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^{133}Cesium Uptake by 10 Ornamental Plant Species Cultivated under Hydroponic Conditions

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Abstract

We focused on the Cs uptake capacities of ornamental flowers. Ornamentals have the advantage of beautifying contaminated environments, and this may have therapeutic effects for individuals, especially in disaster areas. Furthermore, the use of ornamental plants will reduce the risk of pollutants entering the food chain. We hypothesized a strong correlation between high aboveground biomass and high Cs uptake in plants. We assessed the potential of 10 ornamental plant species for remediation of ^{133}Cesium in hydroponic solutions. Sunflower, rapeseed, and cosmos took up larger amounts of ^{133}Cs and showed better growth rates than the other 7 species. When these 3 species were exposed to 3 different concentrations of ^{133}Cs (0.5, 2, and 5 mg/L CsCl), more than 48% of the ^{133}Cs was remediated after 7 days in each case. The highest remediation rate was 67%, by sunflowers grown in 5 mg/L CsCl. Among the 3 species, shoot and root dry weights were highest in sunflower and lowest in cosmos. The rate of ^{133}Cs uptake was strongly correlated with aboveground plant biomass. The ^{133}Cs concentration did not affect plant growth rates in any of the three species.

Keywords: ^{133}Cesium, remediation, sunflower, cosmos, rapeseed

1. Introduction

Due to the nuclear accident at Fukushima, Japan, in 2011, a radioisotope of cesium (^{137}Cs) was spread over an extensive area. ^{137}Cs is moved from soil and water to plants easily, arriving humans directly and indirectly through the food chain. Hence, in order to reduce the risk of radiation for humans it will be essential to remove the ^{137}Cs from contaminated soils and soil solutions (Singh et al., 2009). However, the removal of contaminated surface soils or the immobilization of radionuclides in the soil are physically difficult, costly, and impractical (Zhu & Shaw, 2000).

Phytoremediation which is low-cost and environmentally friendly removal process using plants and a promising technique for the cleaning up of radionuclides such as ^{137}Cs and heavy metal has noted considerably (Kelly & Pinder, 1996; Singh et al., 2009). This possibility has stimulated interest in the study of Cs uptake by plants, since this may be a low-cost alternative for remediating Cs-contaminated sites (Lasat et al., 1997). The land plants have been used to clear toxic ions such as Pb^{2+} from solutions and their many roots cultivated hydroponically (McCutcheon & Schnoor, 2003). Specific transporters for nonessential metal ions do not exist in plants, and the transport systems for essential ions mediated the transport of Cs across a membrane. Additionally, most of the chemical features of Cs are analogous to those of potassium (Pinder et al., 2006). Thus, Cs is absorbed easily by plants (Dabbagh et al., 2008). It is commonly assumed that Cs is taken up by plants via mechanisms participated in the uptake of K^+ and Ca^{2+}. Many transport proteins (low affinity inward-rectifying K^+ channels; nonspecific, voltage insensitive cation channels; high affinity K^+–H^+ symporters; voltage-dependent Ca^{2+} channels; and outward-rectifying cation channels) promote the permeation of Cs^+ ions across root cell membranes in plants (Bystrzejewska-Piotrowska & Bazala, 2008).

Effective remediation will depend on the ability of the phytoremediation crop to accumulate Cs in the aerial parts. There are many studies about efficacious methods for Cs removal from contaminated soils or solutions by many plant species (Broadley & Willey, 1997; Broadley et al., 1999; Tang & Willey, 2003; Singh et al., 2009;

Moogouei et al., 2011; Borghei et al., 2011). Soudek et al. (2004, 2006) showed that there is no significant difference the uptake of Cs between radioactive (^{137}Cs) and stable cesium (^{133}Cs) isotopes by sunflower (*Helianthus annuus* L). White & Broadley (2000) also found that plants did not differentiate between ^{133}Cs and ^{137}Cs isotopes, and they concluded that plants' responses to ^{133}Cs are exemplary of their responses to ^{137}Cs isotopes. Thus, the uptake patterns of ^{137}Cs and ^{133}Cs in plants are similar.

In this study we focused on the Cs uptake capacities of ornamental flowers. Ornamentals have the advantage of beautifying contaminated environments, and this may have therapeutic effects for individuals, especially in disaster areas. Furthermore, the use of ornamental plants will reduce the risk of pollutants entering the food chain. Sunflower (Soudek et al., 2004) and rapeseed (Chou et al., 2005) have high Cs uptake capacities and large aerial biomasses. Therefore, we postulated a strong correlation between many aerial biomass and high Cs uptake in plants. To address the urgent need for remediation of Cs-contaminated land in Fukushima, we examined the ability of remediation of Cs using various flowering species including sunflower and rapeseed. Cs uptake by plants is affected by soil texture, particularly the clay and humus contents, because these components affect the strength of Cs adhesion in the soil (Kang et al., 2012). Therefore, the present study was conducted under hydroponic conditions in order to clarify the potential abilities for Cs uptake by various plants.

2. Materials and Method

2.1 Experiment 1. Differences in ^{133}Cs Uptake and Growth Rates among 10 Species

The following ornamental species are popular and easy to purchase and cultivate in Japan: sensitive plant (*Mimoza pudica*), gazania (*Gazania splendens*), cosmos (*Cosmos bipinnatus*), zinnia (*Zinnia hybrida*), California poppy (*Eschescholzia californica*), saffron thistle (*Carthamus tinctorius*), basket flower (*Centaurea americana*), and cypress vine (*Quamoslit pennata*). Therefore we tested these species and compared their performances with sunflower (*Helianthus annuus*) and rapeseed (*Brassica rapa*), which were reported to have high Cs uptake capacities (Soudek et al., 2004; Chou et al., 2005). Healthy seeds of each species were germinated in cell trays (3.0 cm diameter × 4.5 cm depth) containing commercial horticultural soil, and grown for 14 days in a chamber (MLR-351, Sanyo Electonic Co. Ltd., Osaka, Japan) at 20 °C with relative humidity 80% and a day length of 12 h. After their roots were washed thoroughly in distilled water, the seedlings were moved to containers (310 mm × 235 mm × 960 mm) containing equal volumes of the following nutrient solutions: Farm Ace No.1 (N: 10%, P: 8%, K: 26%, Mg: 0.1%, B: 0.1%, Fe: 0.15%, Mn: 0.1%, Cu: 0.002%, Zn: 0.006 %) and No. 2 (N: 11%, Ca: 16.4%) (Kaneko Seed Co., Ltd., Gunma, Japan). Each container contained 6 plants. Plants were grown in a green house at Meiji University for 7 days. Then the plants were transferred to fresh nutrient solution (as described above) that also contained ^{133}CsCl (5 mg/L, with the concentration of the $^{133}Cs^{+}$ ion at 4.47 mg/L). The plants were grown in the ^{133}CsCl solution for 7 days. All solutions continuously aerated with a pump. The experiment was performed in triplicate.

The shoot height, the longest root length, and the shoot and root dry weights for each plant were measured at the end of the cultivation period. Samples of the ^{133}CsCl solutions were analyzed for ^{133}Cs concentrations. In all experiments the ^{133}Cs concentrations were determined using atomic absorption spectrophotometry (AA-6200, Shimadzu Co., Kyoto, Japan). Each sample was analyzed in triplicate. The percentage of metal uptake was calculated using the equation:

$$\%\ uptake = (C0\text{-}C1/C0) \times 100 \tag{1}$$

where C0 and C1 are the initial and remaining concentrations of the metal, respectively, in the solutions (mg/L) (Moogonei et al., 2011).

2.2 Experiment 2. Differences in 133Cs Uptake and Growth among Sunflower, Cosmos, and Rapeseed in Solutions with 3 Different 133Cs Concentrations

Sunflower, cosmos, and rapeseed showed the highest 133Cs uptake levels and highest growth rates in experiment 1. Therefore, these 3 species were used in experiment 2. The cultivation method was as described for experiment 1. Based on the experiments of Borghei et al. (2011) and Moogonei et al. (2011) we used 3 CsCl solutions of 0.5, 2, and 5 mg/L, with Cs^{+} ion concentrations of 0.47, 1.58 and 3.95 mg/L, respectively. The experiment was performed in triplicate.

2.3 Statistical Analysis

Statistical analyses were performed using Excel statistics software (Excel Statistics 2008 for Windows, Social Survey Research Information Co., Ltd., Tokyo, Japan). All data were subjected to analyses of variance to identify significant differences, and means comparisons were obtained using the Fisher LSD test ($P < 0.05$).

3. Results

3.1 Experiment 1. Differences in ^{133}Cs Uptake and Growth Rates among 10 Species

The percentages of ^{133}Cs taken up by the 10 species after 7 days are shown in Table 1. All plants remained healthy after being transferred to the ^{133}Cs solutions. Sunflower, rapeseed, and cosmos showed the highest rates of ^{133}Cs uptake, with percentages of 69.24, 63.22, and 57.58, respectively.

The mean shoot height, longest root length, and dry weights of shoots and roots are shown for each species in Table 2. Cypress vine (a climbing plant) had the greatest shoot height (37.7 cm) and it was followed by cosmos (23.23 cm) and sunflower (22.0 cm). Cosmos, sunflower and rapeseed had the longest root lengths (24.8, 23.05, and 20.2 cm, respectively). Sunflower yielded the highest dry weights in both shoots and roots, and it was followed by rapeseed with the second-highest weights, and then cosmos.

3.2 Experiment 2. Differences in ^{133}Cs Uptake and Growth among Sunflower, Cosmos, and Rapeseed in Solutions with 3 Different ^{133}Cs Concentrations

The percentages of ^{133}Cs taken up by rapeseed, cosmos, and sunflower over a period of 7 days are shown in Figure 1. In general, the 3 species were able to remove at least 50% of the Cs that was present in the growth solution at the beginning of the experiment, regardless of the starting concentration. The only exception was cosmos grown in 2 mg/ml CsCl, which removed approximately 48% of the ^{133}Cs from the solution. The highest rate of uptake (67%) was by sunflower grown in 5 mg/ml CsCl. Relatively high rates (62-63%) were also shown by sunflower grown in 2 mg/ml CsCl and rapeseed grown in 5 mg/ml CsCl. The rate of uptake by sunflower increased significantly with increasing starting concentrations of CsCl. However, no clear correlations were observed between rate of uptake and starting concentration for either rapeseed or cosmos. Among the three species there were no significant differences in the uptake rates for plants grown in 0.5 mg/L CsCl.

The mean shoot height, length of longest root, and dry weights of shoots and roots are shown for the 3 species in Table 3. None of these parameters were affected by the ^{133}Cs concentrations of the solutions.

Table 1. Uptake of Cs from a hydroponic solution by 10 plant species

Plants	Initial concentration (mg/L)	After 7 days (mg/L ± SD)	Uptake (%)	
Rapeseed	4.47	1.65 ± 0.13	63.22	a[z]
Sensitive Plant		3.67 ± 0.16	17.99	b
Gazania		3.88 ± 0.33	13.24	bc
Cosmos		1.90 ± 0.28	57.58	d
Zinnia		2.13 ± 0.21	52.44	cde
California poppy		3.76 ± 0.38	15.87	bf
Common sunflower		1.38 ± 0.14	69.24	a
Saffron Thistle		3.14 ± 0.31	29.78	g
Basket Flower		3.92 ± 0.28	12.37	bcfh
Cypress Vine		3.38 ± 0.31	24.53	bfgi

Values are mean ± standard deviation.

[z] Different letters indicate statistically significant differences ($P < 0.05$) according to a multiple range test.

Table 2. Growth parameters of 10 plant species cultivated in a Cs solution for 7 days

Plants	Shoot height (cm)	The maximum length of root (cm)	Shoot dry weight (g)	Root dry weight (g)
Rapeseed	14.65 ± 1.60 c	20.20 ± 7.69 a	0.424 ± 0.030 b	0.04 ± 0.005 b
Sensitive plant	3.15 ± 1.07 d	14.20 ± 4.51 b	0.037 ± 0.002 d	0.009 ± 0.001 cd
Gazania	4.80 ± 1.74 d	11.30 ± 3.64 bc	0.028 ± 0.002 d	0.003 ± 0.001 d
Cosmos	23.23 ± 3.02 b	24.80 ± 6.02 a	0.211 ± 0.022 c	0.037 ± 0.002 b
Zinnia	6.75 ± 1.44 d	19.00 ± 5.16 ab	0.08 ± 0.005 d	0.017 ± 0.001 c
California poppy	4.75 ± 0.51 d	7.70 ± 1.01 c	0.021 ± 0.002 d	0.003 ± 0.001 d
Common sunflower	22.00 ± 4.99 b	23.05 ± 2.44 a	0.759 ± 0.040 a	0.129 ± 0.007 a
Saffron thistle	13.44 ± 3.07 c	15.75 ± 3.31 b	0.202 ± 0.027 c	0.031 ± 0.004 b
Basket flower	4.50 ± 1.58 d	14.35 ± 1.30 b	0.059 ± 0.006 d	0.015 ± 0.002 c
Cypress vine	37.7 ± 4.58 a	16.6 ± 4.56 b	0.192 ± 0.018 c	0.033 ± 0.003 b

Values are mean ± standard deviation.

[z] Different letters indicate statistically significant differences ($P < 0.05$) according to a multiple range test.

Table 3. Growth parameters of rapeseed, cosmos and sunflower cultivated in 3 Cs solutions for 7 days

Cs concentration of solution (mg/L)	Shoot height (cm)	The maximum length of root (cm)	Shoot dry weight (g)	Root dry weight (g)
		Rapeseed		
0.5	17.16 ± 1.17 a	28.19 ± 2.48 a	0.457 ± 0.022 a	0.042 ± 0.005 a
2	14.41 ± 1.28 a	23.84 ± 0.93 b	0.443 ± 0.018 a	0.042 ± 0.003 a
5	16.45 ± 0.84 a	24.32 ± 1.84 ab	0.468 ± 0.015 a	0.046 ± 0.003 a
		Cosmos		
0.5	28.75 ± 2.71 a	19.27 ± 0.51 a	0.276 ± 0.011 a	0.034 ± 0.004 a
2	28.14 ± 3.19 a	18.59 ± 1.66 a	0.289 ± 0.015 a	0.034 ± 0.006 a
5	29.95 ± 2.86 a	21.66 ± 1.46 a	0.295 ± 0.014 a	0.037 ± 0.004 a
		Common sunflower		
0.5	30.15 ± 2.55 a	26.48 ± 1.70 a	0.756 ± 0.032 a	0.189 ± 0.013 a
2	28.29 ± 2.19 a	22.03 ± 0.88 b	0.698 ±0.030 a	0.176 ± 0.0012 a
5	30.00 ± 2.58 a	24.62 ± 0.44 ab	0.784 ± 0.036 a	0.166 ± 0.010 a

Values are mean ± standard deviation.

[z] Different letters indicate statistically significant differences ($P < 0.05$) according to a multiple range test.

4. Discussion

In this study we evaluated the potential of 10 ornamental species for the remediation of ^{133}Cs in hydroponic solutions. Sunflower, rapeseed, and cosmos showed the greatest capacities for ^{133}Cs uptake, and they showed higher growth rates than the other 7 species. These results suggest that the rate of ^{133}Cs uptake is correlated with plant biomass, since larger plants absorb greater amounts of water than smaller plants. Previous reports have indicated that sunflower (Soudek et al., 2004) and rapeseed (Chou et al., 2005) have high ^{133}Cs uptake capacities and our study supports those results.

Borghei et al. (2011) grew *Calendula alata* plants hydroponically in CsCl solutions with concentrations of 0.6, 2, and 5 mg/L, and found that 47%, 41%, and 52%, respectively, of the Cs was remediated after 15 days. Moogouei et al. (2011) reported that when *Chenopodium album* and *Amaranthus chlorostachys* were exposed to 0.5 mg/L of CsCl in hydroponic solutions for 15 days, 68% of the Cs was remediated by the C. album plants. Moreover, when *Chromolaena odorata* were exposed for 15 days to solutions with three different levels of ^{137}Cs (1×10^3, 5×10^3, and 10×10^3 kBq/L), remediation was observed at rates of 89%, 81%, and 51%, respectively (Singh et al. 2009). It is known that plants belonging to the family Asteraceae are efficient accumulators of ^{134}Cs (Tang & Willey, 2003; Singh et al., 2009). Singh et al. (2009) have found that plants reside in the families Amaranthaceae, Asteraceae, and Chenopodiaceae are efficient remediators of ^{137}Cs.

Singh et al. (2009) proved that the rate of remediation was greatest during the first seven days of exposure of *C. odorata* plants to ^{137}Cs. In this study, when sunflower was cultivated in a 5 mg/L solution of ^{133}CsCl for 7 days, nearly 70% of the ^{133}Cs was removed from the solution. Moreover, rapeseed, sunflower, and cosmos were all able to remediate at least 48% of the ^{133}Cs present in the hydroponic solution in 7 days, regardless of the initial ^{133}Cs concentration. Therefore, these species may be useful for the remediation of radioactive Cs isotopes from contaminated sites. In Japan, rapeseed flowers in spring, sunflower flowers in summer, and cosmos flowers in autumn. By combining these three species, the remediation will be also attained simultaneously, enjoying the flower from spring to autumn.

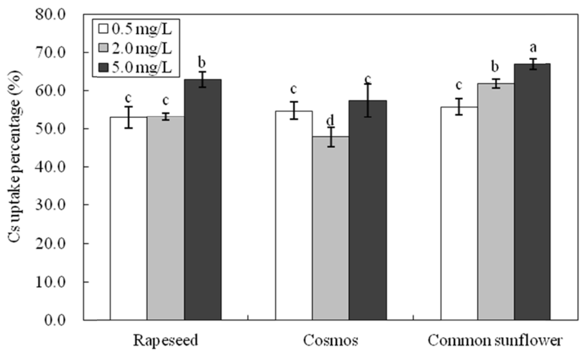

Figure 1. Percentages of ^{133}Cs taken up by rapeseed, cosmos, and sunflower cultivated in three ^{133}Cs solutions for 7 days. The starting CsCl concentrations were 0.5, 2.0, ans 5.0 mg/L. Values are mean ± standard deviation. Different letters indicate statistically significant differences ($P < 0.05$) according to a multiple range test.

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