Natural Plant Selection for Radioactive Waste Remediation

Nan Hu, Dexin Ding and Guangyue Li

Abstract Phytoremediation of radioactive waste is a process that uses plants to remove, transfer, or immobilize radionuclides from the contaminated soil, sediment, sludge, or water, and it is a useful method for treating large-scale low-level radionuclide contamination. However, there have not been established criteria which can be utilized to screen out suitable plant species that are capable of remediating the radioactive waste. In this chapter, important factors influencing the selection of natural plant to remediate radioactive waste, including the characteristics of radioactive waste, the vegetation plant species and vegetation community composition in the radioactive waste deposited area, the concentration of a target radionuclide in the plant, the biomass of the plant, and the concentration of a target radionuclide in the radioactive, are analyzed, and the criteria based on the phytoremediation factor (PF) have been proposed for the selection of natural plant to remediate radioactive waste.

Keywords Phytoremediation · Radionuclide · Radioactive waste · Plant screening · Hyperaccumulator

Contents

N. Hu · D. Ding (✉) · G. Li
Key Discipline Laboratory for National Defense for Biotechnology in Uranium Mining and Hydrometallurgy, University of South China, Hengyang 421001, Hunan People's Republic of China
e-mail: dingdxzzz@163.com

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1 Introduction

In the present chapter, radioactive waste mainly refers to radionuclide-contaminated soil, sediment, sludge, and water. The mechanisms of phytoremediation applicable to radioactive waste include enhanced rhizosphere biodegradation, phytoextraction, phytodegradation, and phytostabilization. Because radionuclides cannot be biodegraded, the mechanisms applicable to remediation of radionuclides are phytoextraction and phytostabilization. Phytoextraction is a process that includes the uptake of radionuclides by plant roots from the contaminated soil and the translocation/accumulation of radionuclides into plant shoots and leaves. The plants are subsequently harvested from the growing area, dried, and disposed of. Phytostabilization involves the production of chemical compounds by plants and their immobilization of radionuclides on the interface between roots and radioactive waste. Radionuclides transport in soil, sediments, or sludges can be reduced through absorption and accumulation by the plant roots; adsorption onto roots; precipitation, complexation, or metal valence reduction in soil within the root zone; or binding to humic (organic) matter through the process of humification. Before phytoremediation can be applied for remediating radioactive waste, the appropriate natural plant species should be selected. The procedures for screening the suitable plant species for phytoremediation of radioactive waste are as follow: First of all, the characteristics of radioactive waste to be remediated should be analyzed; secondly, the vegetation plant species and vegetation community composition in the radioactive waste deposited area should be surveyed; thirdly, the concentration of a target radionuclide in the plant should be determined; fourthly, the biomass of the plant should be calculated; and finally, the concentration of a target radionuclide in the remediated radioactive waste should be measured.

In this chapter, based on the previous work on screening of plant species for phytoremediation of U, Th and ^{226}Ra-contaminated soils from uranium mill tailings impoundment in South China, important factors influencing the selection of natural plant for the remediation of radioactive waste were analyzed, and the criteria based on the phytoremediation factor (PF) were proposed for the selection of natural plant to remediate radioactive waste.

2 Characteristics of Radioactive Waste

The characteristics of radioactive waste are important factors to be considered in selecting the natural plant species for phytoremediation, since they will impact the growth of the candidate for phytoremediation of the radioactive waste. Based on the characteristics of radioactive waste, preliminary treatments, such as adjusting pH value for plant growth, supplying fertilizer to improve the physicochemical properties of radionuclides, and adding the chelating agent to increase the bioavailability of radionuclides in the radioactive waste, could be conducted.

In this chapter, the candidates for phytoremediation of radioactive waste were selected from the natural plants growing in a uranium mill tailings impoundment in South China. The impoundment has a subtropical continental climate with an annual average temperature of 17.9 °C, an annual average rainfall of 1452.0 mm, and an annual average evaporation capacity of 1324.5 mm, and its altitude is from 210.5 to 307.0 m above sea level. It covers an area of approximately 1.70 km^2 and contains approximately 1.88×10^8 t of uranium mill tailings produced by a nearby uranium mill where the uranium ore was processed by acid leaching from 1963 to 1994. The tailings were sandy and without any nutrients and organic matter when they were deposited initially. But at present, on the top of the uranium tailings, many scattered regolith layers in thickness of 1–2 cm with high nutrient content or organic material from the rotten plants have been formed, and many plant species have colonized in the regolith layers.

The characteristics of the uranium mill tailings in the impoundment are presented in Table 1. The particle sizes of the tailings collected from the uranium mill tailings impoundment ranged between 0.040 and 0.074 mm. The pH value of the tailings ranged from 4.42 to 6.10. The reason for this was that the uranium ore was processed by acid leaching in the former uranium ore reprocessing factory and that the uranium mill tailings impoundment was in an acid rain zone (Fan et al. 2010). In this acidic environment, the mobility of the hazardous materials including radionuclides and heavy metals will increase. It was obvious that there was a great difference between the minimum and maximum values of the concentrations of the determined elements in the tailings. Three explanations for this may be given. First, the tailings had the acidic nature, this resulted in the dissolution of the elements from the tailings, and they could flow with the rainfall from one site to another. Second, the tailings had been deposited at the impoundment during different periods from 1963 to 1994, and this resulted in the different releasing order of the elements. Third, different plant species had different uptake activities for the elements from the tailings. The uranium mill tailings also contained considerable nutrients and trace elements needed for growth of plants.

Phytoremediation is limited to shallow soils and sediments. Because the growth of plants used in phytoremediation can be affected by climatic or seasonal conditions (FRTR 2002), this technology may not be applicable in areas with cold climates and short growing seasons.

Table 1 Characteristics of the tailings deposited in the uranium mill tailings impoundment in South China (Li et al. 2011; Hu et al. 2014)

Mill tailings characteristics	
Grain size	0.040–0.074 mm
pH	4.42–6.10
SiO_2	70.65–74.89 %
Fe	1.80–2.10 %
Al	2.85–3.25 %
Ca	3.35–3.56 %
Mg	0.14–0.17 %
P	0.0012–0.093 %
K	0.0027–0.0052 %
B	0.0008–0.0012 %
Mo	0.0063–0.0071 %
Cl^-	0.024–0.031 %
SO_4^{2-}	0.026–0.035 %
NO_3^-	0.28–0.32 %
Total C	2.86–4.52 %
CEC	8.65–9.87 cmol kg^{-1}
U	6.03–46.5 μg g^{-1}
Th	4.75–19.8 μg g^{-1}
^{226}Ra	7.32–29.52 Bq g^{-1}

3 Vegetation Plant Species and Vegetation Community Composition in the Radioactive Waste Deposited Area

The vegetation plant species and vegetation community composition in the radioactive waste deposited area are important for selecting the natural plant species for phytoremediation of radioactive waste. The selected plant species should be the dominant species, since they will cause the minimal impact on the ecological interaction between the local plants and keep the stability of the vegetation community.

An extensive survey was conducted in autumn 2011. To survey the vegetation composition of the flora in the mill tailings impoundment, 9 sampling sites were selected systematically in the uranium mill tailings impoundment (S1–S9, Fig. 1). Six sampling sites were in the dump 1, and the other three sampling sites were in dump 2.

In total, 80 species were recorded in the sampling sites. They belonged to 67 genera in 32 families (Table 2). Most of the species recorded were perennial forbs and grasses. The Poaceae and Asteraceae were the dominant families colonizing the impoundment and had 16 and 13 species, respectively, the Rosaceae and Cyperaceae had 5 species each, and the rest had less than 3 species. There were also some trees, including *Broussonetia papyrifera*, *Paulownia fortunei*, *Cinnamomum camphora*, *Salix matsudana*, *Rhus chinensis,* and *Melia azedarach*. Based on the life-form, most of the species were shallow-rooted, drought-tolerant plants and belonged to common native plants. In terms of the composition of vegetation

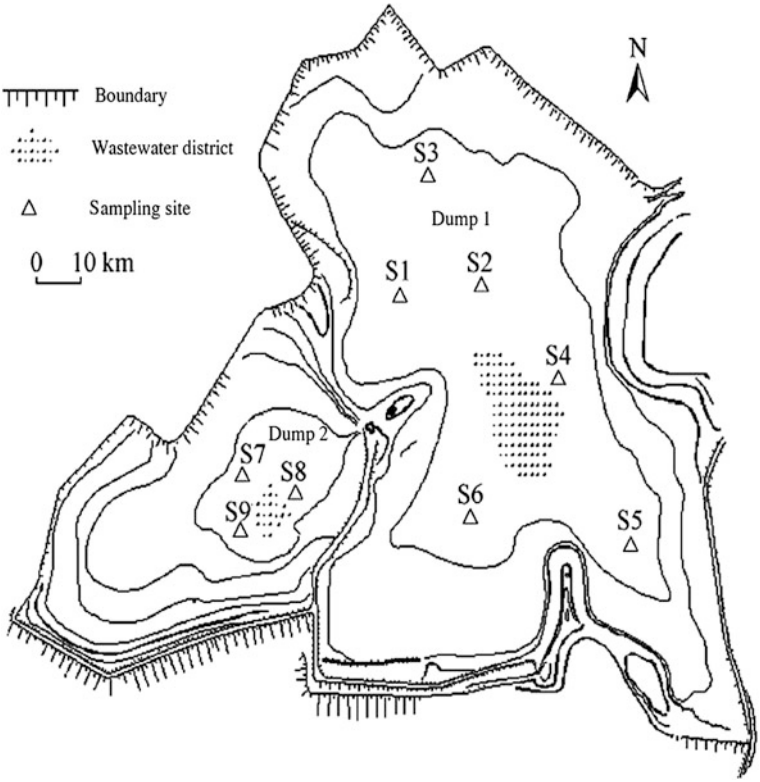

Fig. 1 Distribution of the sampling sites in the uranium mill tailings impoundment in South China (Hu et al. 2014)

community and the life-form, most of the species recorded were 1-year or 2-year perennial herbs, with a small number of trees and shrubs. The trees grew in the impoundment mainly belonged to typical positive pioneer plants.

In the investigation, only 7 species (*Kyllinga brevifolia, Phragmites australis, Imperata cylindrica, Setaria viridis, Pteris multifida, Pteris cretica L. var. nervosa,* and *Pteridium aquilinum*) occurred in all the sampling sites. Furthermore, 12 species, including *Oxalis corymbosa, Avena fatua, Paspalum scrobiculatum, Eleusine indica, Miscanthus floxidulus, Polypogon fugax, Erigeron annuus, Erigeron canadensis, Solanum nigrum, Trema dielsian, R. chinensis,* and *Dryopteris scottii*, occurred in 8 sampling sites. However, there were 13 species including *Persicaria hydropiper, P. fortunei, C. camphora, Cyperus difformis, Rubus alceaefolius, Digitaria sanguinalis, Herba taraxaci, S. matsudana, Amaranthus spinosus, Plantago asiatica, Plantago major, Boehmeria nivea,* and *Medicago sativa* occurring only in sampling sites.

The vegetation composition was influenced by grazing pressure, age of enclosures, and seasonality (Fernandes et al. 2006; Angassa and Oba 2010). Three types

Table 2 Plant community composition on the sampling sites at uranium mill tailings impoundment in South China (Hu et al. 2014)

Family	Species	Abundance[a]								
		S1	S2	S3	S4	S5	S6	S7	S8	S9
Moraceae	*Morus alba*	0	0	1	2	1	0	0	3	0
	Broussonetia papyrifera	0	0	3	5	2	2	0	4	4
	Humulus scandens	0	1	0	4	0	0	0	3	3
Polygonaceae	*Polygonum posumbu*	0	0	2	1	2	1	0	0	2
	P. lapathifolium	0	1	1	2	0	2	0	2	2
	P. hydropiper	0	0	1	0	2	0	0	0	1
Scrophu lariaceae	*Paulownia fortunei*	0	0	1	0	0	0	0	1	2
Lauraceae	*Cinnamomum camphora*	0	0	0	1	0	0	0	1	2
Oxalidaceae	*Oxalis violacea*	1	0	0	1	1	2	1	0	0
	O. corymbosa	1	1	3	4	2	3	0	4	3
Verbenaceae	*Vitex negundo*	0	0	0	4	1	1	0	2	3
	Clerodendrum cyrtophyllum	0	0	3	2	4	3	0	3	3
Cyperaceae	*Kyllinga brevifolia*	1	1	2	4	1	1	1	2	3
	Juncellus serotinus	1	0	2	3	1	1	0	2	2
	Cyperus iria	0	0	2	3	2	0	1	3	4
	C. difformis	0	0	0	1	0	0	1	2	0
	Cyperus rotundus	0	1	3	4	2	2	0	3	4
Rosaceae	*Duchesnea indica*	0	1	0	1	2	1	0	1	0
	Rosa laevigata	0	0	0	2	0	1	1	0	1
	Rubus corchorifolius	0	0	1	0	2	0	2	1	0
	R. alceaefolius	0	0	0	1	0	1	0	0	1
	R. hanceanus	0	1	1	3	3	4	1	2	4
Phytolaccaceae	*Phytolacca acinosa*	0	0	2	0	2	2	0	5	5
Portulacaceae	*Portulaca oleracea*	0	0	2	1	2	1	0	0	2
Poaceae	*Avena fatua*	1	1	2	4	0	2	1	4	4
	Alopecurus aequalis	0	1	0	0	0	1	0	3	4
	Digitaria sanguinalis	0	0	0	0	1	0	0	3	2
	Phragmites australis	3	4	1	2	3	2	4	2	2
	Paspalum scrobiculatum	2	2	1	2	2	2	1	3	0
	P. distichum	0	2	1	0	2	1	0	2	3
	Potamogeton pectinatus	0	0	2	1	2	1	0	1	1
	Poa pratensis	0	0	2	1	2	1	0	3	4
	Rhizoma imperatae	0	0	1	2	0	0	0	1	2
	Imperata cylindrica	2	4	1	2	2	2	4	2	3
	Eragrostis pilosa	0	1	3	2	2	3	0	2	3
	Eleusine indica	1	0	2	1	3	1	2	3	3
	Miscanthus floxidulus	2	1	3	3	5	5	1	3	0
	Phleum alpinum	0	1	1	2	2	2	0	2	2
	Polypogon fugax	1	0	3	2	1	1	1	2	3
	Setaria viridis	2	4	2	2	2	1	4	3	2

(continued)

Table 2 (continued)

Family	Species	Abundance[a]								
		S1	S2	S3	S4	S5	S6	S7	S8	S9
Asteraceae	*Artemisia lavandulaefolia*	1	0	1	3	2	1	0	1	1
	Artemisia capillaris	1	0	2	3	1	3	1	3	4
	Bidens pilosa	0	0	0	1	2	0	0	3	3
	Erigeron annuus	1	1	2	4	2	3	0	2	2
	E. canadensis	1	0	2	1	2	3	1	3	2
	E. sonchifolia	1	0	0	4	1	1	0	1	1
	Herba taraxaci	0	0	0	1	0	1	0	0	1
	H. gnaphaii	0	0	3	1	4	1	0	2	2
	Ixeris chinensis	0	0	2	0	3	2	3	2	3
	Senecio scandens	0	0	1	2	3	2	0	0	2
	Gynura crepidioides	0	0	2	0	0	1	0	1	1
	Youngia japonica	0	0	1	2	2	0	0	0	1
	Xanthium sibiricum	0	0	1	3	1	0	0	2	2
Solanaceae	*Solanum nigrum*	0	2	3	1	3	2	1	3	3
	S. lyratum	0	0	2	2	0	0	0	1	1
Ulmaceae	*Trema dielsian*	1	0	2	3	2	3	2	3	3
	Ulmus parvifolia	0	0	2	1	1	0	0	1	2
Hamamelidaceae	*Loropetalum chinense*	0	0	1	4	1	1	0	4	5
Liliaceae	*Smilax china*	0	0	1	1	0	0	0	1	1
Salicaceae	*Salix matsudana*	0	0	0	0	0	0	0	1	1
Oleaceae	*Ligustrum quihoui*	0	0	0	1	0	1	0	1	1
Amaranthaceae	*Amaranthus spinosus*	0	0	0	1	0	0	0	2	1
	Alternanthera philoxeroides	0	0	0	2	1	1	0	1	1
Euphorbiaceae	*Ricinus communis*	0	0	1	1	2	2	0	3	4
	Mallotus apelta	1	3	0	2	3	3	1	2	0
Anacardiaceae	*Rhus chinensis*	2	1	0	1	1	2	3	2	2
Zingiberaceae	*Alpinia japonica*	0	0	2	0	1	1	0	0	1
Plantaginaceae	*Plantago asiatica*	0	0	1	0	1	0	0	0	1
	P. major	0	0	0	1	0	1	0	1	0
Pteridaceae	*Pteris multifida*	3	2	3	4	2	2	3	4	3
	P. nervosa	3	3	4	2	2	4	2	4	4
Malvaceae	*Hibiscus syriacus*	0	0	0	2	2	1	0	1	3
Aquifoliaceae	*Ilex cornuta*	0	0	3	3	4	3	0	4	3
Pteridiaceae	*Pteridium aquilinum*	3	4	5	5	4	3	2	4	3
Meliaceae	*Melia azedarach*	0	0	1	2	1	0	0	2	3
Papaveraceae	*Macleaya cordata*	0	1	3	4	3	3	2	3	5
Urticaceae	*Boehmeria nivea*	0	0	0	2	0	1	0	0	3
Legum inosae	*Medicago sativa*	0	0	0	0	0	1	0	0	2
	Lespedeza cuneata	0	0	1	1	1	0	0	0	1
Dryopteridaceae	*Dryopteris scottii*	1	1	3	0	2	3	3	2	1

Note [a] Abundance is classified as five grades: 0 means absent; 1 means very rare; 2 means rare; 3 means occasional; 4 means frequent; and 5 means abundant

of vegetation community were formed by the activities of radionuclides in and pH value of the uranium tailings. The plant species in the locations of S4, S8, and S9 formed a relatively stable vegetation community (*C. camphora* and *B. papyrifera* + *Loropetalum chinense* and *Vitex negundo* + *Macleaya cordata* and *Phytolacca acinosa*). The plant species in the locations of S3, S5, and S6 formed the transitional vegetation community (*B. papyrifera* + *Mallotus apelta* and *Ilex cornuta* + *M. floxidulus* and *P. aquilinum*). The plant species in the locations of S1, S2, and S7 formed a simple unstable vegetation community (*P. australis* + *I. cylindrica*) and a vegetation community (*M. apelta* + *R. chinensis* + *S. viridis* + *I. cylindrica* + *P. scrobiculatum*) that was similar to that on the unused grassland.

4 Concentration of a Target Radionuclide in the Plant

The most important step to success in phytoremediation is to identify hyperaccumulators which can accumulate a target radionuclide to a certain concentration in their shoots in terms of dry weight. Baker and Brooks (1989) have proposed that the accumulators should have accumulation capabilities of more than 1,000 mg kg^{-1} for As, Pb, Cu, Ni, and Co, 10,000 mg kg^{-1} for Mn and Zn, and 100 mg kg^{-1} for Cd in their shoots. For an accumulator, the metal concentration in its shoot should be much higher than that in its root, and it should have a special capability of absorbing, transferring, and accumulating the metal in its aboveground part (Baker and Brooks 1989). More than 45 families have been identified to contain some metal-accumulating species, and more than 400 plant species of metal hyperaccumulators have been reported (Salt et al. 1998; Reeves and Baker 2000; Hu et al. 2013). But, the hyperaccumulators for radionuclides have not been defined so far. In recent years, phytoremediation studies concerning the treatment of radionuclide-contaminated soils have been carried out using different plant species under various conditions, and the improvement of the uptake by adding fertilizers, organic acids, or chelating agents (Khatir Sam 1995; Papastefanou 1996; Huang et al. 1998; Carini 1999; Madruga et al. 2001; Blanco Rodríguez et al. 2002; Shahandeh and Hossner 2002; Dushenkov 2003; Karunakara et al. 2003; Shinonaga et al. 2005; Soudek et al. 2007a, b, 2010, 2011; Pulhani et al. 2005; Chen et al. 2005; AbdEl-Sabour 2007; Thiry and Van 2008; Vera et al. 2008, 2009; Cukrov et al. 2009; Blanco Rodríguez et al. 2010; Dragović et al. 2010; Srivastava et al. 2010; Černe et al. 2011; Li et al. 2011; Hu et al. 2014). Also, sunflower (*Helianthus annuus*) and Indian mustard (*Brassica juncea*) were proposed as potential uranium accumulators for uranium phytoextraction in one uranium mill tailings soil and nine acid and calcareous soils contaminated with different rates of uranyl nitrate. However, various factors, such as the physical and chemical properties of the soil, water, and sediment, climatic and seasonal conditions, plant and microbial exudates, bioavailability of metals, and the capability of plants to uptake, accumulate, translocate, sequester and detoxify metals, have influence on phytoremediation efficiency (Pedron et al. 2009). As a result, sunflower (*Helianthus annuus*) and Indian mustard (*Brassica juncea*) have not been

widely utilized for phytoremediation in practice so far (Fellet et al. 2007). Consequently, it is important to develop phytoremediation technology based on the native plant species that are suitable for the phytoremediation of the sites contaminated by particular radionuclides.

In July 2009, 15 dominant plant species belonging to 9 families were collected from the uranium mill tailings impoundment in South China (Li et al. 2011). The concentrations of uranium and thorium in the samples of plant species and tailings were determined. The results are presented in Table 3. Among the plant samples collected, *Cyperus iria* accumulated the highest concentration of U in its shoot which reached 36.4 μg g^{-1} (Air dried or oven dried weight basis of samples (DW)). *Juncellus serotinus* accumulated the highest concentration of Th in its root which reached 3.66 μg g^{-1} (DW).

In September 2009, a wide survey was conducted in the uranium mill tailings impoundment in South China (Ding et al. 2010). Thirty-five plant species were collected, and the concentrations of uranium in the samples were determined. The results are presented in Table 4. *J. serotinus* accumulated the highest concentration of U in its stem which reached 1.52 mg g^{-1} (Ash weight basis of samples (AW)). Furthermore, *K. brevifolia, C. difformis, M. cordata, Geranium carolinianum, E. annuus, P. nervosa, C. iria,* and *A. fatua* accumulated relatively high concentrations of U in their aerial parts.

In September 2011, an extensive survey was conducted in the uranium mill tailings impoundment in South China (Hu et al. 2014). Thirty-three dominant plant species belonging to 16 families were collected, and the activities of ^{226}Ra in the samples were determined. The results are presented in Table 5. There was great variation in the activities of ^{226}Ra in the tissues of different plant species. The average activities of ^{226}Ra in terms of AW for seeds, leaves, stalks, and roots were 30.99, 13.34, 5.772, and 4.515 Bq g^{-1}, respectively. The high activities of ^{226}Ra were found in the leaves of *P. multifida* (150.6 Bq g^{-1} of AW), in the leaves of *P. aquilinum* (122.2 Bq g^{-1} of AW), in the leaves of *D. scottii* (105.7 Bq g^{-1} of AW), and in the seed of *P. fugax* (105.5 Bq g^{-1} of AW). In contrast, the activity of ^{226}Ra was found below the detection limit in the stalk and root of *Ixeris chinensis* and in the stalk of *S. nigrum*.

Although the hyperaccumulators for U, Th, and ^{226}Ra have not been defined so far, Baker and Brooks (1989) have proposed a two criteria approach for defining the metal hyperaccumulator. First, the concentration of an element accumulated in an organism can be higher than that in the soil. Second, the amount of an element accumulated in an organism can be 10 times greater than that in other organisms investigated. Based on this approach, *C. iria* and *J. serotinus* satisfied the criteria for a hyperaccumulator for U. *P. multifida*, *P. aquilinum*, and *D. scottii* satisfied the criteria for a hyperaccumulator for ^{226}Ra. Although the high concentration of a target radionuclide in the plant species has been found in our investigation, all the experiments were carried out on contaminated areas with different histories, different contents of nutrients and organic matter; the areas were situated in different vegetation climates; and the plant species growing naturally on these areas were also quite different. In the further study, the laboratory tests will be conducted to confirm the results.

Table 3 Concentrations of U and Th in the plant and tailings samples collected from the uranium mill tailings impoundment in South China (DW μg g^{-1}) (Li et al. 2011)

Site	Family	Species	Plant part	U		Th	
				Plant	Tailings	Plant	Tailings
1	Gramineae	*Paspalum paspaloides*	Shoot	8.32	26.7	1.21	4.75
			Root	1.98		0.78	
2	Gramineae	*Miscanthus floridulus*	Leaf	0.96	23.3	0.19	8.84
			Stalk	0.64		0.56	
			Root	1.26		1.20	
	Verbenaceae	*Vitex negundo var . cannabifolia*	Leaf	1.53		0.62	
			Stalk	0.61		0.16	
3	Gramineae	*Paspalum orbiculare*	Shoot	6.99	39.6	2.32	19.8
			Root	1.38		0.23	
	Phytolaccaceae	*Phytolacca acinosa*	Seed	3.55		0.55	
			Stalk	1.40		0.09	
	Compositae	*Artemisia capillaris*	Shoot	0.94		0.29	
4	Euphorbiaceae	*Euphorbia hirta*	Shoot	1.70	21.8	0.26	10.4
			Root	4.98		0.75	
5	Moraceae	*Broussonetia papyrifera*	Leaf	1.54	29.9	0.41	17.8
			Stalk	0.78		0.09	
6	Gramineae	*Phragmites australis*	Seed	1.56	46.5	0.42	10.9
			Leaf	0.36		0.06	
			Stalk	20.6		2.52	
			Root	8.87		1.54	
		Cynodon dactylon	Shoot	1.54		0.25	
7	Cyperaceae	*Kyllinga brevifolia*	Seed	1.09	8.93	0.31	16.6
			Leaf	4.03		2.41	
			Root	7.73		0.53	
8	Cyperaceae	*Cyperus iria*	Shoot	36.4	6.03	2.54	19.2
			Root	2.43		1.54	
9	Cyperaceae	*Juncellus serotinus*	Shoot	16.9	42.1	2.21	8.71
			Root	20.8		3.66	
10	Dicksoniaceae	*Cibotium barometz*	Shoot	5.15	17.3	0.33	18.8
			Root	21.3		1.77	
11	Vitaceae	*Parthenocissus quinquefolia*	Leaf	1.58	26.9	0.04	19.5
			Stalk	0.22		0.57	

5 Biomass of the Plant

The potential of a plant to be used in phytoremediation does not merely depend on the concentration of a target element in the plant (Verma et al. 2007). It has been proposed that a plant with low dry biomass would share a low resultant capability of accumulation for an element and would not be suitable for phytoremediation though the concentration of the target element would be very high in this plant (Robinson et al. 1997). The dry biomass of the plant is considered as an important

Table 4 Concentrations of U in the plant samples collected from the uranium mill tailings impoundment in South China (AW mg g^{-1}) (Ding et al. 2010)

Species	Part	U	Species	Part	U
Imperata cylindrica	Shoot	0.014	*P. nervosa*	Shoot	0.146
	Root	0.077		Root	0.127
Eragrostis pilosa	Shoot	0.057	*Ixeris chinensis*	Shoot	0.016
	Root	0.400		Root	0.032
Kyllinga brevifolia	Shoot	0.124	*Artmsiae capillaris*	Shoot	0.005
	Root	0.084		Root	0.234
C. difformis	Shoot	0.721	*Cyperus iria*	Shoot	0.122
	Root	0.338		Root	0.315
Oxalis violacea	Whole plant	0.048	*Setaria viriisd*	Whole plant	0.304
Common mouse-ear	Whole plant	0.024	*Rhus chinensis*	Leaf	0.242
H. gnaphaii	Whole plant	0.335		Stem	0.205
Macleaya cordata	Leaf	0.111	*Ilex cornuta*	Leaf	0.023
	Stem	0.087		Stem	0.350
Clerodendrum cyrtophyllum	Leaf	0.023	*Helicteres angustifolia*	Leaf	BDL
	Stem	0.048		Stem	BDL
Geranium carolinianum	Leaf	0.444	*Eleusine indica*	Leaf	0.032
	Stem	0.004		Stem	0.111
	Root	0.120		Root	0.050
Paspalum scrobiculatum	Leaf	0.115	*Scirpus planiculmis*	Seed	0.160
	Stem	0.082		Stem	0.004
	Root	0.153		Root	0.033
Heteropogon contortu	Leaf	0.022	*Juncellus serotinus*	Leaf	0.416
	Stem	0.050		Stem	1.520
	Root	0.091		Root	0.345
Pteris multifida	Leaf	0.15	*E. canadensis*	Leaf	0.103
	Stem	BDL		Stem	0.004
	Root	0.361		Root	0.610
Erigeron annuus	Leaf	0.466	*Humulus scandens*	Leaf	0.010
	Stem	0.038		Stem	0.128
	Root	0.012		Root	0.036
Solanum nigrum	Leaf	0.005	*Couch grass*	Leaf	0.028
	Stem	0.043		Stem	0.021
	Root	0.144		Root	0.024
Pteridium aquilinum	Leaf	0.037	*Phleum alpinum*	Flower	0.008
	Vein	0.015		Stem	0.088
	Rhizome	0.053		Root	0.191
Polypogan fugax	Fruit	0.012	*Miscanthus floxidulus*	Fruit	BDL
	Leaf	0.102		Leaf	0.013
	Stem	0.14		Stem	0.014
	Root	0.246		Root	0.025
Phragmites australis	Fruit	0.034	*Avena fatua*	Seed	0.568
	Leaf	0.003		Leaf	0.408
	Stem	0.006		Stem	0.021
	Root	0.074		Root	0.070

Note BDL means below detection limit

Table 5 Activities of ^{226}Ra and TF in the frequently occurred plant species from the uranium mill tailings impoundment in South China (AW ^{226}Ra g Bq^{-1}) (Hu et al. 2014)

Family	Species	Plant tissue	Activity	TF
Moraceae	*Broussonetia papyrifera*	Leaf	4.449 ± 0.256a	0.270
		Stalk	0.065 ± 0.002b	0.004
Oxalidaceae	*O. corymbosa*	Leaf	0.685 ± 0.365c	0.042
		Stalk	0.064 ± 0.026b	0.004
		Root	1.256 ± 0.065d	0.076
Verbenaceae	*Clerodendrum cyrtophyllum*	Leaf	1.660 ± 0.085e	0.101
		Stalk	5.786 ± 0.368f	0.351
		Root	16.31 ± 0.854g	0.989
Cyperaceae	*Kyllinga brevifolia*	Leaf	0.871 ± 0.005c	0.053
		Stalk	3.328 ± 0.152h	0.202
		Root	17.94 ± 0.951g	1.088
	Juncellus serotinus	Leaf	0.536 ± 0.022c	0.032
		Stalk	0.006 ± 0.001j	0.000
		Root	0.805 ± 0.025c	0.049
	Cyperus iria	Leaf	0.015 ± 0.002k	0.001
		Stalk	0.004 ± 0.001j	0.000
		Root	0.019 ± 0.001k	0.001
	Cyperus rotundus	Leaf	0.028 ± 0.002l	0.002
		Stalk	0.015 ± 0.001k	0.001
		Root	1.322 ± 0.095d	0.080
Rosaceae	*R. hanceanus*	Leaf	0.005 ± 0.001j	0.000
		Stalk	0.025 ± 0.001l	0.002
		Root	0.068 ± 0.002b	0.004
Poaceae	*Avena fatua*	Seed	5.190 ± 0.352f	0.315
		Leaf	0.515 ± 0.025c	0.031
		Stalk	6.356 ± 0.423f	0.385
		Root	0.325 ± 0.021c	0.020
	Phragmites australis	Seed	0.421 ± 0.025c	0.026
		Leaf	0.271 ± 0.012c	0.016
		Stalk	0.355 ± 0.015c	0.022
		Root	12.36 ± 0.658m	0.749
	Paspalum scrobiculatum	Leaf	10.37 ± 0.520m	0.629
		Stalk	0.008 ± 0.001j	0.000
		Root	0.569 ± 0.025c	0.034
	Imperata cylindrica	Leaf	3.457 ± 0.080h	0.210
		Stalk	0.007 ± 0.001j	0.000
		Root	0.034 ± 0.002l	0.002
	Eragrostis pilosa	Leaf	0.771 ± 0.008c	0.047
		Stalk	0.468 ± 0.028c	0.028
		Root	0.388 ± 0.015c	0.024
	Eleusine indica	Leaf	5.702 ± 0.210f	0.346
		Stalk	7.513 ± 0.365f	0.455
		Root	5.426 ± 0.151f	0.329

(continued)

Table 5 (continued)

Family	Species	Plant tissue	Activity	TF
	Miscanthus floxidulus	Seed	12.65 ± 0.543m	0.767
		Leaf	0.006 ± 0.001j	0.000
		Stalk	1.367 ± 0.082d	0.083
		Root	16.44 ± 0.752g	0.997
	Phleum alpinum	Leaf	1.539 ± 0.062e	0.093
		Stalk	0.500 ± 0.015c	0.030
		Root	0.647 ± 0.018c	0.039
	Polypogon fugax	Seed	105.5 ± 5.321n	6.408
		Leaf	5.039 ± 0.356f	0.306
		Stalk	0.012 ± 0.001k	0.001
		Root	5.699 ± 0.251f	0.346
	Setaria viridis	Leaf	1.340 ± 0.120d	0.081
		Stalk	0.853 ± 0.025c	0.052
		Root	0.682 ± 0.031c	0.041
Asteraceae	*Artmsiae capillaris*	Leaf	0.423 ± 0.023c	0.026
		Stalk	4.494 ± 0.215a	0.272
		Root	21.021 ± 0.541o	1.274
	Erigeron annuus	Leaf	0.025 ± 0.001l	0.002
		Stalk	0.036 ± 0.002l	0.002
		Root	0.045 ± 0.002l	0.003
	E. canadensis	Leaf	2.086 ± 0.121p	0.126
		Stalk	13.55 ± 0.523m	0.822
		Root	7.197 ± 0.251f	0.436
	H. gnaphaii	Leaf	0.956 ± 0.041c	0.058
		Stalk	0.569 ± 0.021c	0.034
		Root	3.271 ± 0.158h	0.198
	Ixeris chinensis	Leaf	0.069 ± 0.005b	0.004
		Stalk	BDL	–
		Root	BDL	–
Solanaceae	*Solanum nigrum*	Leaf	0.182 ± 0.011q	0.011
		Stalk	BDL	–
		Root	0.682 ± 0.021c	0.041
Ulmaceae	*Trema dielsian*	Leaf	3.612 ± 0.245h	0.219
		Stalk	0.081 ± 0.005b	0.005
		Root	1.368 ± 0.052d	0.083
Euphorbiaceae	*Mallotus apelta*	Leaf	0.052 ± 0.004b	0.003
		Stalk	0.125 ± 0.011q	0.008
		Root	0.068 ± 0.008b	0.004
Anacardiaceae	*Rhus chinensis*	Leaf	0.278 ± 0.015c	0.017
		Stalk	8.106 ± 0.561f	0.491
Pteridaceae	*Pteris multifida*	Leaf	150.6 ± 7.65r	9.131
		Stalk	53.65 ± 2.98s	3.251
		Root	1.782 ± 0.092e	0.108
	P. nervosa	Leaf	14.02 ± 0.820m	0.850
		Stalk	2.354 ± 0.105p	0.143
		Root	0.627 ± 0.052c	0.038

(continued)

Table 5 (continued)

Family	Species	Plant tissue	Activity	TF
Aquifoliaceae	*Ilex cornuta*	Leaf	0.702 ± 0.055c	0.043
		Stalk	3.477 ± 0.254h	0.211
Pteridiaceae	*Pteridium aquilinum*	Leaf	122.2 ± 4.325t	7.409
		Stalk	42.36 ± 1.428u	2.568
		Root	13.14 ± 0.522m	0.797
Papaveraceae	*Macleaya cordata*	Leaf	2.100 ± 0.120p	0.127
		Stalk	5.283 ± 0.428f	0.320
		Root	0.248 ± 0.020c	0.015
Dryopteridaceae	*Dryopteris scottii*	Leaf	105.7 ± 6.650n	6.408
		Stalk	29.685 ± 1.050v	1.800
		Root	5.699 ± 0.467f	0.346

Note Data are presented as mean ±SD, $n = 6$. Means of the data within the column with the same letter are not of significant difference ($p < 0.05$)

factor. The removal capability of a plant for a target element in the plant samples collected was assessed by multiplying the concentration of the target element with the dry biomass of the plant. The average biomass (g) and the removal capability for U and Th (μg plant^{-1}) of the plants collected from the uranium mill tailings impoundment in South China are shown in Table 6. *P. australis* had the greatest removal capabilities for U and Th, which could remove 820 μg U and 103 μg Th per plant, respectively.

6 Concentration of a Target Radionuclide in the Radioactive Waste

The concentration of a target element in the tailings is another important factor that determines the duration it takes to complete the phytoremediation. Phytoremediation might be best suited for sites with the levels of radionuclide contamination which are only slightly higher than the cleanup target levels because the resulting amount of time for cleanup becomes reasonable (less than 10 years) and because possible plant toxicity effects are avoided (Schnoor 2002).

The concentrations of U, Th, and ^{226}Ra in the tailings samples collected from the uranium mill tailings impoundment in South China are presented in Table 1. The concentrations of U ranged from 6.03 to 46.5 μg g^{-1}, Th ranged from 4.75 to 19.8 μg g^{-1}, and ^{226}Ra ranged from 7.32 to 29.52 Bq g^{-1} of DW in the uranium mill tailings. The concentrations of U, Th, and ^{226}Ra in the tailings varied greatly with the sampling sites. This was probably caused by the pH value of the tailings in the sampling sites, microbial community composition and its metabolism, and the plant species growing on them (Li et al. 2011; Hu et al. 2014). The minimum and maximum concentrations of U in the tailings exceeded the background concentrations of U in the soil in the impoundment located in Hunan Province by 1.46

Table 6 Average biomass (g) and the removal capability for U and Th (μg plant^{-1}) of the plants collected from the uranium mill tailings impoundment in South China (Li et al. 2011)

Species	Plant part	Biomassing	Removal capability (μg plant^{-1})	
			U	Th
Paspalum paspaloides	Shoot	1.90 ± 0.15	16.6 ± 1.37	2.61 ± 0.23
	Root	0.40 ± 0.06		
Miscanthus floridulus	Leaf	53.50 ± 6.25	102 ± 15.9	56.3 ± 10.2
	Stalk	49.80 ± 8.24		
	Root	15.20 ± 3.63		
Vitex negundo var. cannabifolia	Leaf	16.20 ± 1.32	38.0 ± 4.25	13.5 ± 1.40
	Stalk	21.60 ± 3.65		
Paspalum orbiculare	Shoot	2.40 ± 0.56	17.6 ± 3.96	5.71 ± 1.31
	Root	0.60 ± 0.03		
Phytolacca acinosa	Seed	2.70 ± 0.03	43.6 ± 3.16	3.68 ± 0.21
	Stalk	24.30 ± 2.18		
Artemisia capillaris	Shoot	17.80 ± 1.95	16.7 ± 1.83	5.16 ± 0.57
Euphorbia hirta	Shoot	5.60 ± 0.46	13.5 ± 1.08	2.06 ± 0.16
	Root	0.80 ± 0.06		
Broussonetia papyrifera	Leaf	18.80 ± 2.36	51.2 ± 6.45	10.3 ± 1.29
	Stalk	28.50 ± 3.61		
Phragmites australis	Seed	1.28 ± 0.05	820 ± 114	103 ± 14.1
	Leaf	13.60 ± 1.65		
	Stalk	37.00 ± 5.32		
	Root	5.62 ± 0.36		
Cynodon dactylon	Shoot	0.68 ± 0.02	1.05 ± 0.03	0.17 ± 0.01
Kyllinga brevifolia	Seed	0.22 ± 0.01	7.18 ± 0.89	3.32 ± 0.49
	Leaf	1.30 ± 0.20		
	Root	0.22 ± 0.01		
Cyperus iria	Shoot	1.26 ± 0.13	46.2 ± 4.76	3.42 ± 0.35
	Root	0.14 ± 0.01		
Juncellus serotinus	Shoot	1.42 ± 0.13	28.8 ± 2.62	3.98 ± 0.36
	Root	0.23 ± 0.02		
Cibotium barometz	Shoot	3.64 ± 0.26	37.1 ± 2.62	2.72 ± 0.19
	Root	0.86 ± 0.06		
Parthenocissus quinquefolia	Leaf	18.50 ± 2.19	30.5 ± 3.60	3.93 ± 0.45
	Stalk	5.60 ± 0.64		

and 17.6 times, respectively. When compared to the background concentrations of U in the soil around the world, the minimum and maximum concentrations of U exceeded by 3.01 and 22.80 times, respectively (Nie et al. 2010). The maximum concentrations of Th in the tailings exceeded the background concentrations of Th in the soil in China by 1.55 times. When compared to the background concentrations of U in the soil around the world, the maximum concentrations of Th exceeded by 2.20 times (Nie et al. 2010). The minimum and maximum activities of ^{226}Ra in the tailings exceeded the background activity of ^{226}Ra in the soil in the impoundment located in Hunan Province by 6,150 and 1,525 times, respectively

(Pan and Yang 1988; Li and Zheng 1989). When compared to the background activity of ^{226}Ra in the soil around the world, the minimum and maximum activities of ^{226}Ra exceeded by 9,973 and 2,473 times, respectively (Bowen 1979). The high concentrations of U, Th, and ^{226}Ra in the tailings made the impoundment a potentially hazardous radioactive source to the plants and animals in and around it. It needs to be remediated urgently.

7 Transfer Factor

Baker and Brooks (1989) proposed that the metal hyperaccumulator should satisfy a criterion that the concentration of an element accumulated in an organism can be higher than that in the soil. Based on their definition, the transfer factor (TF) can be defined as the ratio of target element concentration in the plant to that in the tailings, and it can be used as an index for the accumulation of a target element in the plant and its transfer from the tailings to the plant. If TF for a plant is larger than 1 and the amount of the target element accumulated in the plant is relatively small, the removal capability of the plant for the target element can be further improved using various breeding techniques, and it can be used for phytoremediation (Whicker et al. 1999).

The TFs for U and Th of the plants collected from the uranium mill tailings impoundment in South China are presented in Table 7. *C. iria* had a higher TF for U (5.48), compared with the collected plant species and the reported accumulation plants for U (Shahandeh and Hossner 2002; Chen et al. 2005). But the relatively small amount of biomass in *C. iria* may be a limiting factor for phytoremediation in this study (Table 6). TFs for U and Th of the other plant species were lower than one. TF for ^{226}Ra of the plants collected from the uranium mill tailings impoundment in South China is presented in Table 5. The TF for different tissues of the plant species ranged from 0.000 (leaf of *R. hanceanus* and *M. floxidulus*; stalk of *J. serotinus*, *C. iria*, *P. scrobiculatum*, *I. cylindrica*, *I. chinensis*, and *S. nigrum*; root of *I. chinensis*) to 9.131 (leaf of *P. multifida*). Different TF values for the plants tissues may be resulted in part from metabolic rate differences between plant species and cultivations (Chen et al. 2005). The factors such as the concentration of a radionuclide, speciation, pH of the tailings, the plant age, and ecotype may modify the uptake and ratio of the content of the element in the plant shoot to that in the plant root (Florijn et al. 1993; Jiang and Singh 1994; Tu et al. 2002). About 91 tissues of plant species had the TF values of less than 1, only 9 tissues of plant species had the TF values of more than 1. Overall, it was found that most of the plant species investigated had low capabilities of transferring U, Th, and ^{226}Ra from the tailings to the plant tissues. The results were agreeable with the previous research results (Pulhani et al. 2005; Chen et al. 2005; Baeza and Guillén 2006; Soudek et al. 2007a, b, 2010, 2011; Lauria et al. 2009; Vera et al. 2009).

Table 7 Transfer factor (*TF*) and phytoremediation factor (*PF*) for U and Th of the plants collected from the uranium mill tailings impoundment in South China (Li et al. 2011)

Species	TF		PF	
	U	Th	U	Th
Paspalum paspaloides	0.27	0.24	0.59	0.48
Miscanthus floridulus	0.04	0.05	3.58	4.30
Vitex negundo var. cannabifolia	0.04	0.04	1.63	1.53
Paspalum orbiculare	0.15	0.10	0.42	0.28
Phytolacca acinosa	0.04	0.01	1.10	0.19
Artemisia capillaris	0.02	0.01	0.42	0.26
Euphorbia hirta	0.10	0.03	0.44	0.14
Broussonetia papyrifera	0.04	0.01	1.71	0.58
Phragmites australis	0.31	0.16	16.6	8.68
Cynodon dactylon	0.03	0.02	0.02	0.02
Kyllinga brevifolia	0.46	0.11	0.61	0.19
Cyperus iria	5.48	0.13	7.61	0.17
Juncellus serotinus	0.41	0.28	0.57	0.36
Cibotium barometz	0.48	0.03	1.08	0.06
Parthenocissus quinquefolia	0.05	0.01	1.13	0.20

8 Phytoremediation Factor

In sum, phytoremediation of target radionuclides from the tailings mainly depends on three parameters including the target radionuclide concentration in the plant, the plant biomass, and the target radionuclide concentration in the tailings. In order to assess the potential of a plant for phytoremediation more comprehensively, a novel coefficient was proposed and termed as PF (Li et al. 2011). This factor is the ratio of the total amount of a target radionuclide accumulated in the plant shoot to the concentration in the tailings at the site where the plant grows. The calculation formula for PF is defined as follows:

$$\mathrm{PF} = \frac{\text{Target radionuclide concentration in the plant shoot} \times \text{biomass of the plant shoot}}{\text{Target radionuclide concentration in the tailings}}$$

In this formula, the shoot refers to the tissue above ground of the plant including the seed, leaf, and stalk. The PF can be used as an index for the capability of a plant to remove the target element from the tailings.

The PFs for U and Th of the plants collected from the uranium mill tailings impoundment in South China are calculated and presented in Table 7. As shown in the Table 7, *P. australis* had the highest PF for U (16.6) and Th (8.68), and it also had the greatest removal capabilities for U (820 μg plant^{-1}) and Th (103 μg plant^{-1}) (see Table 6), compared with other plants collected. The results indicated that PF was agreeable with the plant removal capability. PF extends the conventional definition of hyperaccumulator, and it can easily be obtained. Although the

concentration of a target radionuclide in a plant does not satisfy the criteria for a hyperaccumulator, the plant may also be considered as the candidate for phytoremediation if it has relatively high biomass. Based on the PF, *P. australis* and *M. cordata* were selected as the candidates for phytoremediation of uranium-contaminated soils (Li et al. 2011; Ding et al. 2011). *Azolla imbircata* was selected as the candidate for phytoremediation of uranium-contaminated water (Ding et al. 2012a; Hu et al. 2012). *P. australis* was selected as the candidate for phytoremediation of thorium-contaminated soils (Li et al. 2011). *P. multifida* was selected as the candidate for phytoremediation of ^{226}Ra-contaminated soils (Ding et al. 2012b; Hu et al. 2014). Although PF provides a novel reference for identification of a plant capable of remediating the tailings and soils contaminated by the radioactive nuclides and heavy metals on a large scale, the plant biomass at a unit area of land is not considered in this factor. It is necessary that further studies should be performed to improve this factor.

9 Conclusion

To screen the suitable plant species for phytoremediation of radioactive waste, the factors, including the characteristics of radioactive waste, the vegetation plant species and vegetation community composition in the radioactive waste deposited area, the concentration of a target radionuclide in the plant, the biomass of the plant, and the concentration of a target radionuclide in the radioactive waste, were analyzed systematically. The PF, which takes into consideration the concentration of a target element in a plant, the plant shoot biomass, and the concentration of the target element in the tailings or soil surrounding the root of the plant, was proposed for the first time to indicate the removal capability of the plant for the target element from the radioactive waste. Using the PF as the criteria, *P. australis*, *M. cordata,* and *Azolla imbircata* were selected as the candidates for phytoremediation of uranium-contaminated soil, *P. australis* was selected as the candidate for phytoremediation of thorium-contaminated soil, and *P. multifida* was selected as the candidate for phytoremediation of ^{226}Ra-contaminated soil.

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