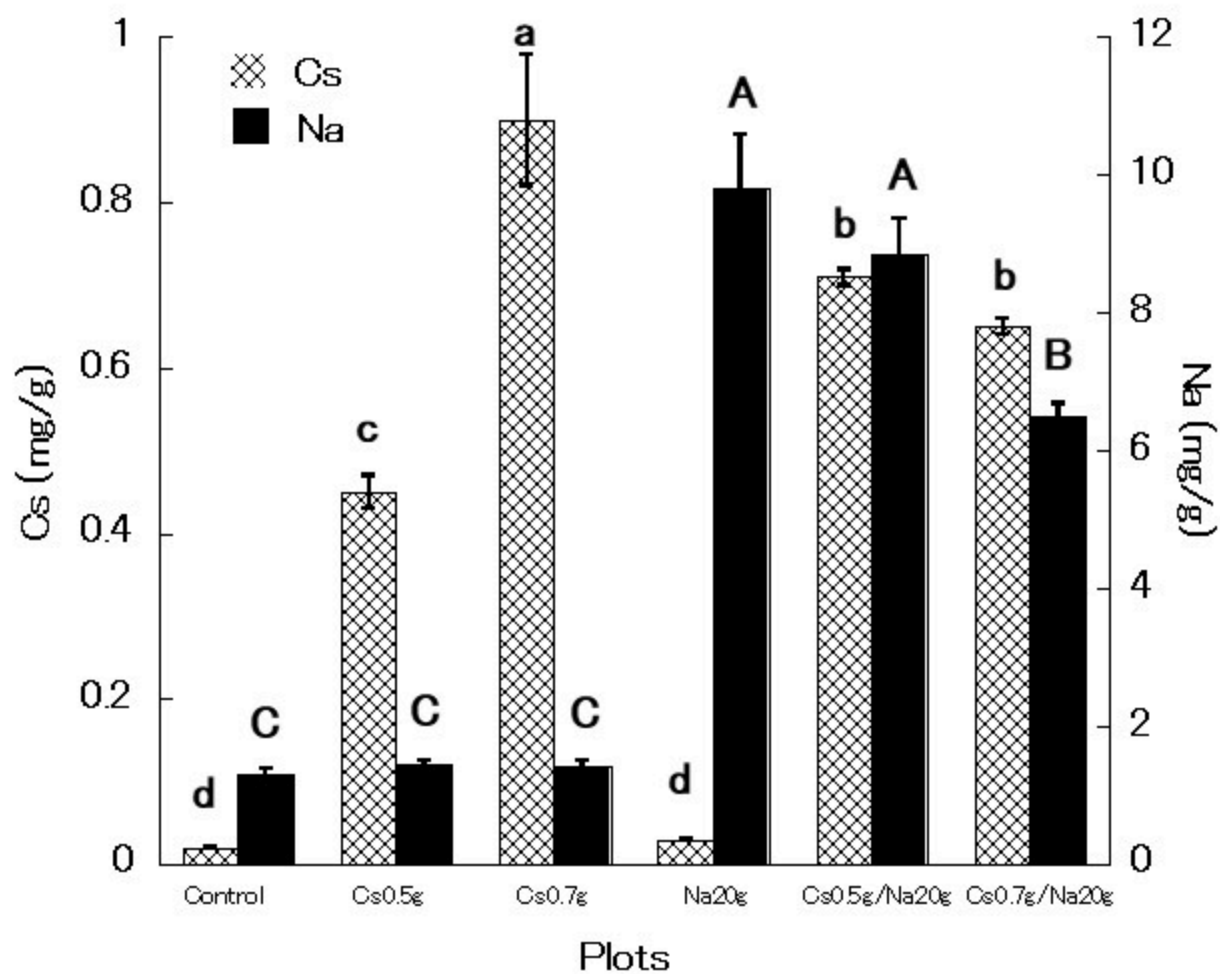


Figure 5

Total Cs and Na contents in the soil at sowing time.

Values followed by different letters are significantly different at $P < 0.05$, as determined by Tukey's multiple range test

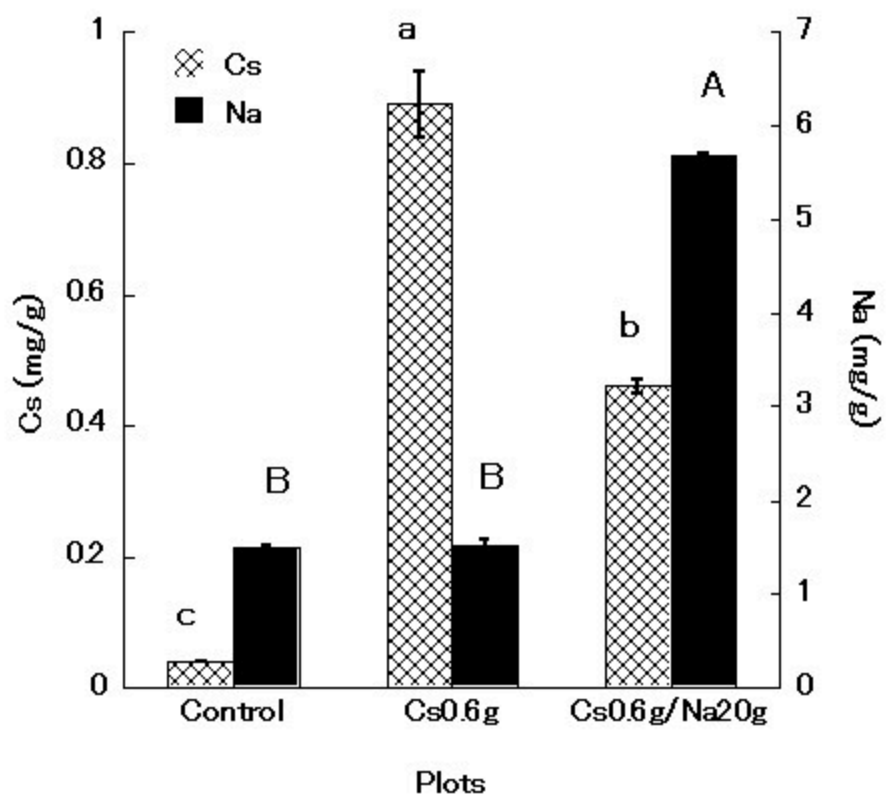


Figure 6

Total Cs and Na contents in the soil at sowing time.

Values followed by different letters are significantly different at $P < 0.05$, according to Tukey's multiple range test

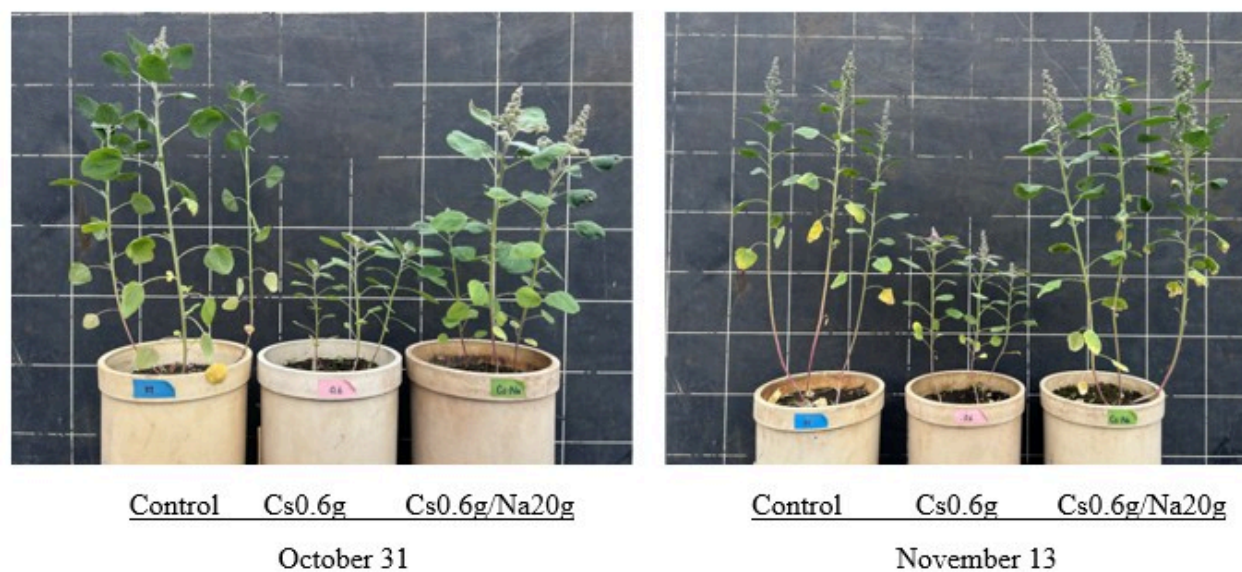


Figure 7

Quinoa growth of each plot with concomitant application of Na

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Tables.docx](#)