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Remediation of Radioactive Contamination in Soils Using Soil Washing Method: A Systematic Literature Review of Artificial and Real Contaminated Samples (2010-2025)

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ABSTRACT

Soil contamination by radionuclides such as cesium (Cs) and uranium (U) poses significant environmental and health risks due to their long half-lives, approximately 30 years for Cs-137 and up to 4.5 billion years for U-238, enabling long-term persistence in soils. Soil washing is considered a promising remediation method due to its efficiency and rapid application. Although soil washing has been studied using both artificial and real contaminated soils, it remains unclear how well laboratory-prepared contamination represents contamination behavior in real soil. This uncertainty limits the use of laboratory removal efficiencies to predict soil-washing performance at real contaminated sites. This study aims to compare the efficiency of soil washing between artificial and real contaminated soils for Cs and U removal. A systematic literature review based on PRISMA 2020 guidelines was conducted on studies published from 2010 to 2025, with data analyzed using a thematic approach focusing on sample type, radionuclide characteristics, washing agents, and operational parameters. Of 54 records initially identified from ScienDirect (n=36) and Google Scholar (n=18), 15 articles met all inclusion criteria. The findings indicate that removal efficiency varies widely depending on soil type, radionuclide characteristics, initial concentration, pH, temperature, contact time, washing cycles, and washing agents. For cesium, artificial soils (n = 8 observations) yielded a mean removal of ~63%, whereas real soils (n = 6) yielded a lower mean of ~57%. For uranium, the only artificial soil study (n = 1) showed a mean removal of ~75%, whereas real soils exhibited a mean removal of ~98%. Cesium is more difficult to remove due to strong adsorption to clay minerals, while uranium is more readily mobilized under acidic conditions. A key limitation of this review is that it was restricted to English-language and freely accessible full-text articles; therefore, the findings should be interpreted within the scope of the available open-access literature. This review highlights the need for direct comparison between artificial and real contaminated soils under the same experimental conditions, followed by field-scale validation before laboratory soil-washing results are generalized to real contaminated sites.

Keywords: Soil washing, removal efficiency, radioactive contamination, remediation, PRISMA 2020 systematic review.



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Remediation of Radioactive Soil Contamination Using Soil Washing Method:
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INTRODUCTION

Soil contamination by radioactive substances is one of the serious impacts of nuclear activity, whether from reactor accidents, industrial waste, or nuclear weapons testing. Radioactive substances such as Cesium-137 (Cs-137) and Uranium-238 (U-238) have long half-lives (approximately 30 years for Cs-137 and 4.5 billion years for U-238) and the ability to bind strongly to soil, particularly to the fine particles, so they can persist in the environment for a very long time [1], [2]. The presence of these radioactive substances not only poses a health risk to humans but can also cause long-term damage to ecosystems [3].

Various remediation methods have been developed to reduce or eliminate radioactive contamination in soil, using physical, chemical, and biological approaches. Some commonly used techniques include solidification-stabilization, electrokinetic, phytoremediation, and soil washing [4], [5]. Of these methods, soil washing is a promising approach because it is time-efficient remediation method and allows a significant portion of contaminated soil to be reused. This technique uses washing solutions such as acids, chelating agents, or surfactants to dissolve or mobilize radioactive contaminants or release them from soil particles, allowing them to be separated and further treated [6].

The basic principle of soil washing lies in the ability of the washing solution to break the bonds between radionuclides and soil components, especially fine fractions such as clay and organic matter. The process stages include pretreatment, washing, solid-liquid separation, and wastewater treatment. The effectiveness of this method is greatly influenced by the physicochemical characteristics of the soil and the type of contaminant [7]. Sandy soils generally perform better than clay soils due to their higher porosity and permeability [5].

This review focuses on cesium-137 (Cs-137) and uranium-238 (U-238) because both radionuclides are environmentally important, have long half-lives, and are commonly found at contaminated sites. Cs-137 is a major gamma-emitting radionuclide at post-accident sites such as Chernobyl and Fukushima [3], while U-238 is a key radionuclide of concern at uranium mining and processing legacy sites [8]. Other

radionuclides, such as strontium-90 (Sr-90) and cobalt-60 (Co-60), can also be released from nuclear accidents and reactor operations. Sr-90, with a half-life of about 28.8 years, is generally more mobile than Cs because it is less strongly adsorbed by clay minerals and behaves chemically like calcium [9]. Co-60, with a half-life of about 5.27 years, is mainly produced by activation and corrosion of structural steel in reactors. Because of its shorter half-life, Co-60 is less commonly associated with long-term legacy contamination [9]. Therefore, Cs and U provide a useful basis for evaluating soil-washing performance.

The use of soil samples type is a crucial aspect in the development and testing of soil washing methods because it will affect the validity of the test results. The samples used can be either real contaminated soil collected from contaminated sites or artificially contaminated soil prepared in the laboratory by spiking clean soil (including clay minerals, which are fine-grained soil constituents) with known concentrations of radioactive substances to mimic specific conditions. Each type of sample has distinct advantages and limitations. Real contaminated soil reflects actual environmental conditions but is highly variable and difficult to replicate in laboratory settings. Conversely, the use of artificial contaminated soil provides better experimental control but is less representative of the complexity of geochemical interactions in the field, such as soil structure, fine particle distribution, and organic matter content [10].

Although many studies have focused on soil washing using artificially contaminated soils, there is limited research comparing how well these methods work on real contaminated soils. Artificial contamination allows research to control factors more easily, but real contaminated sample is much more complex, with varying soil properties and contamination levels. This makes it difficult to know how the results from laboratory experiments apply to real environmental situations. For example, IAEA documentation on uranium production sites [4] reports operational field outcomes without comparison to laboratory data. Other works on Fukushima soils [11], [12] have demonstrated that radiocesium fixation in collapsed clay interlayers and frayed-edge sites strongly limits the transferability of laboratory results to field-scale remediation. However, no review has directly synthesized

and quantitatively compared removal efficiencies obtained from artificial versus real contaminated soils across both Cs and U.

Based on this background, the main problem raised in this study is how the efficiency of soil washing methods is compared when applied to artificial contaminated soil samples versus real contaminated soil, as well as the implications of sample type selection on the accuracy and relevance of remediation results. This review covers both in-situ and ex-situ soil washing applications. The objectives of this study are: (1) to compare the removal efficiency of soil washing between artificial and real contaminated soils; (2) to analyze the influence of radionuclide type, soil characteristics, and operational parameters; and (3) to evaluate the applicability of laboratory findings to real field conditions.

METHODOLOGY

This article was compiled using a systematic literature review approach, referring to the PRISMA Checklist 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [13]. This approach was used to systematically identify, evaluate, and synthesize relevant previous studies related to the efficiency of soil washing methods in remediation of radioactive contamination, particularly by comparing artificial and real contaminated soil samples. The review process was carried out through several stages: literature identification based on keywords, literature selection, data extraction, methodological quality appraisal, and thematic analysis [14].

The literature selection process was conducted using inclusion and exclusion criteria. The literature search was conducted from August 2025 to February 2026. Inclusion criteria included the year of publication of articles within the last 15 years (2010–2025) searched in ScienceDirect and Google Scholar, to ensure relevance to the latest technological developments. Literature identification was conducted using a combination of keywords: "soil washing", "removal efficiency", "radioactive contamination", and "remediation." Articles searched for must be available in full-text PDF format and freely accessible. Furthermore, articles must use artificial or real contaminated soil as test media, and must include quantitative test parameters, such as washing

efficiency, sample characteristics, and operating conditions. Exclusion criteria included articles published before 2010 and discussing remediation techniques other than soil washing, as well as articles with a general scope without specifying the type of soil sample and not available in full-text format or not freely accessible. A total of 54 records were initially identified (ScienceDirect: 36; Google Scholar: 18). After duplicate removal and title/abstract screening, 15 articles met all inclusion criteria, as detailed in the PRISMA 2020 flow diagram (Figure 1).

The data extraction and synthesis phase collected data from the selected articles. Data were extracted using a standardized form, capturing nine variables for each included study: (1) radionuclide type, (2) soil type (artificial/real/both), (3) initial contaminant concentration, (4) washing solvent and concentration, (5) pH, (6) temperature, (7) contact time, (8) removal efficiency, and (9) reported technical or methodological challenges. The methodological quality of each included study was appraised using an adapted Critical Appraisal Skills Programme (CASP) Systematic Review Checklist [15], scoring eight domains relevant to environmental remediation studies: (i) clarity of research question, (ii) appropriate study design, (iii) representativeness of soil samples, (iv) validity of analytical method, (v) accuracy of efficiency measurement, (vi) completeness of reporting, (vii) consideration of confounding parameters, and (viii) reproducibility. The CASP appraisal results for all 15 studies are provided in Table S1. (Supplementary Information). Further, detailed scoring justification for each study is tabulated in Table S2. Any discrepancies during study selection and data extraction were resolved through consensus discussion among the three authors; where consensus could not be reached, the article was excluded. The collected data were analyzed using a thematic approach to identify patterns, similarities, and differences in efficiency between the use of artificial and real contaminated soil. A thematic approach was applied in the form of grouping based on the variables of contaminant type and sample type. This analysis aimed to evaluate the extent to which laboratory-based research results with artificial contaminated soil can be generalized to field conditions with real contaminated soil, as well as to provide

recommendations for a more representative approach. The review article schematic can be seen in Figure 1.

RESULT AND DISCUSSION

Comparison of Soil Remediation Methods

The soil washing method chosen in this study was based on findings from previous research examining remediation methods for radioactively contaminated soil. Each method has its own advantages and disadvantages, as shown in Table 1.

Based on a review of various remediation methods, soil washing is widely used and often offers high removal and efficient approach for radioactively

contaminated soil. Its advantage lies in its ability to effectively remove contaminants from the soil, especially radionuclides and heavy metals, through a relatively rapid process. Furthermore, soil washing can be tailored to various types of radionuclides and soil conditions through the selection of appropriate washing agents, and can significantly reduce the volume of contaminated soil, thereby minimizing the costs of handling and disposing of radioactive waste. Therefore, this method is considered relevant and strategic to be reviewed in the context of radioactively contaminated soil remediation, both on a laboratory scale using artificial soil and for field applications with real soil.

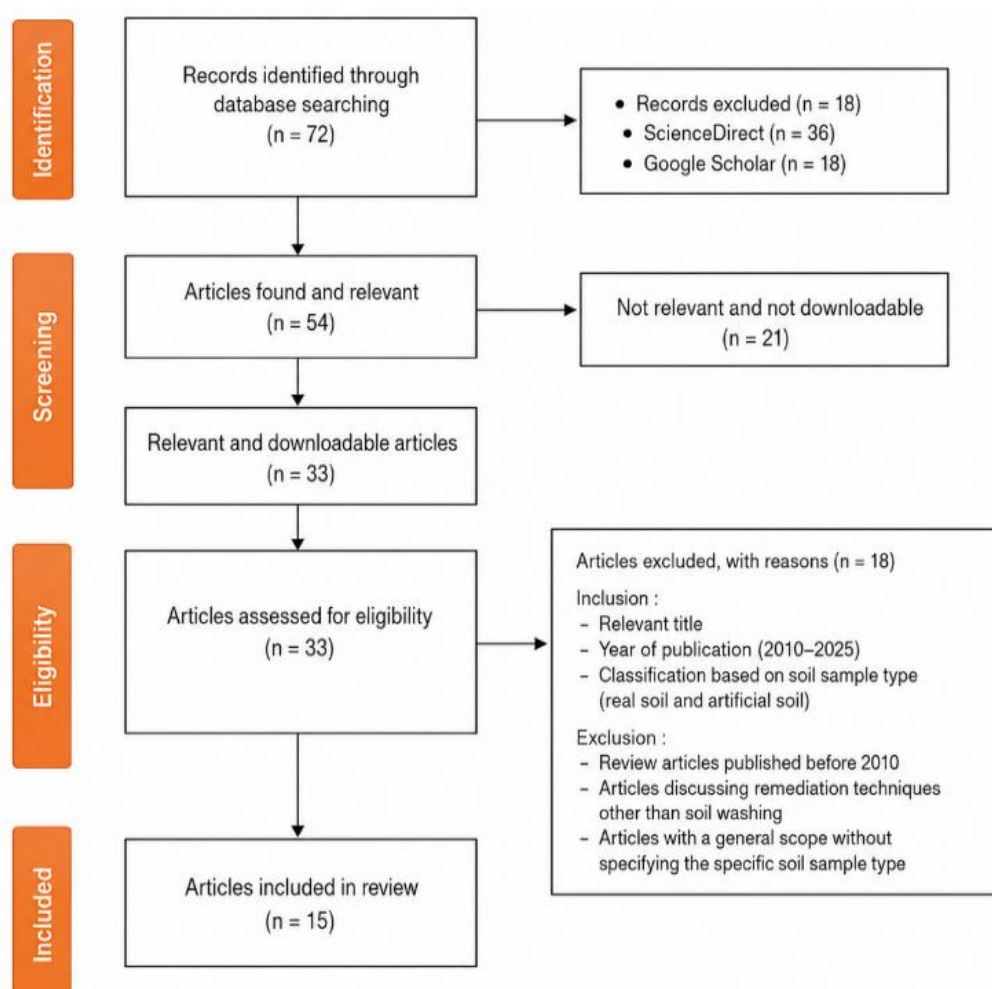


Figure 1. Review Article Scheme
Based on PRISMA 2020 <http://www.prisma-statement.org/>

Table 1. Comparison of Radioactively Contaminated Soil Remediation Methods

Remediation Method	Description	Advantages	Disadvantages	Level of Removal Efficiency	References
Solidification and Stabilization	Immobilization of contaminants with binding materials (such as cement, lime)	<ul style="list-style-type: none"> • Reducing contaminant mobility • Preventing the spread of contaminants • In-situ or Ex-situ 	<ul style="list-style-type: none"> • Does not remove contaminants • Increased volume • Risk of degradation 	50-80% (mobility reduction; not direct % removal)	[5], [16]
Electrokinetics	Low electric current to move contaminant ions to the electrodes	<ul style="list-style-type: none"> • Effective for ionic applications • In-situ or Ex-situ • Minimal interference 	<ul style="list-style-type: none"> • Less effective in impermeable soils • Energy consumption • Long-term 	50-80%	[17], [18]
Phytoremediation	Plants absorb or stabilize contaminants from the soil	<ul style="list-style-type: none"> • Environmentally friendly and aesthetically pleasing • Low cost • In-situ 	<ul style="list-style-type: none"> • Long-term • Limited to low contaminants • Produces contaminated biomass 	Typically <80% (slow, varies with plant species and Cs concentration)	[19], [20]
Soil Washing	Soil washing with chemical agents to remove contaminants	<ul style="list-style-type: none"> • Efficient • Reduces the volume of contaminated soil • Fast 	<ul style="list-style-type: none"> • Produces liquid waste • Can change soil properties 	>80%	[21], [22]

Comparative Analysis of Soil Washing Method for Artificial and Real Contaminated Soils

After conducting a systematic curation of the retrieved literature, 15 articles were selected from an initial pool of 54 relevant studies for inclusion in the meta-analysis. These articles specifically address soil washing for radioactive contamination and report measurable removal efficiency using well-defined soil samples.

To synthesize the results across all 15 studies in Table 2, we calculated three descriptive statistics for cesium and uranium separately, and for artificial versus real soils. Three descriptive statistics used are mean, range, and coefficient of variation (CV). The CV (standard deviation divided by the mean) is reported here as the main variability index because it allows a fair comparison between groups with different mean values [23].

For cesium in artificial soils ($n = 8$ observations, including the artificial-side data

of [24], [25], [26]), removal ranged from below 25% to 90%, with a mean of ~63% and a CV of ~35%. For cesium in real soils ($n = 6$: [1], [24], [25], [26], [27], [28]), removal ranged from 12% to 92%, with a mean of ~57% and a CV of ~62%. Real soils show a slightly lower mean (about 6 percentage points below artificial soils), but the CV is nearly twice as large (ratio ≈ 1.8). This quantitatively confirms the qualitative observation that cesium removal in real soils is both lower and substantially more variable than in artificial soils.

Cesium removal in real contaminated soils is so variable because cesium becomes trapped inside the specific clay structures along with time, specifically in the weathered biotite (2:1 clay minerals type) containing frayed-edge sites. Therefore, cesium is fixed in the clay mineral [11], [29]. Table 2 illustrates this clearly. The two studies about real contaminated soils with the lowest cesium removal both used a single conventional wash

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at room temperature: 12% with BDAB on Fukushima soil [24] and below 25% with chelators [25]. In contrast, another four studies about real contaminated soil that exceeded 40% removal all used more aggressive approaches by using multiple wash cycles (89% with two water cycles [1]; 92% with four heated cycles at 95 °C [27]), strong K⁺ exchange at 1 M (81% [28]), or

chelator–salt combinations (40% with HIDS + NH₄Cl [26]). In short, a single conventional wash cannot overcome cesium fixation in 2:1 clays; cesium removal in real contaminated soil depends on the clay minerals present and on the number and chemistry of wash cycles applied.

Table 2. Systematic Review of Soil Washing Methods for Remediation of Radioactive Contaminated Samples.

Refs.	Contaminant Type	Sample Type	Initial Conc. of contaminant in soil (mg/kg or Bq/kg)	Method/ Solvent	Contaminant Removal Efficiency (% Removal)	Technical/ Methodological Challenges
[33]	Cs-133 (non-radioactive) combined with Cs-137 (radioactive) as radiotracer	Artificial contaminate d soil (Montmorillonite K10)	29,258.2 mg/kg	Cationic Surfactants of benzyldodecyldimethylammonium bromide (BDAB) and dodecyltrimethylammonium bromide (DTAB)	Up to 80-90% Cs removal using 0.02 – 0.05 M of both BDAB and DTAB at 25 °C	Only effective on one type of clay, does not replicate the complexity of real soils
[34]	Cs-133 (non-radioactive)	3 types of artificial contaminated soils (clean soil collected from sites spiked with CsCl); clay and two sandy loams with different levels of organic matter and CaCO ₃	50, 100, and 200 mg/kg for each sample	Ethylenediaminetetraacetic Acid Sodium Salt (EDTA-Na) and Diethylene Triamine Pentaacetic Acid (DTPA)	DTPA > EDTA-Na; up to 70% Cs removal from sandy loams > up to 55 % Cs removal from clay using 0.05 M of both DTPA and EDTA-Na at 25 °C (lower organic matter contents weaken Cs binding, enhancing extracted by chelating agents) Higher initial conc. of Cs in the soil tended to show high removal efficiency	High efficiency but Cs-137 binding has not been tested long term
[35]	Cs-133 combined with Cs-137 as radiotracer	Artificial contaminated soil (Kaolinite)	3,987.3 mg/kg	Cationic surfactant of tetradecyldimethylammonium bromide (TDAB) with or without added ethanol	Up to 84% Cs removal using 0.004 – 0.03 M of TDAB at 25 °C, the addition of ethanol reduces efficiency	Only one type of clay mineral, the addition of ethanol as an additive affected the formation of micelle hence reduced Cs removal efficiency
[36]	Cs-133 (non-radioactive) and Cs-137 (radioactive)	Artificial contaminated soil; sand-sized soil samples were collected from the site of the Korea Atomic Energy Research Institute (KAERI) and	600 mg/kg (Cs-133) and 222 Bq/kg (Cs-137)	HNO ₃ and KCl with different concentrations and temperatures Ion exchange mechanism between Cs ⁺ and H ⁺ or K ⁺ ions	Soil artificially contaminated by Cs-133: Cs removal efficiency using 0.5 M HNO ₃ showed 40.4% at 25 °C and 67.2% at 75 °C. Meanwhile, KCl 0.5 M exhibited 47.1% Cs removal at 75 °C. Soil artificially contaminated by Cs-137: Combination of HNO ₃ 0.5 M, KCl 0.1 M,	It is difficult to remove Cs if it is fixed in the interlayer clay.

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Refs.	Contaminant Type	Sample Type	Initial Conc. of contaminant in soil (mg/kg or Bq/kg)	Method/ Solvent	Contaminant Removal Efficiency (% Removal)	Technical/ Methodological Challenges
		then artificially contaminated with Cs-133 and Cs-137 separately (two different samples)			and nanoparticle of $\text{Fe}_3\text{O}_4@\text{SiO}_2@\text{KTiFC}$ (1 wt% of the soil) at 75 °C showed 76.1% Cs removal	
[37]	Cs-133 (non-radioactive)	Artificial contaminated soils; 3 different soil were taken from agricultural land, urban area, and forest, with typically having similar OM content but containing different clay type content	71, 73, and 68 mg/kg, respectively	CaCl_2 , BaCl_2 , KCl, NH_4Cl , EDTA, Oxalic Acid, NaOH, HCl, and HNO_3	KCl 0.1 M showed the highest removal efficiency (60% Cs removal) among the solvents tested, using similar concentrations at 25 °C Soil containing vermiculite clay exhibited the lowest removal efficiency with all the solvents used.	Complexity of hybrid systems, challenges of wastewater
[24]	Cs-133 combined with Cs-137 as radiotracer Cs-137 (radioactive)	Artificial contaminated soil (Illite) Real contaminated soil (contaminated with Cs-137 collected from Fukushima Prefecture)	9,304 mg/kg 3.52 Bq/kg	Cationic surfactant (BDAB) and acid solution (HCl)	BDAB 0.009 M and HCl 0.009 M demonstrated 60% and 49% Cs removal efficiency, respectively, at 25 °C BDAB 0.05 M showed higher Cs removal (12%) than using HCl 0.05 M (2%), at 25 °C	Comparative study of two agents, no clear quantitative efficiency figures
[1]	Cs-134 + Cs-137 (radioactive)	Real contaminated soil (Fukushima)	9,200 – 12,500 Bq/kg	Multistep washing using water (separation of plant material, addition of adsorbent, grinding)	73.6% - 89.2% Cs removal (for twice washed soil) at 25 °C	Complex multistep process, influenced by residual plant material
[27]	Cs-137 (radioactive)	Real contaminated soil (radiation contamination from nuclear facilities based on particle size fractions)	N/A	H_2SO_4 with different temperatures, 4 washes	Bulk soil: 56% and 92% Cs removal at 25 °C and at 95 °C, respectively, for 4 times washing. 4 times washing at 95 °C based on particle size: Cs removal for particle size > 2 mm, 1 – 2 mm, 0.075 – 1 mm, and < 0.075 mm showed 93.8%, 91.6%, 72.4%, and 57.7% Cs removal efficiency, respectively.	Soil particle size affects removal efficiency

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Refs.	Contaminant Type	Sample Type	Initial Conc. of contaminant in soil (mg/kg or Bq/kg)	Method/ Solvent	Contaminant Removal Efficiency (% Removal)	Technical/ Methodological Challenges
[28]	Cesium (Cs)	Real contaminated soil (sandy loam) from the topmost layer (0–20 cm) near a nuclear power plant in South Korea	1.47 mg/kg	K ⁺ solution	Up to 81.3% Cs removal using K ⁺ solution 1 M	Addressing soil nutrient release, optimizing Cs ⁺ substitution
[25]	Cs-137 (radioactive)	Real and artificial contaminated soils. The soil was taken from the sites	N/A	Citric acid, acetic acid and EDTA (chelating agent) ranging from 0.001 to 1 M concentrations	EDTA > citric acid > acetic acid; Real > artificial due to differences in soil characteristics, particularly real contaminated soil contains lower organic matters (Low % removal; <25%)	Artificial contaminated soil has limited applicability and does not fully reflect the complexity of Cs-137 bonds in natural soils
[26]	Cs-133 (non-radioactive)	Artificial contaminated soil (clean Ultisol, Leaf-mold, and Andosol soils were contaminated by Cs-133)	33.8 to 38.9 mg/kg	HIDS (biodegradable chelator) combined with NH ₄ Cl	Cs removal using HIDS 0.05 M + NH ₄ Cl 0.05 M was 29% from Leaf-mold, 33% from Andosol, and 40% from Ultisol (artificially contaminated soil). Meanwhile, Cs removal reached 40% in real contaminated soil	Focus on biodegradable agents that are effective and environmentally friendly
	Cs-137 (radioactive)	Real contaminated soil taken from Fukushima Prefecture	N/A			
[2]	Uranium	Artificial contaminated soil; Mining soils (4 soil types), characterized by particle size distribution, texture, and chemical composition	N/A	Water, H ₂ SO ₄ , and NaCl + Na ₂ CO ₃	H ₂ SO ₄ 0.1 M, NaCl 100 g/L + Na ₂ CO ₃ 10 g/L > water U removal efficiency was 89-99% from Soil 2; 64-70% from Soil 3; 50-65% from soil 4; and 40-67% from Soil 1 Soil 2 has the highest sand content	Effectiveness varies, depending on the degree of remediation for different soil types and reagents
[30]	Uranium (radioactive)	Real contaminated soil, fine fraction soil (<0.2 mm) contaminated with uranium	0.2421 Bq/kg	Magnetic separation + two-step chemical washing (H ₂ SO ₄ , HNO ₃ , Na ₂ CO ₃ , NaHCO ₃)	U removal efficiency followed the general order H ₂ SO ₄ > HNO ₃ > Na ₂ CO ₃ ≈ NaHCO ₃ , ranging from 72.0% to 98.8%. Higher concentration, temperature, and two-step washing generally resulted in greater U removal efficiency, with 1.0 M > 0.5 M and 75 °C > 25 °C	Handling fine soil fractions using magnetic separation for contaminants is often a challenge.

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Refs.	Contaminant Type	Sample Type	Initial Conc. of contaminant in soil (mg/kg or Bq/kg)	Method/ Solvent	Contaminant Removal Efficiency (% Removal)	Technical/ Methodological Challenges
[31]	Uranium (radioactive)	Real contaminated soil taken from decommissioning of uranium conversion facility	0.049 Bq/kg	Three consecutive washes using H ₂ SO ₄ , pH monitoring.	U removal efficiency by H ₂ SO ₄ 0.05 M at first, second, and third wash was 89%, 97%, and 99%, respectively, at 25 °C	Reducing the amount of radioactive waste from high concentration acid leaching, correlation between uranium leaching and pH changes
[32]	Uranium (radioactive)	Real contaminated soil	0.026 Bq/kg	Two consecutive washes using H ₂ SO ₄ + NaClO ₃ (oxidant)	U removal efficiency by H ₂ SO ₄ 0.3M + NaClO ₃ at 65 °C was 94% and 97% after first and second wash, respectively	The effectiveness of soil washing is limited by specific operating conditions, fine soil fractions, and process complexity.

For uranium, the pattern is reversed. The only artificial-soil U study [2] reported four removal efficiencies between 65% and 99% across four spiked soils (mean ~75%, CV ~21%). The three real-soil U studies showed 97–99% removal (mean ~98%, CV ~1.1%), which is about 19 times less variable than the artificial-soil results [30], [31], [32].

Uranium shows a different pattern from cesium. In the reviewed real-soil studies, uranium could be removed very effectively using acid-based washing. For example, uranium removal reached about 97–99% when sulfuric acid was used in several washing steps [30], [31], [32]. This happens because acid can dissolve uranium-containing materials in the soil, making uranium easier to separate from the soil particles.

In the artificial-soil study, uranium removal was more variable, ranging from about 40% to 99% [2]. This difference was mainly related to soil texture. Sandy soil showed the highest uranium removal, while finer soils or soils with more organic matter showed lower removal. This suggests that soil type still plays an important role, even when the same contaminant and washing method are used.

However, these results should be interpreted carefully. The reviewed studies did not directly test artificial and real contaminated soils under the same conditions. Therefore, the differences observed between artificial and real soils may not be caused only by the

sample type. They may also be affected by another factor such as soil properties, initial radionuclide concentration, washing solution, pH, temperature, and contact time. These factors are discussed in the following subsections.

a. The Influence of Sample Type and Soil Characteristics on Soil Washing Efficiency

The efficiency of soil washing for the remediation of radioactive contaminated soil is strongly influenced by the type of soil sample and its physicochemical characteristics. In this study, two types of samples were identified in the reviewed literature, namely artificial contaminated soil and real contaminated soil. Artificial soil samples are generally prepared under controlled laboratory conditions, while real contaminated soils are collected directly from contaminated sites. Artificial soils often produce higher removal efficiencies because their composition is more homogeneous and experimental variables can be controlled more easily. For example, cesium removal using cationic surfactants such as BDAB and DTAB on montmorillonite K10 reached efficiencies of approximately 80–90% [33]. Similarly, the use of chelating agents such as EDTA-Na and DTPA in artificial soils showed relatively high cesium extraction efficiency, with DTPA demonstrating better performance due to its stronger complexation capability [34].

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In contrast, soil washing applied to real contaminated soil generally shows lower and more variable removal efficiencies due to the complex characteristics of natural soils. Studies conducted on radiocesium-contaminated soils reported removal efficiencies approximately <25%, but the process was influenced by factors such as plant residues and fine soil particles [25]. In addition, hybrid soil washing processes combined with adsorption techniques have been developed to improve removal performance, although such approaches introduce additional operational complexity and wastewater management challenges [37].

Soil characteristics such as particle size, mineral composition, and organic matter content also play an important role in determining washing efficiency. Radionuclides such as Cs^+ tend to bind strongly to clay minerals through cation exchange mechanisms, particularly in fine soil fractions with high surface area [24], [26], [32], [34], [37]. Song and Nam (2023) reported that potassium-based washing solutions can enhance cesium removal through the substitution of Cs^+ by K^+ at cation exchange sites, achieving removal efficiencies of up to about 81.3% [28].

Furthermore, soil organic matter can influence radionuclide mobility [25], [34]. Tameta et al. (2021) showed that dissolved organic matter may cover adsorption sites on clay minerals and modify cesium adsorption behavior [38]. The mineralogical composition of soil also determines contaminant retention and transport processes, as soil surface chemistry controlled by clay minerals and organic matter significantly affects contaminant mobility in soil matrices [39].

Artificial soils tend to produce higher removal efficiencies due to controlled experimental conditions, whereas real contaminated soils present greater challenges because of their heterogeneous composition and stronger radionuclide binding mechanisms.

b. The Influence of Radionuclide Type: Cesium vs Uranium

The type of radionuclide present in contaminated soil plays a crucial role in determining the effectiveness of soil washing processes. In this review, the most frequently studied radionuclides are cesium and uranium, both of which exhibit different

geochemical behaviors in soil systems. These differences influence contaminant binding mechanisms, mobility, and the selection of appropriate washing agents.

Cesium generally exists as a monovalent cation (Cs^+) that strongly binds to clay minerals through ion-exchange mechanisms, particularly within the interlayer sites of illite and montmorillonite. This strong fixation limits cesium mobility and makes its removal more challenging. Several studies have shown that cesium removal efficiency can be enhanced through ion-exchange processes, where competing cations such as potassium (K^+) replace Cs^+ at clay mineral exchange sites. Hybrid soil washing systems combining chemical extraction and adsorption have therefore been developed to improve cesium removal from contaminated soils [37]. In addition, studies on cesium sorption behavior indicate that soil texture, clay content, and pore water chemistry significantly influence the transport and retention of cesium in soil matrices [40].

In contrast, uranium typically occurs in soil as the uranyl ion (UO_2^{2+}), which can form soluble complexes under acidic or carbonate conditions. This chemical behavior makes uranium more responsive to chemical leaching processes. Acid-based washing solutions such as sulfuric acid or nitric acid have been widely reported to effectively mobilize uranium from contaminated soils, particularly in mining-related environments [32]. These acid leaching processes dissolve uranium-bearing minerals and significantly enhance removal efficiency.

Furthermore, the behavior of radionuclides in soil is also influenced by broader environmental factors, including soil composition, mineral structure, and the chemical interactions between contaminants and soil components. Chernysh et al. (2024) highlighted that the retention and mobility of radionuclides in soil systems are strongly controlled by mineral composition, soil texture, and environmental conditions [41]. These factors determine the strength of contaminant binding to soil particles and ultimately influence the efficiency of remediation technologies such as soil washing.

Cesium contamination is generally more difficult to remediate due to its strong adsorption to clay minerals, whereas uranium can be more readily mobilized through acid dissolution mechanisms. Therefore, the

selection of washing agents and operational conditions should be tailored to the specific geochemical characteristics of the target radionuclide.

c. The Influence of Solvent Type on Soil Washing Efficiency

The type of washing solvent is a critical factor influencing soil washing efficiency, as it governs radionuclide mobilization through mechanisms such as ion exchange, complexation, dissolution, and surfactant-enhanced desorption. The selection of appropriate solvents must therefore consider both contaminant characteristics and soil properties. In general, washing agents include inorganic acids, chelating agents, surfactants, and salt-based or mixed solutions, each exhibiting different mechanisms and effectiveness [42]

Surfactants, particularly cationic types (BDAB, DTAB, TDAB), show high effectiveness for cesium removal, achieving up to 80–90% efficiency in artificial soils [33], [35]. However, solvent modification (e.g., ethanol addition) may reduce efficiency due to micelle instability [35]. Chelating agents such as EDTA and DTPA enhance removal through complexation, with DTPA outperforming EDTA (up to 70%), although efficiency decreases in real soils (<25%) [25], [34]. Biodegradable chelators (e.g., HIDS) provide moderate efficiency (29–40%) with improved environmental sustainability, supporting the development of greener washing agents [26], [43], [44].

Inorganic acids (H_2SO_4 and HNO_3) are highly effective for uranium removal due to dissolution mechanisms, achieving efficiencies up to 89–99% [2], [30], [31], [32], while their effectiveness for cesium is generally lower and depends on soil characteristics [27], [36], [37]. Salt-based solutions, particularly K^+ systems, enhance cesium removal via ion exchange, reaching up to 81.3% efficiency [28], and can be further improved through combined or multistep washing processes [1].

Solvent effectiveness depends on the compatibility between solvent type, contaminant behavior, and soil characteristics. Acidic solutions are more suitable for uranium, while ion exchange systems and surfactants are more effective for cesium, with chelating agents providing intermediate performance. The development of mixed and

environmentally friendly washing agents is essential to balance remediation efficiency and sustainability [45].

d. The Influence of pH Conditions (Acidic, Alkaline, and Neutral) on Soil Washing Efficiency

The pH of the washing solution is a key operational parameter influencing soil washing efficiency, as it controls radionuclide speciation, solubility, and adsorption behavior. Changes in pH alter the interaction between radionuclides and soil particles, thereby affecting their mobility and removal. Figure 2 summarizes the aqueous speciation of U(VI) and Cs^+ as a function of pH under typical groundwater conditions, calculated from formation constants recommended by the NEA-OECD Thermochemical Database [46], [47].

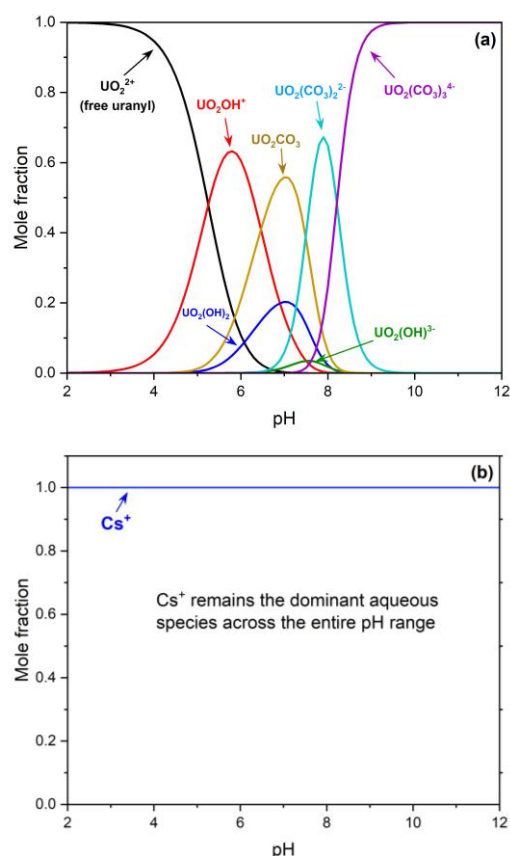


Figure 2. Aqueous speciation of (a) U(VI), $[\text{U(VI)}]_{\text{tot}} = 1 \times 10^{-6}$ M, atmospheric $p\text{CO}_2 = 10^{-3.5}$ atm, calculated with NEA-OECD database [46], [47]; and (b) Cs^+ as a function of pH at 25 °C, $[\text{Cs}^+]_{\text{tot}} = 2.5 \times 10^{-6}$ [50].

Under acidic conditions, soil washing efficiency generally increases due to enhanced dissolution and desorption. For uranium-contaminated soils, the free uranyl cation UO_2^{2+} dominates U(VI) speciation at pH 2–4 (Figure 2a), and acids such as H_2SO_4 and HNO_3 promote mineral dissolution and uranyl formation, achieving high removal efficiencies up to 89–99% [2], [30], [31], [32]. For cesium, acidic conditions enhance removal through ion exchange, where H^+ competes with Cs^+ at adsorption sites, although effectiveness depends on soil mineralogy [27], [36], [37]. In illite- and weathered-biotite-bearing soils, partial collapse of frayed-edge sites can sequester Cs^+ even at low pH [11], [29].

In alkaline conditions, removal mechanisms differ, involving changes in surface charge and ion exchange. For uranium, under alkaline conditions in the presence of carbonate (pH > 8, total dissolved $\text{CO}_3^{2-} \gtrsim 10^{-3} \text{ M}$), U(VI) is dominated by the highly soluble carbonate complexes $\text{UO}_2(\text{CO}_3)_2^{2-}$ and $\text{UO}_2(\text{CO}_3)_3^{4-}$ (Figure 2a) [48], [49]. The thermodynamic stability of these complexes ($\log \beta \approx 16.61$ for $\text{UO}_2(\text{CO}_3)_2^{2-}$ and 21.84 for $\text{UO}_2(\text{CO}_3)_3^{4-}$ at 25 °C [46]) makes carbonate-based washing solutions ($\text{Na}_2\text{CO}_3/\text{NaHCO}_3$) an effective non-acidic alternative for U removal [30], with the additional benefit of reducing soil structural damage compared with strong-acid treatment. By contrast, cesium remains strongly bound to clay under alkaline conditions [37], because Cs^+ speciation does not change with pH (Figure 2b; Cs^+ does not undergo hydrolysis under environmentally relevant conditions [50]) and OH^- does not effectively displace Cs^+ from clay interlayer sites [29].

At near-neutral pH, radionuclide mobility is generally low due to stable adsorption. Cesium is strongly retained by clay minerals [24], [33], [34], [37], with binding governed by ion-exchange selectivity at frayed-edge sites (FES) and interlayer wedges of 2:1 clay minerals; FES typically represent only 0.1–2.0% of total cation-exchange capacity but bind Cs^+ with high affinity [29], [51]. Uranium removal is limited without acidic or complexing conditions [2], [31], because U(VI) speciation transitions through $\text{UO}_2(\text{OH})^+$, $\text{UO}_2(\text{OH})_2(\text{aq})$, and $\text{UO}_2\text{CO}_3(\text{aq})$ (Figure 2a), all of which adsorb strongly to oxide and clay surfaces [48]. Therefore, additional agents are typically required to enhance removal at neutral pH.

pH influences soil washing efficiency through the balance of dissolution, ion exchange, and precipitation processes. Acidic conditions are more effective for uranium, while cesium removal depends on ion exchange mechanisms under specific chemical conditions. Effective pH selection therefore depends on the target radionuclide and the dominant binding mineralogy: low-pH leaching is generally most effective for U; for Cs, neither acidic nor alkaline conditions fully overcome interlayer fixation, and removal must rely on ion-exchange selectivity (e.g., K^+ , NH_4^+) combined with thermal or hydrothermal treatment to expand collapsed interlayers [12]. These findings are consistent with previous studies highlighting the role of pH in controlling contaminant solubility and desorption [42], radionuclide mobility [52], and soil physicochemical stability [53].

e. The Influence of Temperature on Soil Washing Efficiency

Temperature is an important operational parameter that influences the efficiency of soil washing processes in removing radionuclides from contaminated soils. Increasing temperature generally enhances reaction kinetics, contaminant solubility, and the interaction between washing agents and soil particles, thereby improving contaminant desorption and removal efficiency [27], [36].

Higher temperatures can accelerate ion exchange, dissolution, and complexation reactions between radionuclides and washing solutions. In uranium-contaminated soils, elevated temperatures promote the dissolution of uranium-bearing minerals and increase the formation of soluble uranyl species, which facilitates contaminant extraction during soil washing processes [54]. Temperature can also enhance contaminant diffusion within soil pores, allowing radionuclides trapped in fine soil fractions to migrate more easily into the washing solution [32].

However, excessively high temperatures may cause several operational limitations. High temperatures can degrade certain washing agents, particularly organic chelating agents and surfactants, which may reduce their effectiveness during remediation processes. In addition, elevated temperatures may alter soil physicochemical properties, including mineral stability and organic matter

content, potentially affecting soil quality after treatment [42].

Environmental studies have also shown that temperature influences radionuclide mobility and migration in soil systems. Changes in temperature can modify chemical speciation, diffusion processes, and adsorption behavior of radionuclides in soils, thereby affecting the overall effectiveness of remediation technologies [41], [55].

Temperature notably affects soil washing efficiency by enhancing contaminant desorption and dissolution processes. Nevertheless, temperature optimization is necessary to achieve effective contaminant removal while maintaining solvent stability and minimizing adverse impacts on soil properties [30].

f. The Influence of Contact Time on Soil Washing Efficiency

Contact time between the washing solution and contaminated soil is a critical operational parameter that governs the kinetics of radionuclide removal processes, including ion exchange, complexation, and dissolution. Sufficient contact time enables washing agents to penetrate soil pores and interact effectively with adsorption sites, thereby enhancing contaminant desorption and mobilization.

In cesium-contaminated soils, contact time is critical due to the slow desorption of Cs^+ from clay minerals. In artificial soils, high removal efficiency can be achieved within short durations; for example, BDAB and DTAB achieved 80–90% removal within approximately 1–2 hours [33]. In contrast, chelating agents such as DTPA and EDTA require longer contact times (several hours up to 24 hours) to reach equilibrium, with removal efficiencies up to 70% in sandy soils and 55% in clay soils [34].

For real contaminated soils, longer or repeated contact is necessary due to stronger binding and heterogeneity. A single washing step using BDAB (0.05 M) resulted in only ~12% cesium removal within 1–2 hours [24], whereas multistep washing increased removal to 73.6–89.2% after two cycles, with cumulative contact times of approximately 3–6 hours or more [1].

In uranium-contaminated soils, contact time plays a different role due to faster acid-driven dissolution mechanisms. In artificial soils, H_2SO_4 (0.1 M) achieved 89–99%

removal within several hours [2]. In real soils, repeated washing significantly improves efficiency, increasing from 89% to 99% after three cycles [31], and up to 97% after two cycles using $\text{H}_2\text{SO}_4 + \text{NaClO}_3$, with cumulative contact times of about 3–9 hours [32].

These findings are consistent with previous studies indicating that increasing contact time enhances removal efficiency until equilibrium is reached, beyond which further extension provides limited benefit [56]. Moreover, contact time interacts with other operational parameters, such as washing solution type and solid-to-liquid ratio, which collectively determine the overall effectiveness of soil washing processes [57].

g. The Influence of Initial Radionuclide Concentration on Soil Washing Efficiency

Initial radionuclide concentration is an important experimental condition that can influence removal efficiency in soil washing studies. Based on Table 2, the reviewed studies used very different initial contaminant levels. For Cs, the initial concentration ranged from low concentration, such as 1.47 mg/kg Cs in real contaminated sandy loam soil [28], to high concentrations in artificial contaminated soil, such as 29,258.2 mg/kg Cs in montmorillonite K10 [33]. Other artificial Cs-contaminated soils used intermediate concentrations, including 50–200 mg/kg [34], 68–74 mg/kg [37], and 33.8–38.9 mg/kg [26]. Real radiocesium-contaminated soils were commonly reported in radioactivity units, such as 9,200–12,500 Bq/kg in Fukushima soils [1] and 3.52 Bq/g in Fukushima paddy soil [24].

This wide variation makes direct comparison of removal efficiency difficult. A high removal percentage does not always mean that the treated soil has a low residual contamination level, while a low percentage removal may occur when the initial concentration is already low or when Cs is strongly fixed in soil minerals. For example, artificial Cs-contaminated montmorillonite K10 with high initial Cs loading showed 80–90% removal using cationic surfactants [33]. However, real Fukushima soil with much lower radiocesium activity showed only about 12% removal using BDAB and about 2% using HCl [24]. This difference suggests that initial concentration alone cannot explain removal efficiency; soil mineralogy, contaminant

fixation, and matrix complexity also strongly affect Cs release.

In some studies, higher initial Cs concentration tended to increase the apparent removal efficiency because a larger fraction of Cs may remain in more exchangeable or weakly bound forms. For example, Elshazly et al. reported that artificial soils spiked with 50, 100, and 200 mg/kg Cs showed different removal behavior, and higher initial Cs concentration tended to increase Cs removal by EDTA-Na and DTPA [34]. However, this trend was not universal. Radhi and Alzubadi reported low Cs removal of generally less than 20–25% even when different chelating-agent concentrations and mixing ratios were used [25]. Therefore, the effect of initial concentration must be interpreted together with soil type, organic matter, clay content, and washing-agent chemistry.

For U-contaminated soils, the reviewed studies also showed large differences in initial concentration. Artificially contaminated uranium soils had relatively low U concentrations, ranging from approximately 2.15 to 5.74 ppm [2]. In contrast, real U-contaminated soils from nuclear facility or uranium conversion sites had much higher activities, such as 26 Bq/g [32], 48.96 Bq/g [31], and up to 242.1 Bq/g in the fine soil fraction [30]. Despite these high initial concentrations, acid-based washing achieved high U removal efficiencies, commonly reaching 89–99% [27]–[29]. This indicates that U removal is strongly controlled by acid-driven dissolution and uranium speciation, although the initial concentration remains important for determining whether the treated soil can reach clearance or disposal criteria.

Therefore, removal efficiency should not be interpreted only as a percentage value. Initial concentration and residual concentration after washing should also be reported because they determine the actual remediation outcome. This is especially important when comparing artificial and real contaminated soils, because these sample types often differ not only in soil properties and radionuclide fixation, but also in initial contaminant concentration. Future studies should use similar initial concentration ranges when comparing artificial and real contaminated soils under the same washing conditions.

h. Technical Challenges and Practical Implications

Although soil washing has demonstrated promising results for the remediation of radionuclide-contaminated soils, several technical challenges remain in its practical implementation. One of the main issues is the generation of secondary wastewater that must be properly treated before disposal. In addition, soil washing efficiency is highly dependent on operational parameters such as pH and temperature, which require careful control during the remediation process [1].

Previous studies have also reported that certain solvent combinations may reduce process efficiency. For example, Wijayanto (2023) found that the addition of ethanol in cationic surfactant systems could decrease cesium desorption efficiency due to instability in micelle formation and chemical interactions within the washing solution [35].

Furthermore, soil washing processes often require additional treatment stages, including solid–liquid separation, wastewater treatment, and verification of post-remediation contamination levels. These additional steps increase the complexity and operational costs of the technology. Therefore, the effectiveness of soil washing should be evaluated not only based on contaminant removal efficiency but also on practical considerations such as operational feasibility, economic cost, and long-term environmental impact. These challenges highlight the need for adaptive and sustainable remediation strategies tailored to site-specific soil conditions and environmental regulations.

i. Relevance to Real Land Case Studies and Foundation for Further Research

Real-world soil contamination requires remediation methods that are not only technically effective but also adaptable to site-specific soil characteristics. This literature review indicates that results obtained from artificial contaminated soils may not fully represent the complexity of natural soil systems. In field conditions, the presence of clay minerals, organic matter, and heterogeneous soil structures can significantly influence radionuclide binding and reduce soil washing efficiency.

Fukushima Prefecture, Japan.

After the 2011 Fukushima Daiichi accident, a large amount of radiocesium-contaminated surface soil was produced. This created a need for soil treatment methods that can reduce contaminated soil volume and support possible soil reuse. In one study using actual Fukushima contaminated soils, multistep soil washing removed 73.6–89.2% of Cs under controlled multi-cycle conditions [1]. However, this result was achieved using several combined steps, including repeated washing, plant matter separation, fine-particle separation, and grinding. This shows that real contaminated soil may require a more complex treatment process than laboratory-prepared soil.

A clearer comparison between artificial and real contaminated samples was shown in another Fukushima-related study using model illite and actual Fukushima paddy soil. In the model clay sample, Cs removal was much higher (60% Cs removal), while in actual Fukushima soil, a surfactant, so called BDAB, removed only about 12% of Cs and HCl removed only about 2% [24]. This difference suggests that low removal in real soil is not only caused by the washing agent, but also by the complex soil matrix and the strong binding of Cs to clay minerals such as weathered biotite and partially collapsed illite [11], [12].

Central Asian uranium legacy sites.

Under the IAEA Strategic Master Plan for Environmental Remediation of Uranium Legacy Sites in Central Asia [8], seven priority sites have been targeted: Mailuu-Suu, Min-Kush, and Shekafar in Kyrgyzstan; Istiklol and Degmay in Tajikistan; and Charkesar and Yangiabad in Uzbekistan. At Mailuu-Suu, 23 tailings dams contain approximately 1.9 million m³ of uranium-mining residues. Remediation has so far focused on containment, relocation of high-risk tailings, and stabilization rather than soil washing, primarily because of the very large volumes involved, the difficulty of managing acidic leachate at scale, and seismic instability in the Fergana Valley [8]. This contrasts with the laboratory-scale acid washing literature, where 89–99% U removal is routinely achieved [2], [30], [31], [32], and highlights that field-scale deployment is constrained as much by waste-management and regulatory factors as by intrinsic chemical efficiency.

Lab-to-field validation challenges. Most laboratory studies reviewed here have not been validated at field scale. The principal methodological challenges in this transition are: (i) heterogeneity of contaminant distribution and aging within soil profiles; (ii) the longer in-situ contact times required for aged contamination compared with freshly spiked artificial soils; (iii) the much larger volumes of secondary wastewater requiring on-site treatment, particularly when chelating agents or acids are used; and (iv) regulatory constraints on acidic effluent management and on-site waste storage. Bridging these challenges will require pilot- or field-scale studies that explicitly track removal efficiency, secondary-waste production, and post-treatment soil function in parallel.

Therefore, further research is needed to validate laboratory findings using real contaminated soils through field-scale or pilot-scale studies. Future studies should evaluate the effectiveness of various washing agents such as EDTA, citric acid, and nitric acid under both laboratory and field conditions. In addition, investigations on changes in soil physicochemical properties after washing treatments and the potential integration of soil washing with other remediation technologies, such as adsorption or phytoremediation, are recommended.

Such research efforts are expected to contribute to the development of more effective and site-specific remediation strategies for radionuclide-contaminated soils, particularly in regions with environmental conditions similar to those in Indonesia.

j. Limitations of the Study

Following PRISMA 2020 reporting guidance [13], we acknowledge three methodological limitations of this review. First, inclusion was restricted to freely accessible full-text articles, which may exclude relevant subscription-based studies and may introduce a selection bias toward open-access publications. Second, only English-language publications (2010–2025) were reviewed, which may overlook valuable evidence published in other languages such as Japanese, Korean, Russian, or Chinese journals where significant radioactive remediation research has been conducted. Third, only three of the 15 included studies used both artificial and real soils, limiting direct comparability between the two soil types. For

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future updates of this review, broader database access (including subscription-based journals via institutional library) and inclusion of non-English literature are recommended to capture the full body of available evidence.

CONCLUSION

This systematic review demonstrates that soil-washing efficiency for the remediation of radioactive contaminated soils is governed by complex interactions among radionuclide chemistry, soil mineralogy, washing-agent selection, and operational parameters. A clear numerical comparison between artificial and real contaminated soils is still difficult because the reviewed studies did not test both soil types using the same experimental conditions. The synthesized data reveal a clear pattern: Cs removal is consistently lower and more variable in real contaminated soils ($n = 6$; mean $\sim 57\%$, range 12% to 92%, CV $\sim 62\%$) than in artificial contaminated soils ($n = 8$; mean $\sim 63\%$, range $<25\%$ to 90%, CV $\sim 35\%$). It is about 6 percentage points lower on average and approximately 1.8 times more variable between studies, reflecting that interlayer fixation in 2:1 clay minerals; for U, multistep acid washing achieves consistently high efficiencies in real contaminated soils ($n = 3$; mean $\sim 98\%$, range 97–99%, CV $\sim 1.1\%$) compared with the wider variability observed in the only artificial contaminated soil study (mean $\sim 75\%$, range 65–99%, CV $\sim 21\%$), reflecting the dominant role of pH- and carbonate-dependent speciation. Laboratory-derived efficiencies should not be assumed to transfer directly to field deployment, particularly for Cs in clay-rich soils. For U, acid-based multistep washing has reached small-scale technological maturity, but its field deployment remains constrained by acidic-effluent management.

Despite its effectiveness, soil washing faces challenges such as wastewater generation and process complexity, highlighting the need for optimized, site-specific, and environmentally sustainable approaches. Further research is required to validate laboratory findings at field scale and to develop more efficient and sustainable washing systems.

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All researchers who are involved are the main contributors.

DECLARATION OF AI-USAGE

During the preparation of this work the authors used ChatGPT from OpenAI to check language clarity and grammar. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

REFERENCES

- [1] M. Funakawa, A. Tagawa, and N. Okuda, "Testing of Multistep Soil Washing for Radiocesium-Contaminated Soil Containing Plant Matter," in *Insights Concerning the Fukushima Daiichi Nuclear Accident Vol. 4*, The Atomic Energy Society of Japan, 2021, pp. 125–137. doi: 10.15669/fukushimainsights.vol.4.125.
- [2] A. D. Radu, A. Woinaroschy, E. Panțuru, and A. Filcenco-olteanu, "Uranium Soils Decontamination By Washing Method," *U.P.B. Sci. Bull., Series B*, vol. 75, no. 4, pp. 13–22, 2013.
- [3] G. Steinhäuser, A. Brandl, and T. E. Johnson, "Comparison of the Chernobyl and Fukushima nuclear accidents: A review of the environmental impacts," Feb. 01, 2014, *Elsevier*. doi: 10.1016/j.scitotenv.2013.10.029.
- [4] IAEA, "Environmental Contamination from Uranium Production Facilities and their Remediation," in *Proceedings of an International Workshop*, 2005.
- [5] I. H. Yoon, C. W. Park, I. Kim, H. M. Yang, S. M. Kim, and J. H. Kim, "Characteristic and remediation of radioactive soil in nuclear facility sites: a critical review," Oct. 14, 2021, *Springer Science and Business Media Deutschland GmbH*. doi: 10.1007/s11356-021-16782-2.

- [6] S. Khalid, M. Shahid, N. K. Niazi, B. Murtaza, I. Bibi, and C. Dumat, "A comparison of technologies for remediation of heavy metal contaminated soils," *J. Geochem. Explor.*, vol. 182, pp. 247–268, Nov. 2017, doi: 10.1016/j.gexplo.2016.11.021.
- [7] H. Wijayanto and S. Nakashima, "Influence of head group structure of cationic surfactants on the desorption of cesium from clays and clay minerals," *Appl. Clay Sci.*, vol. 228, Oct. 2022, doi: 10.1016/j.clay.2022.106649.
- [8] IAEA, *Strategic Master Plan for Environmental Remediation of Uranium Legacy Sites in Central Asia*, 2nd ed. Vienna: International Atomic Energy Agency, 2021. Accessed: May 15, 2026. [Online]. Available: https://www.iaea.org/sites/default/files/18/05/strategic_master_plan_v1_may_2018.pdf
- [9] I. Smičiklas, S. Dimović, M. Jović, A. Milenković, and M. Šljivić-Ivanović, "Evaluation study of cobalt(II) and strontium(II) sorption-desorption behavior for selection of soil remediation technology," *International Journal of Environmental Science and Technology*, vol. 12, no. 12, pp. 3853–3862, Dec. 2015, doi: 10.1007/s13762-015-0817-y.
- [10] T. Ohnuma and K. Ishii, "An analysis of radioactivity distribution in soil particles using an autoradiogram method," *Cogent Eng.*, vol. 4, no. 1, Jan. 2017, doi: 10.1080/23311916.2017.1326200.
- [11] H. Mukai *et al.*, "Cesium adsorption/desorption behavior of clay minerals considering actual contamination conditions in Fukushima," *Sci. Rep.*, vol. 6, Feb. 2016, doi: 10.1038/srep21543.
- [12] X. Yin *et al.*, "Effective and efficient desorption of Cs from hydrothermal-treated clay minerals for the decontamination of Fukushima radioactive soil," *Chemical Engineering Journal*, vol. 333, pp. 392–401, Feb. 2018, doi: 10.1016/j.cej.2017.09.199.
- [13] M. J. Page *et al.*, "The PRISMA 2020 statement: an updated guideline for reporting systematic reviews," *BMJ*, p. n71, Mar. 2021, doi: 10.1136/bmj.n71.
- [14] S. F. Zahro and S. Adityosulindro, "Literature Review: Penggunaan Bahan Berbasis Limbah Sebagai Adsorben untuk Degradasi Zat Warna pada Air Limbah," *Jurnal Kesehatan Lingkungan Indonesia*, vol. 22, no. 3, pp. 359–368, Oct. 2023, doi: 10.14710/jkli.22.3.359-368.
- [15] Critical Appraisal Skills Programme, "Systematic Reviews Checklist - CASP," CASP - Critical Appraisal Skills Programme. Accessed: May 14, 2026. [Online]. Available: <https://casp-uk.net/casp-tools-checklists/systematic-review-checklist/>
- [16] S. H. Lim, S. H. Lee, J. S. Song, and K. H. Kim, "Solidification of radioactive soil waste through volume reduction and stabilization: Characteristic evaluation and waste acceptance criteria satisfaction," *Journal of Hazardous Materials Advances*, vol. 10, May 2023, doi: 10.1016/j.hazadv.2023.100324.
- [17] M. Gavrilescu, L. V. Pavel, and I. Cretescu, "Characterization and remediation of soils contaminated with uranium," *J. Hazard. Mater.*, vol. 163, no. 2–3, pp. 475–510, Apr. 2009, doi: 10.1016/j.jhazmat.2008.07.103.
- [18] G. N. Kim, S. S. Lee, D. Bin Shon, K. W. Lee, and U. S. Chung, "Development of pilot-scale electrokinetic remediation technology to remove ⁶⁰Co and ¹³⁷Cs from soil," *Journal of Industrial and Engineering Chemistry*, vol. 16, no. 6, pp. 986–991, Nov. 2010, doi: 10.1016/j.jiec.2010.05.014.
- [19] P. Rani, P. Vats, J. Singh, K. Raj, and K. Jat, "Advances in Soil Remediation Technologies," *New Era Agriculture Magazine*, vol. 3, no. 3, pp. 165–171, Aug. 2024, [Online]. Available: <https://www.researchgate.net/publication/383670314>
- [20] G. Nurliati *et al.*, "Literature survey and analysis of phytoremediation strategies for Cs-137 decontamination," *Nuclear Engineering and Design*, vol. 427, Oct. 2024, doi: 10.1016/j.nucengdes.2024.113414.

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- [21] P. Song, D. Xu, J. Yue, Y. Ma, S. Dong, and J. Feng, "Recent advances in soil remediation technology for heavy metal contaminated sites: A critical review," *Science of the Total Environment*, vol. 838, Sep. 2022, doi: 10.1016/j.scitotenv.2022.156417.
- [22] C. S. Byun, S. Lee, J. Kang, W. Park, D. Kim, and J. Lee, "Soil Washing Technology Demonstration for Removal of Multi-Nuclides in Natural Background Soil," *Journal of Nuclear Fuel Cycle and Waste Technology*, vol. 22, no. 4, pp. 399–410, Dec. 2024, doi: 10.7733/jnfcwt.2024.038.
- [23] G. F. Reed, F. Lynn, and B. D. Meade, "Use of Coefficient of Variation in Assessing Variability of Quantitative Assays," *Clinical and Vaccine Immunology*, vol. 10, no. 6, pp. 1162–1162, Nov. 2003, doi: 10.1128/CDLI.10.6.1162.2003.
- [24] H. Wijayanto, M. Tsujimoto, T. Basuki, and S. Nakashima, "Comparison of cationic surfactant and acid solution for remediation of actual ¹³⁷Cs-contaminated soil from Fukushima prefecture," in *AIP Conference Proceedings*, American Institute of Physics Inc., Nov. 2021. doi: 10.1063/5.0066492.
- [25] F. M. Radhi and A. A. Alzubadi, "Effect of chelating agents on removal of ¹³⁷Cs from contaminated soil," *Iraqi Journal of Physics*, vol. 15, no. 35, pp. 158–168, Oct. 2017, doi: 10.30723/ijp.v15i35.65.
- [26] H. Sawai, I. M. M. Rahman, C. Lu, Z. A. Begum, M. Saito, and H. Hasegawa, "Extractive decontamination of cesium-containing soil using a biodegradable aminopolycarboxylate chelator," *Microchemical Journal*, vol. 134, pp. 230–236, Sep. 2017, doi: 10.1016/j.microc.2017.06.010.
- [27] U.-R. Park, G.-N. Kim, S.-S. Kim, H.-M. Park, W.-S. Kim, and J.-K. Moon, "A Study on the Removal of Cesium in Soil Contaminated with Radiation Using a Soil Washing Process," in *Transactions of the Korean Nuclear Society Spring Meeting Gwangju*, Daejeon, May 2013, pp. 30–31.
- [28] H. Song and K. Nam, "Development of a potassium-based soil washing solution using response surface methodology for efficient removal of cesium contamination in soil," *Chemosphere*, vol. 332, Aug. 2023, doi: 10.1016/j.chemosphere.2023.138854.
- [29] S. M. Park, D. S. Alessi, and K. Baek, "Selective adsorption and irreversible fixation behavior of cesium onto 2:1 layered clay mineral: A mini review," *J. Hazard. Mater.*, vol. 369, pp. 569–576, May 2019, doi: 10.1016/j.jhazmat.2019.02.061.
- [30] I. Kim, I.-H. Yoon, J.-H. Kim, S. Chang, and H.-K. Lee, "An innovative approach to remediation of uranium-contaminated fine soil using magnetic separation and chemical washing," *Journal of Hazardous Materials Advances*, vol. 18, pp. 1–5, May 2025, doi: 10.1016/j.hazadv.2025.100641.
- [31] J.-Y. Jung, B.-M. Jun, M. Oh, T.-J. Kim, and H.-C. Eun, "A Study on Behaviors of the Uranium Dissolution From Uranium-Contaminated Soil During an Acid Wash Process," *Journal of Nuclear Fuel Cycle and Waste Technology*, vol. 23, no. 1, pp. 97–105, Mar. 2025, doi: 10.7733/jnfcwt.2025.010.
- [32] S. S. Kim, G. S. Han, G. N. Kim, D. S. Koo, I. G. Kim, and J. W. Choi, "Advanced remediation of uranium-contaminated soil," *J. Environ. Radioact.*, vol. 164, pp. 239–244, Nov. 2016, doi: 10.1016/j.jenvrad.2016.08.005.
- [33] H. Wijayanto and S. Nakashima, "Effectiveness of Cesium Desorption by Cationic Surfactant Based on Its Hydrophilic Structure on Montmorillonite K10," *Urania: Jurnal Ilmiah Daur Bahan Bakar Nuklir*, vol. 29, no. 1, p. 53, Apr. 2023, doi: 10.17146/urania.2023.29.1.6962.
- [34] A. A. A. Elshazly, I. M. Farid, M. A. Rizk, and M. H. H. Abbas, "Removal of cesium from contaminated soils using EDTA-Na and DTPA chelating agents," *Benha Journal of Applied Sciences (BJAS)*, vol. 8, no. 5, p. 2023, 2023, [Online]. Available: <http://bjas.journals.ekb.eg>
- [35] H. Wijayanto, "Analysis of Ethanol Addition on The Formation of Cationic Surfactant Micelles and Its Implication on Cesium Desorption from Kaolinite,"

- UNESA Journal of Chemistry, vol. 12, no. 3, Sep. 2023.
- [36] J. H. Kim, S. M. Kim, I. H. Yoon, H. M. Yang, and I. Kim, "Novel two-step process for remediation of Cs-contaminated soil assisted by magnetic composites," *Chemical Engineering Journal*, vol. 424, Nov. 2021, doi: 10.1016/j.cej.2021.130554.
- [37] S. M. Park, T. Kim, Y. H. Kim, and K. Baek, "Hybrid process of combined soil washing and selective adsorption to treat Cs-contaminated soil," *Chemical Engineering Journal*, vol. 423, Nov. 2021, doi: 10.1016/j.cej.2021.129921.
- [38] Y. Tameta, R. Tamura, M. Kimura, M. Sasamoto, N. Kamei-Ishikawa, and A. Ito, "Effect of dissolved soil organic matter on cesium adsorption by zeolite and illite," *J. Environ. Manage.*, vol. 289, Jul. 2021, doi: 10.1016/j.jenvman.2021.112477.
- [39] H. Hong, C. Liu, and Z. Li, "Chemistry of soil-type dependent soil matrices and its influence on behaviors of pharmaceutical compounds (PCs) in soils," Dec. 01, 2023, *Elsevier Ltd.* doi: 10.1016/j.heliyon.2023.e22931.
- [40] H. F. D. Supratman *et al.*, "Sorption and diffusion studies of radiocesium in soil samples from Ibu Kota Nusantara region of Indonesia," *Environmental Chemistry and Ecotoxicology*, vol. 7, pp. 252–262, Jan. 2025, doi: 10.1016/j.enceco.2024.12.008.
- [41] Y. Chernysh *et al.*, "Soil Contamination by Heavy Metals and Radionuclides and Related Bioremediation Techniques: A Review," Jun. 01, 2024, *Multidisciplinary Digital Publishing Institute (MDPI)*. doi: 10.3390/soilsystems8020036.
- [42] H. Zhang, Y. Xu, T. Kanyerere, Y.-S. Wang, and M. Sun, "Washing Reagents for Remediating Heavy-Metal-Contaminated Soil: A Review," *Front. Earth Sci. (Lausanne)*, vol. 10, Jun. 2022, doi: 10.3389/feart.2022.901570.
- [43] S. Gluhar, A. Kaurin, and D. Lestan, "Soil washing with biodegradable chelating agents and EDTA: Technological feasibility, remediation efficiency and environmental sustainability," *Chemosphere*, vol. 257, Oct. 2020, doi: 10.1016/j.chemosphere.2020.127226.
- [44] X. Mao, R. Jiang, W. Xiao, and J. Yu, "Use of surfactants for the remediation of contaminated soils: A review," Mar. 01, 2015, *Elsevier B.V.* doi: 10.1016/j.jhazmat.2014.12.009.
- [45] Z. M. Gusiati, D. Kulikowska, and B. Klik, "New-generation washing agents in remediation of metal-polluted soils and methods for washing effluent treatment: A review," Sep. 01, 2020, *MDPI AG*. doi: 10.3390/ijerph17176220.
- [46] R. Guillaumont *et al.*, "Update on The Chemical Thermodynamics of Uranium, Neptunium, Plutonium, Americium and Technetium," 5th ed., F. J. Mompean, M. Illemassene, C. Domenech-Orti, and K. Ben Said, Eds., Issy-les-Moulineaux, France: OECD Nuclear Energy Agency, Data Bank, 2003.
- [47] S. Nair, L. Karimzadeh, and B. J. Merkel, "Sorption of uranyl and arsenate on SiO₂, Al₂O₃, TiO₂ and FeOOH," *Environ. Earth Sci.*, vol. 72, no. 9, pp. 3507–3512, Nov. 2014, doi: 10.1007/s12665-014-3258-x.
- [48] E. L. Mühr-Ebert, F. Wagner, and C. Walther, "Speciation of uranium: Compilation of a thermodynamic database and its experimental evaluation using different analytical techniques," *Applied Geochemistry*, vol. 100, pp. 213–222, Jan. 2019, doi: 10.1016/j.apgeochem.2018.10.006.
- [49] W. Dong and S. C. Brooks, "Determination of the formation constants of ternary complexes of uranyl and carbonate with alkaline earth metals (Mg²⁺, Ca²⁺, Sr²⁺, and Ba²⁺) using anion exchange method," *Environ. Sci. Technol.*, vol. 40, no. 15, pp. 4689–4695, Aug. 2006, doi: 10.1021/es0606327.
- [50] M. A. Hamoud, S. F. Abo-Zahra, M. A. Attia, H. H. Someda, and M. R. Mahmoud, "Efficient adsorption of cesium cations and chromate anions by one-step process using surfactant-modified zeolite," *Environmental Science and Pollution Research*, vol. 30, no. 18, pp. 53140–53156, Apr. 2023, doi: 10.1007/s11356-023-25644-y.

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- [51] A. Cremers, A. Elsen, P. De Preter, and A. Maes, "Quantitative analysis of radiocaesium retention in soils," *Nature*, vol. 335, no. 6187, pp. 247–249, Sep. 1988, doi: 10.1038/335247a0.
- [52] R. E. A. Mohammad *et al.*, "Tackling environmental radionuclides contamination: A systematic review of chemical, biological, and physical remediation strategies," Aug. 01, 2025, *Elsevier B.V.* doi: 10.1016/j.ceja.2025.100802.
- [53] K. Cho, E. Myung, H. Kim, C. Park, N. Choi, and C. Park, "Effect of soil washing solutions on simultaneous removal of heavy metals and arsenic from contaminated soil," *Int. J. Environ. Res. Public Health*, vol. 17, no. 9, May 2020, doi: 10.3390/ijerph17093133.
- [54] G. N. Kim, S. S. Kim, J. K. Moon, and J. H. Hyun, "Removal of uranium from soil using full-sized washing electrokinetic separation equipment," *Ann. Nucl. Energy*, vol. 81, pp. 188–195, Jul. 2015, doi: 10.1016/j.anucene.2015.01.046.
- [55] T. Y. Wais *et al.*, "Investigation of natural radionuclide transfer from soil to wheat," *Sci. Rep.*, vol. 15, no. 1, Dec. 2025, doi: 10.1038/s41598-025-11797-y.
- [56] X. J. Zheng *et al.*, "Remediation of Heavy Metal-Contaminated Soils with Soil Washing: A Review," Oct. 01, 2022, *MDPI*. doi: 10.3390/su142013058.
- [57] M. S. Kim, N. Koo, J. G. Kim, and S. H. Lee, "Effects of washing solution, washing time, and solid-solution rate on the maximum heavy metals removal efficiency," *Applied Sciences (Switzerland)*, vol. 11, no. 14, Jul. 2021, doi: 10.3390/app11146398.