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Phytoremediation of Uranium-238 and Thorium-232 in Contaminated Soils Using Native Dryland Shrubs

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ABSTRACT

Introduction: This study investigated the phytoremediation potential of *Atriplex canescens*, *Haloxylon aphyllum*, and *Nitraria schoberi* for decontaminating soil polluted with radioactive elements.

Materials and Methods: Contaminated soil was collected from a uranium mine site. Compost and sawdust were used as soil amendments. Radionuclide activities and concentrations were determined using gamma spectrometry and ICP-MS.

Results: *H. aphyllum* demonstrated the highest uptake of radioactive elements, accumulating 58 $mg.kg^{-1}$ of Th-232 and 28.08 $mg.kg^{-1}$ of U-238, respectively. Considering their initial concentrations, the thorium removal efficiency was higher than that of uranium, with a maximum of 85% for Th-232 achieved by *H. aphyllum*. Plant roots accumulated higher concentrations of radionuclides than the stems. A comparison of phytoremediation factors (TF, BAF, and BCF) indicated that *H. aphyllum* had a greater stabilization potential than the other two species. Furthermore, phytoextraction was identified as the dominant remediation mechanism.

Conclusion: Compost application enhanced the phytostabilization potential of all three plants (e.g., as indicated by the increase in BCF, which reached a maximum of 0.45 for *H. aphyllum*). In contrast, sawdust had an inhibitory effect, likely due to the disruption of the C/N ratio, which prevented plant growth. *H. aphyllum* showed significant potential for radioactive soil rehabilitation, particularly when it was amended with compost.

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Introduction

Soil pollution is a significant global issue caused by several anthropogenic activities, including mining, smelting, military operations, electronic manufacturing, fossil fuel consumption, waste disposal, and agrochemical use [1]. As non-renewable resources are depleted and contribute to environmental degradation, nuclear energy has emerged as a climate-friendly alternative for sustainable development [2, 3]. Although nuclear energy does not produce carbon emissions, it can introduce environmental risks owing to radioactive pollution and potential adverse effects from accidental radiation release [4].

U-238 and Th-232 and their decay products are significant natural radionuclides that emit high radiation doses [5, 6]. These elements are of considerable concern due to their toxicity and the

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detrimental effects of their radiotoxicity [7], including substantial damage to the nervous system, spleen, kidneys, nephrons, liver, and lungs, as well as allergic reactions, dermatitis, immune system defects, genotoxicity, cellular malfunction, and cancer [7, 8]. Hence, developing cost-effective and eco-friendly remediation strategies for radioactive-contaminated soils is an essential environmental priority [9, 10].

Various physical, chemical, and biological cleanup methods have been reported, although field-scale studies are limited [11]. Recently, high-cost physical and chemical techniques, such as chemical inactivation or landfill sequestration, have been superseded by biological strategies employing plants (phytoremediation) and microorganisms, as these represent cost-effective and eco-friendly in situ treatments [9, 11]. Phytoremediation is a promising ecological technology that utilizes plants resistant to high toxin concentrations and is capable of accumulating contaminants [1, 9]. The success of phytoremediation lies in the diverse mechanisms used by plants to cope with excess toxic elements like radionuclides [12]. Plants typically absorb radioactive elements through epidermal root cells, likely via the same molecular pathways used for essential cations (e.g., calcium, iron, and magnesium) and anionic compounds (e.g., bicarbonate and phosphate), with the cell wall facilitating this absorption [7, 12]. These elements can be collected and transported within the cytoplasm, sequestered in vacuoles, or mobilized from roots to shoots [12].

Several factors can be used to evaluate the phytoremediation potential (phytoextraction/ phytostabilization) in plants, including the bioaccumulation factor (BAF), translocation factor (TF), and bioconcentration factor (BCF). BAF is defined as the ratio of chemical concentration in the plant to that in the soil, and it measures the effectiveness of pollutant concentration in aboveground tissues [13]. TF is the ratio of contaminant concentration in roots to that in shoots, indicating the efficiency of chemical transfer from roots to shoots [14]. BCF is a measure of the transfer of elements from soil to different plant tissues. It is defined as the ratio of the elemental concentration in a specific plant organ (e.g., root or shoot) to the total elemental concentration in the soil within the root zone [15]. A plant is suitable for phytoextraction if BCF and TF are greater than one, and for phytostabilization if BCF > 1 and TF < 1[16].

Hyperaccumulator species are particularly recommended because of their extensive root systems. Their capacity for element absorption is 50–500 times higher than that of typical plants, and they are strongly resistant to harsh environments with high levels of toxic pollutants[12, 17, 18]. Therefore, selecting native plant species that are well-adapted to the local climate and environmental conditions is essential [19]. Although significant efforts have been made to phytoremediate heavy metal-contaminated soils, a critical gap exists in applying this technology to radionuclide-contaminated regions, especially those with harsh conditions (e.g., salinity, drought, and poor soil quality) that limit plant survival and growth [20, 21].

Given Iran's hot and arid climate, *Atriplex canescens*, *Haloxylon aphyllum*, and *Nitraria schoberi* are the dominant shrub species used for reclaiming desertification-affected areas and for animal feed [22-24]. Most native shrubs in dry areas have a relatively longer lifespans than fodder plants. *A. canescens* and *N. schoberi* are halophyte shrubs with high tolerance to harsh conditions such as elevated soil salinity, alkalinity, and aridity [22, 23]. Similarly, *H. aphyllum* is highly adaptable to intense sunlight, heavy snow, dry climates, and moderately saline soils [22]. These characteristics make these plants excellent candidates for rangeland improvement in semi-arid regions of South Africa. Soil amendments, such as biochar and compost, can enhance pollutant uptake and soil nutrition [25]. Sawdust is another amendment that can increase soil organic content and has been noted for its role in adsorbing and removing pollutants [10].

While amendments are known to improve soil quality, their application in radionuclide

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phytoremediation, particularly in arid regions, remains underexplored. Combining well-adapted native plants with soil conditioning could provide a novel and practical strategy for rehabilitating radioactive-contaminated sites in arid landscapes. The key novelty of this study is its focus on a practical and natural solution for arid regions through the simultaneous application of well-adapted native plants with minimal maintenance, alongside an assessment of the effect of adding amendments such as compost and sawdust. This study primarily aimed to investigate the field application potential of these plants for radioactive soil decontamination and to evaluate the impact of soil amendments (compost and sawdust).

Materials and Methods

Soil Sample Collection and Characterization

In coordination with the Atomic Energy Organization of Iran, soil samples were collected from the top 10 cm of surface soil. After homogenization, the samples were transferred to the laboratory. A stone crusher was used to break the soil into smaller fragments (≤ 2 cm). The physicochemical properties of the soil, including its structure, pH, electrical conductivity (EC), organic content, and U-238 and Th-232 concentrations and activities, were determined.

Soil Preparation, Plant Cultivation, and Phytoremediation Experiments

Atriplex canescens, *Haloxylon aphyllum*, and *Nitraria schoberi* were obtained from a greenhouse in Yazd Province, Iran. Amendments (compost and sawdust) were chosen for their relevance in altering soil organic matter and their potential to influence radionuclide bioavailability [10, 25]. Three experimental settings were established for each plant species: 1) untreated contaminated soil (control), 2) contaminated soil amended with compost, and 3) contaminated soil amended with sawdust. This design was implemented to evaluate the effects of the amendments on radionuclide uptake.

Three plastic pots, each containing 4 kg of contaminated soil, were amended with a 3:1 compost-to-sawdust mixture. Soil pH was determined by adding 15 mL of distilled water to 15 g of soil, mixing for 30 min with a magnetic stirrer, and allowing the mixture to stand for 24 h to ensure complete dissolution and uniformity of anions and cations before measurement with a pH meter. Soil samples were also analyzed for organic matter content, electrical conductivity, and specific anion and cation concentrations [26].

In this study, phytoremediation experiments were performed in ambient air near a greenhouse located in Meybod City (a tropical area within Yazd Province). Figure 1 shows the pot arrangement under actual conditions.

Figure 1: Real conditions of the phytoremediation study.

Owing to the favorable conditions for monitoring plant growth, the plants were cultivated and allowed to grow for six months in ambient air. The plants were periodically irrigated, and stem growth was measured weekly.

After conducting the experiments, phytoremediation factors such as the bioaccumulation factor (BAF), translocation factor (TF), and bioconcentration factor (BCF) were calculated. Finally, the phytoremediation potential (phytoextraction/phytostabilization) of the studied plant species was evaluated.

Radioactive Measurements

Preparation and analysis of U-238 and Th-232 were carried out by the Atomic Energy Organization of Iran, and the obtained data are presented and discussed in this study. It should be noted that radioactive concentrations were measured using an ICP-MS instrument. The

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specifications of the gamma measuring device are as follows: radiation type: gamma and x-ray; energy: 50 KeVe3 MeV. Final gamma measurements were performed using a high-purity germanium (HPGe) gamma spectrometer (CANBERRA) with a relative efficiency of approximately 25% for the qualification and quantification of Cs-137, Ra-226, Th-232, and K-40 radionuclides. All samples were counted for approximately 60,000 s, with a limit of 0.01 mSv/hr. The values were obtained through laboratory analysis and calculation. Laboratory experts included uncertainty calculations.

To detect radionuclide biosorption, plants were harvested after six months. Roots and stems were separated and washed first with tap water and then with distilled water to thoroughly remove soil particles. After cleaning, the plants were air-dried in the laboratory for approximately two days and then oven-dried at 70 °C overnight. Dry weight was determined by measuring the weight difference before and after oven drying. Dried plant material was placed inside a muffle furnace (550 °C, 3 h) until ash was obtained. Subsequently, 1 g of each plant ash was digested with a 3:1 mixture of nitric and hydrochloric acids (HNO~3~–HCl). To determine the residual radionuclide concentrations in the soil, approximately 10 g of rhizosphere soil was collected from each pot. The soil samples were dried and stored at room temperature for several days. HPGe measurements indicated that direct detection of U-238 concentrations was impossible; therefore, laboratory experts calculated the concentration indirectly using Th-232 [27].

Chemicals and Instruments

All chemical reagents were of analytical grade and obtained from Merck Company. The pH and EC were measured using a pH meter (2000) and an EC meter (CTR). The Atomic Energy Organization of Iran analyzed the radionuclide activities.

Statistical Analysis

All statistical analyses were performed using the SPSS software (version 26). The normality of the data distribution was assessed using the Shapiro-Wilk test, and the homogeneity of variances was verified using the Breusch-Pagan test. A two-way ANOVA was employed to compare the groups, with a significance level set at $p < 0.05$. Owing to the experimental design, there was one case per treatment combination [28].

Results

Soil Characterization

The main characteristics of the contaminated soil are listed in Table 1. The soil had a loamy texture, was alkaline (pH = 9), and had a low organic content (0.7%). The major cation was K +. The concentrations of U-238 and Th-232 were 85 mg.kg^{-1} and 33 mg.kg^{-1}, respectively.

Table 1. Characteristics of the studied contaminated soil

Parameters	Value
Texture	Loam
pH	9
EC (dS.m^{-1})	5.91
Organic matter (%)	0.7
Saturation Percentage (SP%)	38
Cl^{-} (meq.kg^{-1})	22.8
P (mg.kg^{-1})	11.4
K (mg.kg^{-1})	189
Mg (mg.kg^{-1})	22.2
Ca (mg.kg^{-1})	29
Hardness Ca.Mg (mg.L^{-1})	51.2
U-238 (Bq.kg^{-1})	2113.1 ± 57.3
Th-232 (Bq.kg^{-1})	109.5 ± 7.0

Radioactive Phytoremediation

Plant changes were regularly monitored through the stem growth. After one month, plants in sawdust-treated pots were destroyed, making the results unanalyzable. Figure 2 shows the growth trends for each plant setup in this study.

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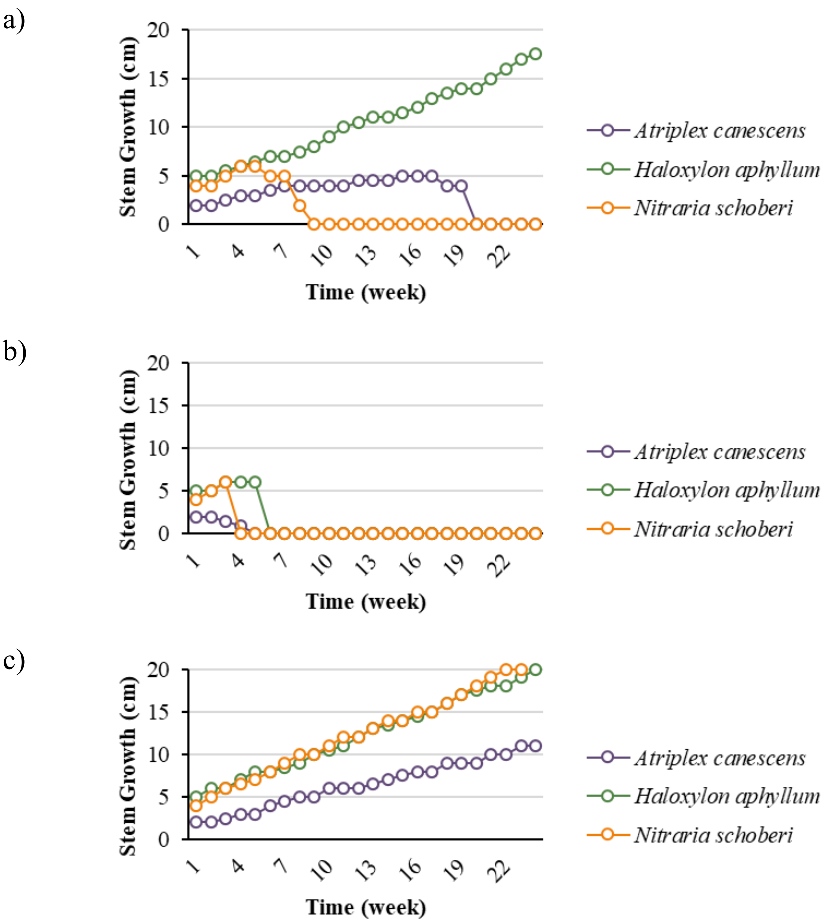

Figure 2: Stem growth monitoring in different treatment setups: a) Contaminated Soil, b) Sawdust-amended Soil, c) Compost-amended Soil.

As shown in Figure 2, compost-amended soil supported the highest growth of all plants (Figure. 2c), whereas sawdust-amended soil resulted in plant death (Figure. 2b). *H. aphyllum* exhibited increased growth in both contaminated and compost-amended soils. Although *A. canescens* had a lower growth rate, *N. schoberi* and *H. aphyllum* showed increased growth trends in the compost treatment. These species did not grow well in contaminated soil and perished within a few weeks.

Figure 3 illustrates the U-238 and Th-238 uptake by each plant after six months.

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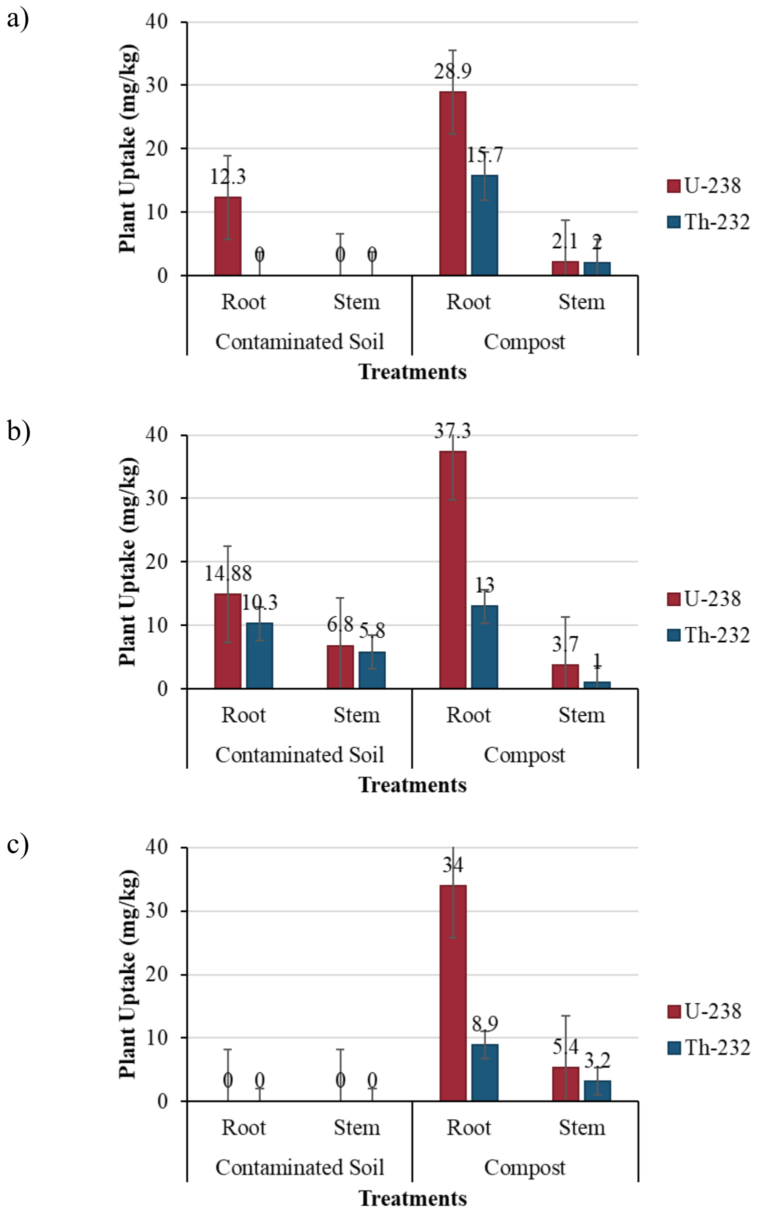

Figure 3: U-238 and Th-232 uptake by the plants: a) *A. canescens*, b) *H. aphyllum*, c) *N. schoberi.*

As shown in Figure 3, *H. aphyllum* in compost-amended soil performed best after six months. The roots of each plant absorbed higher concentrations of radionuclides than the stems. The highest U-238 and Th-232 uptake was 37.3 mg.kg^{-1} (by *H. aphyllum* roots) and 15.7 mg.kg^{-1} (by *A. canescens* roots) in the compost treatment, respectively. The soil removal efficiencies for each plant and amendment are shown separately in Figure 4.

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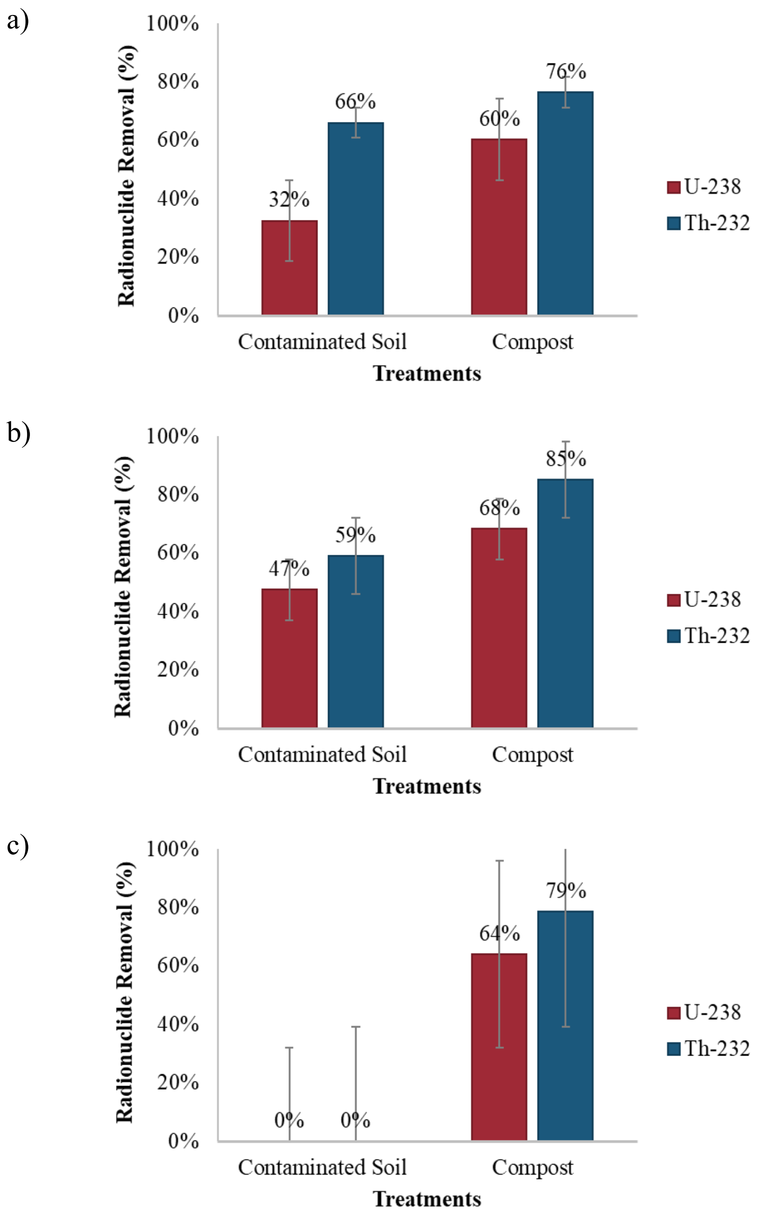

Figure 4: U-238 and Th-232 removal efficiency in different treatments: a) *A. canescens*, b) *H. aphyllum*, c) *N. schoberi.*

The highest efficiencies were observed in all compost-amended pots. Th-232 removal was higher than U-238 removal across all treatments. Additionally, *H. aphyllum*-planted soil removed the most U-238 (68%) and Th-232 (85%) compared to soils planted with *N. schoberi* and *A. canescens*.

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Table 2: Radionuclide uptake and remaining values in different setups

Elements (mg.kg^{-1})	Contaminated soil (control)									Compost-amended soil								
	A. canescens			*H. aphyllum*			*N. schoberi*			*A. canescens*			*H. aphyllum*			*N. schoberi*		
	Root	**Stem**	**Residual***	**Root**	**Stem**	**Residual**	**Root**	**Stem**	**Residual**	**Root**	**Stem**	**Residual**	**Root**	**Stem**	**Residual**	**Root**	**Stem**	**Residual**
U-238	12.3	NM	57.4	14.88	6.8	44.7	NM	NM	NM	28.9	2.1	33.7	37.3	3.7	27	34	5.4	30.7
Th-232	NM	NM	11.22	10.3	5.8	13.55	NM	NM	NM	15.7	2	7.77	13	> 1	4.92	8.9	3.2	7.08

NM: Not Measurable
* Remaining concentration of radionuclides in the pots

As the distribution of all parameters, except for the thorium removal percentage and removed amount, deviated from normality according to the Shapiro-Wilk test, log transformation was applied to these two parameters. The Breusch-Pagan Test confirmed the homogeneity of variance across the factor levels. Two-way ANOVA results indicated that amendment type had a significant effect on U-238 uptake by roots ($p = 0.041$), whereas plant type did not ($p = 0.48$). Neither amendment type ($p = 0.613$) nor plant type ($p = 0.506$) significantly affected U-238 uptake by the stems. Similarly, amendment type ($p = 0.98$) and plant type ($p = 0.25$) did not significantly affect Th-232 uptake by roots, nor did they affect Th-232 uptake by stems ($p = 0.97$ and $p = 0.26$, respectively).

Phytoremediation potential was calculated using the translocation factor (TF), biological accumulation factor (BAF), and biological concentration factor (BCF).

Table 3: Phytoremediation potential of the studied plant species

Plant Types	**Treatment Setups**	**Factors**					
		TF [a]		**BAF** [b]		**BCF** [c]	
		U-238	**Th-232**	**U-238**	**Th-232**	**U-238**	**Th-232**
Atriplex canescens	Contaminated soil (control)	-	-	-	-	0.14	0.2
	Contaminated soil + compost	0.07	0.13	0.02	0.06	0.34	0.45
Haloxylon aphyllum	Contaminated soil (control)	0.46	0.56	0.08	0.17	0.18	0.29
	Contaminated soil + compost	0.10	0.08	0.04	0.03	0.44	0.37
Nitraria schoberi	Contaminated soil (control)	-	-	-	-	-	-
	Contaminated soil + compost	0.16	0.36	0.04	0.09	0.4	0.25

a: translocation factor
b: biological accumulation factor
c: biological concentration factor

As shown in Table 3, all the factors were below 1. However, *H. aphyllum* had the highest TF for uranium and thorium in the contaminated soil.

Discussion

Radioactive soil remediation was investigated using three plant species, *A. canescens*, *H. aphyllum*, and *N. schoberi*, as unique indicators of Iran's arid regions. The primary goal of this study was to assess the potential of native shrubs for remediating radioactive soil. Initial soil characterization revealed a loamy texture, characterized by a combination of sand, silt, and clay in similar proportions [29]. The soil was alkaline (pH = 9) and had low organic content (0.7%), with potassium as the major cation (Table 1).

The pH and EC values suggest high concentrations of carbonate and bicarbonate ions. These anions likely combine with sodium, imparting a sodic nature to the soil and elevating the pH to alkaline levels [30, 31]. Given the low organic content, adding organic matter as a soil amendment was necessary [32]; hence, compost was applied as a

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common organic source [9, 33]. Shiqi et al. (2019) evaluated physicochemical properties of soil from a uranium ore area in China, reporting a pH of 7.18–7.71 and organic matter between 20.91 and 31.33 g/kg [34]. These results contrast with those of the present study.

Japer (2025) investigated uranium and thorium phytoremediation by *Helianthus annuus L.*, *Phragmites australis,* and *Cyperus* cultivated on three soil samples (two reclaimed phosphate mine soils from the East and West Nile, respectively, and one old soil fertilized with phosphate) over 30, 45, and 60 days (75 samples). He reported the structural composition of sandy loam in reclaimed soils that originated from the parent material. This is consistent with the findings of the present study. Meanwhile, clay texture predominated in the old soil samples in Japer's study. The pH values were close to 8 for the reclaimed soils, while the old soil had a pH of 7.75, both of which were lower than the value observed in the present study (pH = 9). He stated that land-use types and soil depth influence soil pH. The phosphate (P) and total (K) content of the examined soils ranged from 0.11 (in the old soil samples) to 11.96% (in the reclaimed soils due to the continuous application of phosphate-based fertilizers). Conversely, the total K content of the examined soils was higher in the old soils (21.29%) than in the reclaimed soils (< 0.05%). In the current study, the concentrations of P and K were 11.4 and 189, respectively, indicating a sufficient potential for plant growth (35). The concentrations of radionuclides in Japer's study ranged from 50 to 70 $mg.kg^{-1}$ for U and 13 to 18 $mg.kg^{-1}$ for Th [35], which are much lower than the values measured in the current study.

Plants cultivated in sawdust-amended pots were destroyed (Figure. 3b), making it impossible to measure related results. Alongside the soil's low organic content (0.7%), the high carbon content in sawdust likely immobilized plant-available nitrogen. During sawdust biodegradation, nitrogen may be drawn from the soil and away from plant roots, causing plant weakness and reduced growth. Therefore, raw sawdust is not an appropriate amendment, and it is recommended to be used in compost or mulch. It has been reported that sawdust mulch can help prevent moisture loss, inhibit weed growth, and reduce soil temperature [36].

H. aphyllum exhibited a similar growth trend in both remaining treatments (contaminated and compost-amended soils), with higher growth in the compost-amended soil (Figure. 2a, c). *N. schoberi* growth was higher in compost-amended pots, similar to *H. aphyllum* (Figure. 2c), but the plant died in unamended soil (Figure. 2a). *A. canescens* showed different growth rates, thriving in compost-amended soil but drying after five months in contaminated soil, probably because of the soil composition and high contaminant levels. Radionuclide accumulation in plants can cause physiological, biochemical, and anatomical side effects, such as growth and photosynthesis inhibition, membrane lipid and protein oxidation, enzyme deficiency, impaired water and nutrient uptake, and DNA breakdown, resulting in reduced plant height and root length, chlorosis, and necrosis [7, 18, 37].

Radionuclides absorbed by plant organs (roots and stems) were determined using Plasma Atomic Emission Spectrometry (PAES). Compost-amended soil contributed to higher radionuclide absorption, particularly uranium, compared to contaminated soil. Compost can improve phytoremediation in contaminated areas by reducing metal(loid) mobility and providing essential nutrients that promote plant growth and stress tolerance [9, 38]. Compost is also rich in micronutrients like magnesium, zinc, and iron, which are essential for plant health [39].

Ullah et al. (2023) found that Zn addition increased the Cu tolerance index of lettuce by 18% [40]. In another study (2024), it was reported that Se(VI) improved root morphology, antioxidant activity, and physiology in wheat grains [41]. Thus, compost may enhance radioactive phytoremediation. Moreover, the behavioral similarities between radionuclides and heavy metals indicate that conventional remediation techniques may be effective for their removal.

The roots of all three plants absorbed higher radionuclide concentrations than the stems. For uranium, root uptake was 37.3, 34, and 28.9 $mg.kg^{-1}$

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for *H. aphyllum*, *N. schoberi*, and *A. canescens*, respectively, whereas stems absorbed minimal amounts (Figure. 3). Plants employ various mechanisms to mitigate oxidative stress from radionuclides, including sequestration in root tissues, compartmentalization in vacuoles and cell walls, and chelation with organic molecules and antioxidant enzymes [7, 42].

In contrast, Japer's study reported high mobility for both uranium and thorium, with greater accumulation in plant shoots than in roots. Regarding uranium, the highest concentration (211.3 mg.kg^{-1}) was found in the shoots of *H. annuus L.* cultivated for 60 days in old soil, while the lowest (8.37 mg.kg^{-1}) was in the shoots of the same species at 30 days in reclaimed soil from the East Nile. For thorium, the highest concentration (28.8 mg.kg^{-1}) was measured in the roots of *Cyperus*, while the lowest (1.11 mg.kg^{-1}) was in the roots of *H. annuus L.*, both taken at 30 days in the East Nile reclaimed soil [35].

The lowest residual U-238 and Th-232 concentrations were found in *H. aphyllum* pots amended with compost (27 and 4.92 mg.kg^{-1}, respectively). The highest residual U-238 (57.4 mg.kg^{-1}) was observed in contaminated soil with *A. canescens*, and the highest Th-232 (13.55 mg.kg^{-1}) was observed in contaminated soil with *H. aphyllum*. This suggests that compost treatment enhanced radionuclide transfer to plants, likely for the reasons noted above. Although absorption is the primary phytoremediation mechanism, other processes, such as phytoextraction, may also be involved. For instance, considering the removed concentrations of uranium (58 mg.kg^{-1}) and thorium (28.08 mg.kg^{-1}), only 41 mg.kg^{-1} of uranium and 14 mg.kg^{-1} of thorium were absorbed by *H. aphyllum* organs (Table 2). Factors such as radionuclide concentration, dynamics in plants, plant species, and gene expression of transfer proteins determine absorption levels and mobility within plant organs [7, 43].

Uranium absorption was higher than thorium absorption, which could be attributed to the different chemical properties of uranium and thorium [43]. Uranium is more bioavailable as uranyl cations, uranyl carbonate complexes, uranyl phosphate, and uranyl citrate, which are easily absorbed by plants. Thorium mobility is lower than that of uranium, which limits its bioavailability [11, 43]. Soil properties, such as pH, organic matter, and ion exchange capacity, could reduce thorium absorption. For example, soil phosphates can form low-solubility thorium phosphate salts, reducing their availability for root absorption [44]. Although uranium was absorbed at higher concentrations than thorium, considering their initial soil concentrations, thorium was removed more efficiently, with *H. aphyllum* and *N. schoberi* removing 85% and 79%, respectively, in compost-amended soil (Figure. 4b, c). The observed difference between the uptake and efficiency of U-238 and Th-232 is due to elemental mobility. Uranium has high mobility and bioavailability, leading to high absorption [44, 45]. However, its high initial concentration resulted in a lower removal efficiency. In contrast, thorium is typically immobile, forming insoluble precipitates and binding to soil particles. The high thorium removal efficiency indicates that the compost and plant roots successfully enhanced thorium bioavailability for the plants [9, 38]. This shows that phytoremediation is highly effective for stabilizing less mobile contaminants, such as thorium.

Wetle et al. studied uranium uptake in six native desert plant species at an abandoned uranium mine in the Sonoran Desert, Arizona, USA, and found that larger, long-lived woody shrubs and trees (*Larrea tridentata*, *Prosopis velutina*, *P. microphylla*) accumulated higher uranium concentrations than smaller herbaceous species (*Eriogonum inflatum*, *Sphaeralcea ambigua*, *E. farinosa*) [45]. Ren et al. enhanced uranium phytoremediation using *Sesbania rostrata* with mycorrhiza and rhizobium, observing a positive symbiosis: uranium removal was 50.5–73.2% with mycorrhiza and rhizobium, versus 7.2–23.3% with *S. rostrata* alone [46]. Alsabbagh and Abuqudaira, studying uranium phytoremediation using sunflowers in Jordanian soil, found that translocated uranium increased with soil uranium concentration, mostly accumulating in roots, with only 3% in shoots [47].

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Two-way ANOVA revealed a significant effect of amendment type ($p = 0.041$). This effect could be driven by the compost treatment with the previously mentioned advantages, resulting in a significantly higher uptake than the control and sawdust treatments ($p < 0.05$).

The phytoremediation potential results (Table 3) showed that none of the factors exceeded one; thus, none of the studied species was classified as a hyperaccumulator. However, *H. aphyllum* had the highest BCF for uranium and thorium in contaminated soil, indicating a greater stabilization ability than other species. Additionally, *H. aphyllum* had the highest TF, suggesting a higher extraction capability. Compost amendment increased the phytostabilization potential of all three plants. In Japer's study, the transfer factor (TF) depended on the harvest time, plant species, and temperature of the plants. He stated that TF in all three plants was higher at 45 and 60 d than at 30 d. While thorium was non-detectable, all TF values for uranium were higher than 1, indicating that *H. annuus L.*, *Cyperus,* and *P. australis* are suitable candidates for radionuclide phytoremediation. In other words, uranium can be strongly absorbed by the three plants studied. After 60 days, the highest uranium removal efficiency was 22.50% by *H. annuus L.* cultivated in old soil, compared to a maximum of 19.05% by *P. australis* (East Nile reclaimed soil) and 18.75% by *H. annuus L.* (West Nile reclaimed soil) [35].

Overall, compared to previous studies, phytoremediation of U-238 and Th-232 using *A. canescens*, *H. aphyllum*, and *N. schoberi* was successful in this study. Compost-amended soils outperformed contaminated soils, positively affecting radioactive accumulation, whereas sawdust was inhibitory. U-238 was absorbed at higher concentrations than Th-232, roots were more effective than stems, and *H. aphyllum* showed the highest phytoremediation potential.

As mentioned earlier, conventional ex-situ techniques, such as excavation and landfill disposal, offer rapid cleanup but are expensive, harmful to the environment, and may transfer the contamination problem to other environments [9, 11]. In contrast, the in situ phytoremediation strategy investigated in the present study is low-cost and ecologically safe, making it particularly beneficial for post-mining and nuclear industry-affected landscapes in water-scarce regions. By utilizing native species adapted to arid conditions, this approach offers a practical and ecologically appropriate alternative to energy-intensive engineering.

However, a primary drawback of the present study is its timeframe, which was limited to a six-month period. Future research should assess the long-term performance, potential for pollution from decaying plant organs, and safe management strategies for contaminated biomass. In addition, investigating the microbial communities associated with the rhizosphere of these shrubs could reveal pathways to enhance bioremediation efficiency.

Conclusion

This study successfully evaluated the potential of native shrub species (*A. canescens*, *H. aphyllum*, and *N. schoberi*) for phytoremediation of soils contaminated with U-238 and Th-232 in arid environments. Due to their long lifespan, plants have shown satisfactory potential for radioactive soil clean-up, especially when combined with soil amendments such as compost. U-238 exhibited higher mobility and bioavailability than Th-232 in soil. However, the thorium removal efficiency was notably higher. According to the phytoremediation potential factors, phytoextraction is the primary phytoremediation mechanism. These findings suggest that *H. aphyllum* is a promising candidate for radionuclide remediation in dry ecosystems. The findings of the present study are particularly advantageous for developing low-cost, sustainable remediation strategies for contaminated sites, such as uranium mines. Furthermore, the use of native shrubs, along with compost, could offer benefits in improving soil quality, plant growth, and survival compared to non-native hyperaccumulators.

This study indicates successful phytoremediation under real conditions. However, future research should focus on long-term experiments to assess the pollution risks from decaying plant organs and their appropriate management strategies. Moreover,

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characterizing the associated rhizosphere microbiota could reveal pathways to improve the efficiency of bioremediation.

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Conflict of Interest

The authors declare no potential conflicts of interest.

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Ethical Approval

This study was approved by the Ethics Committee of Shahid Sadoughi University of Medical Sciences (IR.SSU.SPH.REC.1400.070).

Authors' Contributions

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