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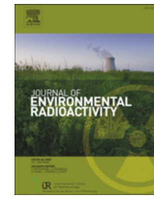

The uptake of Cs and Sr from soil to radish (*Raphanus sativus* L.)- potential for phytoextraction and remediation of contaminated soils

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ABSTRACT

The ^{133}Cs and ^{88}Sr uptake by plant *Raphanus sativus* L. was studied during cultivation in outdoor potted-soil. The distribution, accumulation of ^{133}Cs, ^{88}Sr and the antioxidant responses in plants were measured after 30 and 60 days of cultivation. The results showed that the uptake capacity of radish for ^{88}Sr was far higher than that for ^{133}Cs when the concentration of ^{88}Sr was as the same as that of ^{133}Cs in the soil (The concentration of ^{88}Sr or ^{133}Cs in the soil was from 2.5 mg kg^{-1} to 40 mg kg^{-1}). The highest ^{88}Sr accumulation was 239.18 μg g^{-1} dw, otherwise, the highest ^{133}Cs accumulation was 151.74 μg g^{-1} dw (The concentration of ^{88}Sr in the soil was 40 mg kg^{-1}), and the lowest ^{88}Sr accumulation was 131.03 μg g^{-1} dw, otherwise, the lowest ^{133}Cs accumulation was 12.85 μg g^{-1} dw (The concentration of ^{88}Sr in the soil is 5 mg kg^{-1}). The ^{88}Sr and ^{133}Cs TF values were 1.16–1.72 and 0.24–0.60, respectively. There was little influence of high concentration of ^{88}Sr on the total biomass of plants, so the radish is one of the ideal phytoremediation plant for Sr polluted soils. The important physiological reasons that radish had good tolerance to ^{88}Sr stress were that the MDA content was higher under the ^{88}Sr stress than that under the ^{133}Cs stress, and the activities of POD and CAT were lower under the ^{88}Sr stress than that under ^{133}Cs stress.

1. Introduction

Soil contamination with radionuclides is a problem at many nuclear installations and is disposal by excavation, shipping and the burial of contaminated soils is costly and it is also a labor intensive procedure (Fuhrmann et al., 2003). Application of plants to clean up soils contaminated by radionuclides and/or toxic elements (which is phytoremediation) is increasingly applied (Lasat et al., 1998; Vanek et al., 2001; Watt et al., 2002). Phytoextraction has been suggested as an alternative to existing physical and chemical remediation methods resulting in almost a 100-fold decrease in quantity of soils requiring disposal, but it is time consuming and leads to accumulation of radioactive biomass (Zhu and Smolders, 2000; Furhmann et al., 2004; Vandenhove and Van Hees, 2004). Choosing the right hyperaccumulator is the most important factor in the phytoextraction of the radionuclide polluted soils or water (Singh et al., 2008; Veresoglou et al., 1995; Broadley and Willey, 1997; Chou et al., 2005). The responses of plants to nuclide stress in soils and the characteristics of uptake and accumulation are some important features as a kind of hyperaccumulators (Ehlken et al., 2002). Currently, the hyperaccumulators for phytoremediation of heavy metal polluted soils have been extensively studied (Eapen and D'Souza, 2005; Mohan Murali Achary et al., 2008; Sheng et al., 2008; Peng et al., 2008; Willey, 2005). While there are few studies on the hyperaccumulator for phytoremediation of Cs and Sr polluted soils (Eapen et al., 2006). Meanwhile, as the stable isotopes of ^{137}Cs and ^{90}Sr, ^{133}Cs and ^{88}Sr can imitate the migration and distribution of ^{137}Cs and ^{90}Sr in the plant-soil system very well (Tsukada et al., 2005; Soudek et al., 2004). Radish was chosen as the research object in this experiment to investigate the characteristics of uptake and the antioxitant responses in ^{133}Cs and ^{88}Sr polluted soils, in order to lay some theoretical foundations for phytoremediation of soil contamination with radionuclides.

2. Materials and methods

2.1. Plant material and treatment

The experiment was carried out with outdoor potted plants in the lab block of life science in Southwest University of Science and

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Technology in Mianyang, Sichuan ($E = 104°42'$, $N = 31°32'$, elevation: 462 m). The soil of the experiment, which was yellow earth, came from the nursery test base in the garden center of Southwest University of Science and Technology. The pH of the soil in H_2O and KCl were measured with the pH meter. The soil organic matter were measured according to the Tyurin's method; Mix each gram of grinded and sieved soil even with 5 ml deionized water, and the electrical conductivity of the soil were measured with a conductivity meter after it is static. Table 1 is the main physical–chemical characteristics of the soil.

Each pot (diameter 25 cm, height 20 cm) was put into 4.5 kg of soil and some calcium superphosphate. Spray clean water before sowing. The seeds were sown on March 2, 2008. The radish seeds (purchased from the Mianyang seed company) were sown evenly in each treatment group, 3 seeds for each pot, 3 pots for each treatment, with three replications. Since the radionuclides sets on the soil surface by sedimentation and enters the inside with the time going, ^{133}CsCl or $^{88}Sr(NO_3)_2$ solution were sprayed separately and evenly on the soil surface of each pot based on the concentrations in Table 2 in the next day after sowing.

Watered the plants regularly during the experiment. Maintained a field water capacity of 70%. The management level for each treatment field should be the same.

2.2. Measuring the physiological and biochemical indexes

The chlorophyll content, Malondialdehyde (MDA), the activity of catalase (CAT) and peroxidase (POD) are the important physiological and biochemical indexes reflecting plant stress degree. They can reflect injury severity rate of plant in the contaminated soils. The leaves were taken from the plants and each physiological index was measured in 30 and 60 days after sowing, respectively. The MDA content was measured with the TBA colorimetry (Li et al., 2000). The total chlorophyll content was measured at 652 nm with 95% ethanol colorimetry and calculated (Li et al., 2000). The activity of CAT was measured with the ultraviolet absorption method (Li et al., 2000). The activity of the POD was measured with Li's method (Li et al., 2000). The experiment results were the average values of three repeated tests.

2.3. Measuring the ^{133}Cs and ^{88}Sr contents

The radish plants were harvested after 60 days sowing and divided to two parts, viz. roots and above-ground parts. The weeds and stones in the air-dried radish plant sample was removed and passed through 2 mm sieve then rinsed in deionized water. They were dried to a constant weight in an oven and then measured for dry weight. Different parts of plants were pulverized with a stainless steel blade. The sample plants were washed with distilled water, weighed exactly 0.5 g after-sample and place it in the conical flask and 10 mL acid mixture (volume ratio of nitric acid: perchloric acid is 3:1) was added in it. Being covered for an overnight, the liquid samples were washed into the Kjeldahl flask and dispelled on the electric stove until it began to give out white smoke. The digestive juice was colorless and transparent. It was into the constant volume of 50 Ml with 0.5 mol L^{-1} nitric acid. The graphite furnace atomic absorption spectroscopy (AA700, Perkin Elmer Company, USA) was used to measure the content of ^{133}Cs and ^{88}Sr.

Table 1
Physical–chemical characteristics of the soil.

Parameters	Values
pH in H_2O	7.14
pH in KCl	6.32
Organic matter (%)	1.26
Electrical conductivity (mS/cm)	1.17

2.4. Measuring the biomass

The whole plants were used for biomass measurement after sowing 60 days. The plant samples were washed with distilled water and separated from the above-ground parts and the root parts with scissors. Firstly, samples were air-dried in cool and well-ventilated places, then were oven dried (68 °C ± 2 °C, 24 h). The dry weight of each part was weighed to calculate the biomass.

2.5. Determination of the TF value

TF = nuclide content in the above-ground parts/nuclide content in the root parts.

2.6. Data analysis

Microsoft Excel 2003 (U.S., Microsoft), DPS3.1 Software (China) and the Origin 6.0 mapping software (U.S., Microcal) were used for data analysis.

3. Results

3.1. Uptake characteristics and TF of ^{133}Cs and ^{88}Sr in radish

The ^{133}Cs and ^{88}Sr contents in each treatment of plants were measured after sowing 60 days and the results are showed in Table 3. It can be found from the Table 3 that the contents of ^{133}Cs and ^{88}Sr in control plants were less than the minimum detectable amount. The total content of ^{133}Cs in the radish rose with the increase of the ^{133}Cs concentration in the soil. There was no significant difference between the treatments of 2.5 and 5 mg kg^{-1}, while the difference between other treatments was very significant. For the ^{88}Sr treatments, except that the difference for the total contents with 2.5 and 10 mg kg^{-1} treatments was not significant, the situations of other treatments were similar to those of ^{133}Cs treatments. For ^{133}Cs stress, the content of ^{133}Cs in above-ground parts of the plants rose with the gradient increase of the concentration. There was no significant difference between the three treatments of 2.5, 5 and 10 mg kg^{-1} ($p > 0.05$). The ^{133}Cs content of the 40 mg kg^{-1} treatment was the highest, which was 43.62 μg g^{-1} dw. The ^{133}Cs content in roots also rose with the increase concentration of ^{133}Cs in the soil. The difference between the treatments was very significant ($p < 0.01$). The highest content was 13.17 times than that of the lowest. The transfer factor (TF) of ^{133}Cs for each treatment was lower than 1. The ^{133}Cs content in roots was higher than that of the above-ground parts.

The ^{88}Sr contents of the above-ground parts in 2.5 and 5 mg kg^{-1} treatments were lower, and the content for the 40 mg kg^{-1} treatment was the highest, which was 133.54 μg g^{-1} dw. The ^{88}Sr content of the root parts in the 5 mg kg^{-1} treatment was the lowest, and the content for the 40 mg kg^{-1} treatment was the highest, which was 105.64 μg g^{-1} dw. It can also be found that the transfer factor (TF) of each treatment for ^{88}Sr was higher than 1, i.e. the ^{88}Sr content of the above-ground parts was higher than that of roots, which means that the transfer capacity of Sr toward the above-ground parts was stronger inside radish. With the same treatment concentration, the uptake capacity of radish roots for ^{88}Sr was stronger than that for ^{133}Cs, especially the absorbed ^{88}Sr was 10.21 times than the absorbed ^{133}Cs in 2.5 mg kg^{-1} treatment. This difference decreased gradually with the increase of the concentration of the treatment, which was only 1.58 times when it was 40 mg kg^{-1} treatment.