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Review Article

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Optimized Phytoremediation Process for the Sustainable Management of Radionuclides in the Food Chain

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Abstract

Heavy metal contamination has increased because of rapid industrialization, rising industrial waste, increasing agricultural inputs, and mining. Radionuclides were unconfined into the geo environment because of authorized nuclear waste discharge, nuclear weapons testing, and other activities. The environment is contaminated by a range of metals, including radionuclides, that can disrupt biogeochemical cycles, in all its components, including the air, water, and soil. Heavy metals and radionuclides are important environmental contaminants that are cytotoxic, mutagenic, and carcinogenic. Therefore, the improper use of such harmful toxic drugs requires proper attention. Without proper management, the risk of RN mobilization to the food chain through the channels of crops and animal's results in biomagnifications. Vegetables that have radioactive and heavy metal deposits have an impact on human health. Vegetable contamination levels rose as a result of higher Gomati River contamination with heavy metals (HMs) like Cd, Cr, Ni, Pb, and Zn from industrial and agricultural runoff. This increased contamination could be harmful to consumers' health.Because of its capacity to clean up damaged and contaminated landscapes without generating further ecological disruptions, phytoremediation has gained widespread acceptance in both developed and developing countries. We have also covered a variety of phytoremediation methods for the environmentally friendly removal of certain pollutants.The review also includes crucial elements for improving phytoremediation approach using several soil amendments, including biochar, organic materials, organic acid exudes, humic compounds, and criteria for choosing hyperaccumulator plants. Traditional remediation methods are prohibitively expensive for soil and water. As a result, phytoremediation has enormous potential to not only contain toxicants but also to recover useful components. In addition, potential future effects of such an improved phytoremediation are also proposed.

Keywords

Sustainability, Life on land, Clean water and sanitation, Good health and well-being

Introduction

Growing urbanization and industrialization have boosted the generation of heavy metals and radionuclides into the geo environment. Radiation-emitting materials are essential for many biomedical and industrial applications and have been used extensively in research and development. Nuclear power plants are the source with the highest production of radioactive elements, producing around 95% of the radioactivity produced by all sources [1]. Radionuclides that are frequently found in the environment include uranium 238 and plutonium 239, as well as radium 226 and cobalt 60. However, nuclear power reactors may produce radionuclides like cesium-137, iridium-192, thallium-201, and strontium-90 by splitting elemental atoms [2-4]. There is a serious concern from the radioactive contamination, especially for the environment. Due to their connections to potassium and calcium, some of them are emitters, which could harm DNA [3].

Leukemia, leucopoenia, and potentially catastrophic conditions such kidney and genetic problems have all been associated to prolonged exposure to these RNs [4]. On the soil surface radionuclides are deposited because of oil drilling, mining, and grinding [5]. Additionally, chemical leaching and natural weathering can release radionuclides into the soil [6]. Radionuclides eventually integrate into the soil's structure after being deposited on the soil's surface. After then, the radionuclides can either remain in the soil solution, bond with soil constituents, or soak onto soil particles. Organic matter and oxides found in soil can momentarily bind radionuclides under specific environmental conditions, allowing for their release [7]. The quantity of bound radionuclides and the amount of time after radionuclide deposition are frequently correlated linearly. When radionuclides become adsorbed or bound within the soil, their bioavailability to soil invertebrates, microbes, and plants is diminished.

However, when radionuclides persist in the soil solution, they become accessible to soil organisms and plants. According to Chirakkara and Reddy. [6], radionuclide bioavailability is significantly influenced by the type of radioactive deposition, the timing of the deposition, and the characteristics of the soil. The radionuclides ^{137}Cs and plutonium securely bind to soil particles, decreasing their bioavailability, according to Wang et al. [5]. Nuclides like radioactive cesium (^{134}Cs and ^{137}Cs), iodine-131, silver-110 and tellurium-129 were found to be distributed in soil [8]. According to IAEA standards, the Kyshtym disaster, which took place on September 29, 1957, in a Soviet nuclear fuel reprocessing facility, was given a level 6 classification by INES. The core of the British atomic bomb programme in Sellafield, England, was destroyed by fire on October 10, 1957, and 740 tera becquerels of level-5 iodine-131 were released into the environment [8]. Over the past century, the nuclear industry has released huge amounts of anthropogenic radionuclides into the environment, contaminating local, regional, and global environments [9]. The 1986 Chernobyl and 2011 Fukushima nuclear accidents released enormous amounts of atmospheric radionuclides as gases, volatiles, and refractory elements [10, 11]. Nuclear weapon testing, nuclear waste leaks, and therapeutic and farmed trials with isotopes as tracer agents also contribute to radioactive pollution [10, 12]. Radionuclides do not decay and reach the food chain from soil and water [13]. Thus, radionuclide remediation is becoming more significant. In agricultural areas affected by radionuclide contamination, selecting crops that are less prone to accumulate these contaminants is crucial. Additionally, using phytoremediation plants as cover crops or intercropping them with food crops can help reduce radionuclide uptake by edible plants. Regular monitoring of both the phytoremediation plants and food crops is essential to ensure that radionuclides are effectively sequestered and do not enter the food chain. This involves testing soil, plant tissues, and food products for radionuclide levels

Remediation techniques should be used to stop the mobility of radionuclides into dissimilar environments, including earthly, atmospheric, and marine ones, to reduce the pollution somewhat or wholly. There are several different remediation techniques that have been developed over the years, including mechanical ones such soil burning, excavation and disposal, soil laundry, solidifying, and electric field application. The ineffectiveness of toxins at low concentrations, the irreversible degradation of the physico chemical and biotic features of the soil, and the ensuing secondary contamination are just a few of the major downsides of these approaches. Given the aforementioned factors, the creation of remediation techniques that are inexpensive, efficient, and ecologically friendly is essential. Phytoremediation has become widely accepted in both wealthy and developing nations due to its ability to restore damaged and polluted landscapes. This technology is now becoming quite important because of its possible applications in actual ecosystems [14].

Phytoremediation, a method of remediation based on plants, absorbs, and removes pollutants or lessens their bioavailability and mobility in soil [15]. They can be beneficial even in contaminated situations with low concentrations due to their extensive root systems. Phytoremediation makes it possible for a method that is both economically and environmentally sound and can be applied widely. Additionally, by limiting erosion and metal leaching, this process stabilizes soil fertility by releasing a variety of organic compounds into the soil. Nevertheless, like previous strategies, phytoremediation seems to offer a way to effectively decontaminate the polluted land.

Radionuclides

The origins of radionuclide contaminations in the environment

Naturally occurring radioactive materials encompass many isotopes such as uranium (U), thorium (Th), radium (Ra), radon (Rn), plumbum (Pb), and polonium (Po), which originate from geological processes such as volcanic activity, erosion, and weathering. Anthropogenic activities are responsible for the discharge of naturally occurring radioactive materials as well as technologically enhanced naturally occurring radioactive materials. The activities encompassed within this category consist of nuclear weapons testing, minerals mining and milling, operation of nuclear power plants, disposal of nuclear waste, occurrences of nuclear accidents, manufacturing of phosphate fertilizers, burning of fossil fuels, as well as production and utilization of radioisotopes for medicinal or scientific purposes [10, 13, 16] (Figure 1). ^{131}I is used to diagnose and treat thyroid cancer, while ^{14}C tracks chemical changes in agricultural experiments [17]. However, the Chernobyl and Fukushima accidents released large amounts of anthropogenic radionuclides like ^{133}Xe, ^{131}I, ^{134}Cs, ^{137}Cs, and ^{90}Sr into the atmosphere, polluting terrestrial and aquatic environments [18]. 1.2 x 10^7 TBq of radiation spilled from Chernobyl [19]. The Fukushima nuclear accident released massive amounts of radionuclides (^{133}Xe, ^{85}Kr, ^{131}I, ^{133}I, ^{134}Cs, and ^{137}Cs) into the atmosphere, contaminating oceans and land [11]. The Fukushima accident also caused acute radiation sickness, cancer, and

Table 1: Shows the most common environmental radionuclides.

Isotope	Half life	Principal radiation	Main sources	Ref.
^{90}Sr	29.1 y	β radiation	Nuclear accidents, test of nuclear weapons, geological repository of nuclear waste	[21]
^{89}Sr	50.52 d	β radiation	Nuclear accidents, test of nuclear weapons	[22]
^{238}U	4.5×10^{9} y	α, β and γ radiation	Geological repository of nuclear waste, test of nuclear weapons, uranium mining/milling, natural sources	[23]
^{235}U	7×10^{8} y	α, β and γ radiation	Geological repository of nuclear waste, test of nuclear weapons, uranium mining/milling, natural sources	[10]
^{134}Cs	2.06y	β and γ radiation	Nuclear accidents and weapons testing	[24]
^{137}Cs	30.17y	β and γ radiation	Geological repository of nuclear waste, nuclear accidents, test of nuclear weapons, fuel reprocessing	[25]
^{239}Pu	2.41×10^{4}y	α radiation	Geological repository of nuclear waste, nuclear accidents, test of nuclear weapons, fuel reprocessing	[26]
^{226}Ra	1600y	α and γ radiation	Uranium mill tailings and production of phosphate fertilizers	[27]
^{3}H	12.35y	β radiation	Nuclear accidents, test of nuclear weapons, nuclear plants	[28]
^{129}I	1.57×10^{7} y	β and γ radiation	Geological repository of nuclear waste, test of nuclear weapons, fuel reprocessing, natural sources	[10]
^{131}I	8.02d	β and γ radiation	Nuclear accidents, test of nuclear weapons	[29]
^{14}C	5.7×10^{3} y	β radiation	Nuclear power plants, geological repository of nuclear waste, test of nuclear weapons, natural sources	[30]
^{40}K	1.3×10^{9}y	β radiation	Natural sources	[31]
^{232}Th	1.14×10^{10}y	α and β radiation	Mineral mining/milling, test of nuclear weapons, natural sources	[31]

mental illness showed in table 1 [20]. Radionuclides can penetrate aquatic ecosystems or soil matrix and enter the food chain, producing health problems (Figure 1).

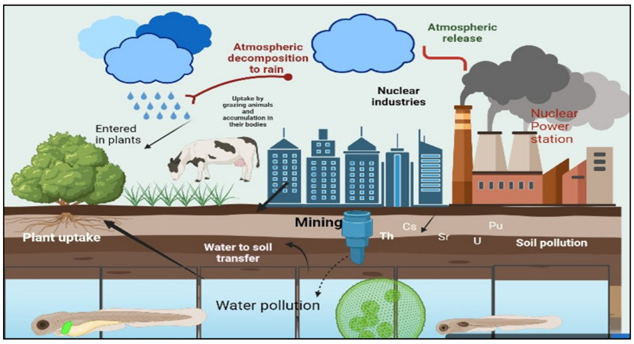

Figure 1: Illustrates the many sources of radionuclides and the pathways by which they are released into the environment.

The threat of radionuclide

Due to their lengthy half-lives and carcinogenicity, people absorb radionuclides through water, food, and aerosols [32]. Ionising radiation breaks DNA and releases very responsive free radicals that cause cancer and genomic damage [33]. Uranium (mainly ^{234}U, ^{235}U, and ^{238}U) accumulates in kidneys, liver, muscle, cardiovascular, and nervous systems, while ^{131}I is toxic to the thyroid gland and may cause thyroid cancer after childhood or adolescent exposure [34] .^{90}Sr, a chemical counterpart of calcium, accumulates in human bones and teeth and is one of the most radiotoxic metals. ^{90}Sr may cause leukaemia and skeletal cancer [35]. Cesium and potassium are chemically identical and distribute similarly in human organ-tissues, with high amounts in skeletal muscle [36] Radionuclide exposure alters metabolic and immune pathways, increases DNA lesions and mutation rates, morphological abnormalities, and oxidative stress, decreasing survival and reproduction rates in vertebrates like bank voles (*Myodes glareolus*) and barn swallows (*Hirundo rustica*) [37]. Dispersed radionuclides from nuclear accidents like Fukushima have affected coastal ecosystems.

Remediation Strategies for the Process

Remediation refers to the systematic approach employed to mitigate the impact of pollutants and safeguard the environment against their potentially detrimental repercussions, with the aim of ensuring the well-being of future generations. Various physicochemical and biological strategies have been employed to address the removal of hazardous materials. These processes are recognized as demanding due to their associated costs and technical difficulties shown in figure 2.

Phytoremediation

Phytoremediation strategies

Various methodologies, such as elimination, separation, combustion, solidification/stabilization, sterilization, heating, solvent extraction, oxidization by chemicals, among others, can be employed for the remediation of polluted soils and residues. The drawbacks of these procedures include their high cost and the fact that they sometimes require moving contaminated materials to treatment facilities, which increases the danger of secondary contamination [38]. Therefore, in situ techniques that are less damaging to the environment and more cost-effective are currently preferred. In this situation, phytoremediation methods are a good alternative provided by biotechnology.

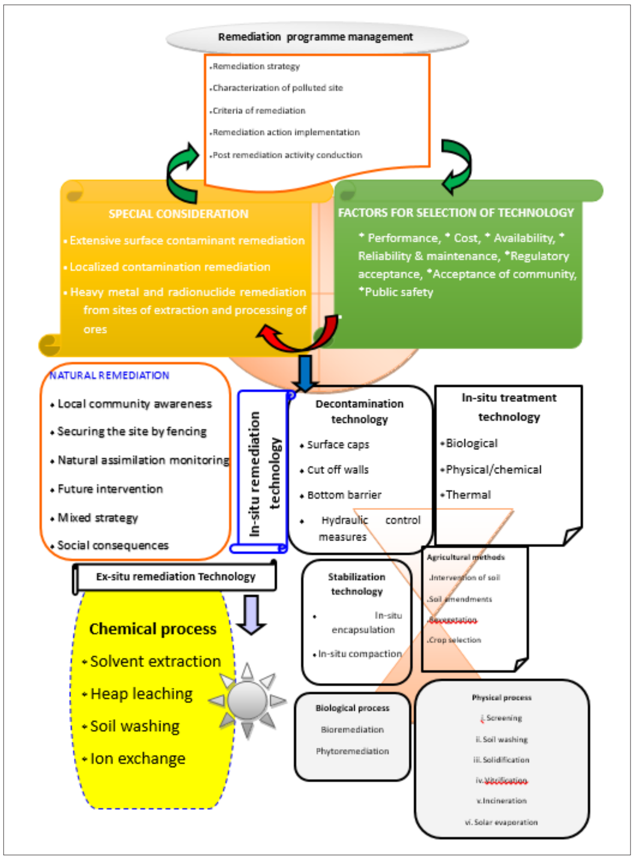

Figure 2: Schematic representation of phytoremediation strategies.

Toxic compounds can be removed, degraded, or isolated from the environment using plants and the microbes that live on or in them [39]. The words "phytoremediation" and "remediation" come from the Latin root "remedium," which means "to remedy" or "to correct," and the Greek word "phyton," which means "plant. Phytoremediation may be applicable to various substances, including inorganic compounds such as NO_3^-, NH_4^+, and PO_4^{3-}, radioactive chemical elements like U, Cs, and Sr, petroleum hydrocarbons such as BTEX, pesticides and herbicides such as atrazine, bentazone, and chlorinated and nitroaromatic compounds, explosives like TNT and DNT, chlorinated solvents such as TCE and PCE, industrial organic wastes including PCPs and PAHs, as well as other substances.

Phytoremediation methods come in a variety of sense modality, dependent on the chemical make-up of the impurity (whether it is volatile, sluggish, or susceptible to breakdown in the plant or the soil) and the structures of the plant (Figure 3). Thus, phytoremediation fundamentally consists of six distinct techniques, albeit a plant may employ more than one at once. Organic pollutants are broken down (metabolised) inside plant cells by specialised enzymes such as nitrate reductase (which break down nitroaromatic compounds), dehalogenases and laccases (which break down anilines). Populus species and *Myriophyllium spicatum* are the plants with these enzymatic systems [15]. Contaminants, whether organic or inorganic, are absorbed into the lignin of the cell walls of roots or into humus during phyto stabilization (also known as phyto immobilization). By the direct action of root exudates, metals are precipitated as insoluble forms and subsequently trapped in the soil matrix. Avoiding contaminant mobilisation and limiting their soil dissemination are the key goals [15].

Plants grown for this purpose include species from the genera *Haumaniastrum, Eragrostis, Ascolepis, Gladiolus*, and *Alyssum*. Phytovolatilization process depends on plants' capacity to absorb and volatilize specific metals and metalloids [4]. Organic substances can also be employed with this method. The process of phytoextraction, also known as phytoaccumulation, phyto absorption, or Phyto sequestration, includes the roots absorbing pollutants, which are then transported and accumulated in the aerial parts. Although it can be employed with other elements (Se, As), it is primarily applied to metals (Cd, Ni, Cu, Zn, and Pb). Hyperaccumulator plants (*Elsholtzia splendens, Alyssum bertolonii*) which can hold more absorptions of metals in their airborne parts are preferred for this procedure.

Phytoremediation of radionuclide

Specific green plants are used in phytoremediation technique, which has been proven to be a successful phenomenon, to clean up polluted environments. Different plant species that are paired with bacteria can facilitate cleanup efforts and demonstrate their capacity as nature's recyclers by restoring contaminants to their original forms. The bioremediation subcategory of phytoremediation serves as a key element in the management of radionuclide and heavy metal contamination [32]. This plant-based remediation technique mobilises different elements into the tissues of the plants and enables metal accumulation in diverse plant components. It describes a group of plants known as hyper-accumulators and their inherent capacity to bio-accumulate, destroy, or reduce inoffensive toxins found in soils, water, or the atmosphere. With engineering and biological solutions for enhancing and optimising the process, studies and understanding regarding the molecular and physiological systems behind phytoremediation have recently begun. The phytoremediation mechanisms, which include phytoextraction, phyto stabilization, phytodegradation, and phytovolatilization, require longer times to reach the same degrees of decontamination as traditional approaches, resulting in less environmental disturbances. Toxins can be concentrated into smaller, easier-to-dispose-of amounts of material using phytoremediation techniques [24].

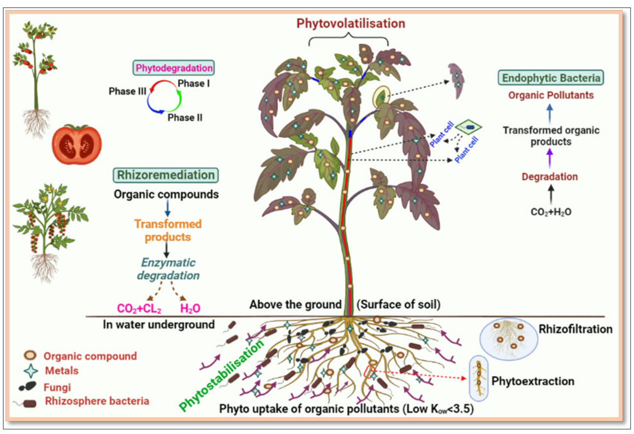

Figure 3: Phytoremediation solutions as a sustainable approach for mitigating the presence of radionuclides.

The transfer of pollutants from plant roots to shoots may be a potential strategy for decontaminating heavy metals and radionuclides. It ought to be able to transmit the metals to plant components and degrade, absorb, accumulate, and absorb them [25]. There are more than 400 plant species that are extremely metal accumulators, and more than 45 families have been found to contain some of these species. Research on phytoremediation, or the treatment of radionuclide-contaminated soils, has been conducted recently. This research involves the use of various plant species under varied conditions, as well as improvement by the addition of fertilisers, organic acids, or chelating agents. Comparing phytoremediation to other remediation methods, the following benefits are particularly promising:

- Both at the site and out of site, phytoremediation is more cost-effective than conventional procedures.
- Simple monitoring of plants that accumulate excess energy.
- A natural approach that uses plants and soil microbes to safeguard the environment in an eco-friendly manner.
- Using a technique called phyto mining, precious metals can be recovered and reused.

However, there are several restrictions on the application of phytoremediation methods:

- It is constrained by the size of the plant's surface area and the depth of its roots.
- Slow development and prolonged procedure.
- While leaching of toxins into groundwater cannot be totally stopped, it is possible to stabilize or partially degrade them in contaminated areas.
- The growth circumstances and soil quality affect a plant's ability to survive.

Choosing plant taxa for phytoremediation strategies should be the main priority. First, different varieties of plants have varying capacities for absorbing toxins, and second, the environment and nutrients at the contaminated places must be suitable for the growth of the plant. However, the main methods, namely phytoextraction, allow plants to convert water, sediment, or soil pollutants into biomass that can be harvested. The adoption of the phytoextraction method has grown over the past 20 years, whereas the focus of phyto-stabilization technology is the long-term steadiness and holding of the radionuclides in the rhizosphere zone of the soil [26].

Enhancing the Effectiveness of Phytoremediation with Natural Amendments

Addition of organic soil amendments

The flexibility and bioavailability of minor elements play an important role in the efficacy of phytoremediation, which can be controlled by adding organic or inorganic soil amendments [17]. By facilitating the bio-chelators, which raise the bioavailability and flexibility of soil contaminants, adding organic amendments to the soil can boost the effectiveness of phytoextraction. The impacts that soil amendments have on plants are crucial for enhancing the growth characteristics of plants. The three approaches that are most usually utilised are adding biochar, adding carbon-based acid exudes from plant materials, and adding organic compounds such humic substances.

Accumulation of Biochar

With the addition of biochar, the effectiveness of phytoremediation can be increased since biochar has strong surface-assimilative capabilities due to its carbon atmosphere structure, which encompasses a large surface area due to high micro porosity. It can be produced by pyrolyzing waste biomass in an environment with little oxygen [19]. Recent research has mostly concentrated on understanding how to use biochar to immobilize soil contaminants and so reduce their bioavailability and subsequent phytotoxicity. The pH of the soil is dramatically raised by the addition of biochar, causing pollutants to precipitate. In addition to this, biochar also improves soil fertility by delivering and holding nutrients [28], which has significant advantages for agriculture. As a result, it increases biomass production. Biochar can typically be added in amounts ranging from 1% to 5%, depending on the soil's texture and the crop being cultivated there [8]. The improvement of soil's physical and biochemical qualities, such as nutrient and water retention, biological activity, cation exchange capacity, and nutrient cycling, is thought to be the cause of biochar's role in mediating better plant development [20]. However, it has been shown that adding biochar increased both the entrance of xenobiotics and the loss of innate soil organic matter. Because of this, it is essential to research the long-term advantages of biochar for its effects on the environment, which highlights the need for additional research on the kinds of plant materials and the viability of their application [30].

Composting

The process entails the decomposition of intricate organic waste through the utilization of diverse microorganisms, resulting in the conversion of said waste into typical constituents such as humus, micronutrients, and inorganic elements. The introduction of organic matter into the soil leads to an increase in its nutrient content, hence promoting plant growth and mitigating the adverse impacts of toxins. Through many mechanisms including as adsorption onto soil particles, complexation with other minerals, precipitation of highly mobile elements, and redox reactions, the introduction of compost into the soil has the potential to alter the bioavailability and mobility of heavy metals [31].

Plant root exudates

Plant root exudates, which contain a variety of organic acids, greatly alter the bioavailability of soil constituents. These typically have modest molecular weights and are chelating metals, making them easily biodegradable [12]. It is well known that chelators like EDTA, vanillic acid, gallic acid, and citric acid increase the mobility of the elements [13]. Additionally discovered to be useful against poisoning symptoms brought on by pollutants are the root exudates. As a result, several researchers have concentrated on using synthetic chelators to aid in the smooth uptake of pollutants. Radionuclide bioavailability in soil has been examined in relation to the addition of soil amendments. Such additions include chelating chemicals and mycorrhizal fungus or other microbial root connections [24]. In a relatively short time, intraradices increase the aboveground biomass of switchgrass (*Panicum virgatum*), Johnsongrass (*Sorghum halepense*), and bahia love grass (*Eragrostis bahiensis*), as well as the accumulation of ^{137}Cs. Chelating compounds made in the lab bind radionuclides to produce complexes that are bioavailable to plants. Chelating agents have been found to effectively enhance the bioavailability of radionuclides in soil. The plant species that are connected and have gathered radionuclides due to their increased bioavailability are also provided in the list. The results of the greenhouse experiment indicate that cabbage, tepary beans, Indian mustard (*Brassica juncea*), and reed canary grass exhibited a higher degree of absorption of ^{137}Cs. Regrettably, the presence of ^{137}Cs resulted in a decrease in the overall biomass yield of the plants. However, a field experiment revealed no discernible impacts of ammonium on Redroot pigweed (*Amaranthus retroflexus)*; biomass production [5]. As an industrial by-product, citric acid is readily available, biodegradable, and it promotes uranium hyperaccumulation in plants [25].

Humic substances

Humic substances are naturally occurring organic materials that are created in the top layer of soil because of the breakdown and degradation of plant and animal remains. Their ability to form stable complexes aids in either immobilising or mobilising the metal ions. Three major kinds of humic compounds found in soil include humic acid, fulvic acid, and humine. The precipitation of humine occurs in solutions with either strong acidity or basicity. However, the retrieval of humic acids and fulvic acid from soil and other solid phase sources can be achieved more readily by employing a strong alkaline solution. However, it has been found that different metal species are given varying phytoextraction capacities by humic acid, as particular metals, such as copper and lead, have a strong attraction for organic materials, which reduces their bioavailability [4]. As organic matter builds up in the soil, the pH of the soil is somewhat lowered, which causes metals to become soluble.

Selection of prospective hyper accumulators

The efficacy of phytoremediation is contingent upon the function of hyperaccumulators. As a result, hyper accumulators that can accumulate and withstand toxins at higher concentrations through intracellular complexes are preferred. The two plant species that have demonstrated the most efficacy in the process of rhizofiltration are *Helianthus annuus*, commonly known as sunflower, and *Eichornia crassippes*, also referred to as water hyacinth. Both have been observed to acquire substantial proportions of radionuclides (namely, ^{137}Cs, V, and ^{90}Sr) over relatively short time frames ranging from a few hours to a few days [5]. Sunflowers were used to phyto-remediate a pond close to the Chernobyl nuclear reactor. The roots of the sunflowers acquired up to 8 times more ^{137}Cs than those of timothy or foxtail, resulting in a bioaccumulation coefficient of 4900-8600 [5]. In a study conducted in Ashtabula, Ohio, it was shown that sunflowers at the age of four weeks exhibited a remarkable ability to extract over 95% of uranium from a contaminated wastewater site within a span of 24 h [16].

Based on the findings of Wang et al. [5], it was observed that water hyacinth cultivated in water with a pH level of 9 exhibited a significant accumulation of 90Sr, with approximately 80-90% of the element being predominantly localised in the roots. Amaranth cultivars exhibit a significant capacity for above-ground biomass production, resulting in the accumulation of notable quantities of ^{137}Cs up to 3000 Bq kg^{-1}. Chirakkara et al. [6], even though the CF of ^{137}Cs shows that these radio nuclides mostly remain in the roots. The becqueral unit (Bq) represents the rate of decay in seconds. After 35 days of development, the maximum ^{137}Cs concentration is obtained [6]. The species in the Umbelliferae and Legume families acquire the most ^{90}Sr [5] mentioned in table 2.

Pinus radiata and *Pinus ponderosa* pine seedlings collect 1.5–4.5% of ^{90}Sr in their shoots. The plants must be harvested to remove the radionuclides. The collection of radionuclides at their maximum concentrations necessitates the harvesting of plants to remove them from the site. From the location where they have collected radionuclides to their maximum concentrations. Rhizofiltration plants are eliminated from the water because radionuclides build up in their roots. The shoots of plants used for phytoextraction are cut off and harvested, leaving the roots to produce further shoots. Before being disposed of in a radioactive-waste site, the harvested biomass can be either incinerated/combusted at high temperatures to oxidise the radionuclides into ash or composted to concentrate the radionuclides into smaller biomass [7]. Low bioavailable U and Pu concentrations in soils can be treated with citric acid to release U into the soil solution and with sulphate to release Pu. Broadcast into the soil would be seeds of *B. juncea, Glomus mosseae* mycorrhizal fungi, switchgrass, and Johnsongrass. If there are radionuclides deep in the dump, tree species like ponderosa pine, juniper, or oak could potentially be replanted into the soil.

Radionuclide levels would be checked monthly in the soil and plant shoots. Spiderwort would be planted to act as a radionuclide indication after two months. The plants would be cut down, and the branches would be burned in the appropriate places so that the radionuclides would be collected in the ash. The ash would be buried at a landfill for hazardous trash [30]. Once the trees had accumulated the maximum amount of radioactive material, they would be entirely removed. They would also be burned and disposed of correctly. If sufficient knowledge of the mechanisms behind metal transport is attained, phytoremediation may be commercially effective. Hyperaccumulators, such as Thlaspi, serve as an excellent model system for investigating the underlying processes and genetic regulation of metal hyperaccumulation. These plants exhibit genetic mechanisms that control the uptake of metals from the soil by their roots and subsequent distribution to various plant tissues. Multiple areas within the plant exhibit potential for gene regulation, hence influencing the hyperaccumulation characteristic [27].

These genes are responsible for regulating the processes involved in the absorption of metals from the soil by roots, as

Table 2: Examples of plants used in environmental phytoremediation of anthropogenic radionuclides in soil and water.

Plant species	Family	Medium	Environment	Radionuclide	Ref.
Zea mays	Gramineae	Soil	Terrestrial	U	[36]
Helianthus annus	Compositae	Water, Soil	Terrestrial	^{137}Cs,^{90} Sr,^{123}I, U,^{226}Ra	[30]
Calotropis gigantea	Asclepiadaceae	Water, Low level nuclear waste	Terrestrial	^{137}Cs,^{90} Sr	[37]
Amaranthus retroflexus	Amarathaceae	Soil	Terrestrial	^{137}Cs,^{90} Sr	[24]
Typha latifolia	Typhaceae	Water	Aquatic	U	[25]
Eichhornia crassipes	Pontederiaceae	Water	Aquatic	^{137}Cs,^{90} Sr	[26]
Pteris multifida	Pteridaceae	Uranium mill tailings	Terrestrial	^{226} Ra	[27]
Dryopteris scottii	Dryopteridaceae	Uranium mill tailings	Terrestrial	^{226} Ra	[38]
Cyperus iria	Cyperaceae	Soil	Terrestrial	^{223}Th	[38]
Miscanthus floridulus	Gramineae	Soil	Terrestrial	^{210}Po,^{210}Pb	[25]
Brassica campestris	Brassicaceae	Soil	Terrestrial	^{137}Cs	[21]
Phaseolus vulgaris	Fabaceae	Water	Terrestrial	U	[39]
Apium nodiflorum	Apiaceae	Water	Aquatic	U	[38]
Lemma minor	Araceae	Water	Aquatic	U	[23]

well as enhancing the solubility of metals in the soil surrounding the roots. Additionally, they facilitate the transportation of metals into the cells of the roots. Subsequently, the metals are introduced into the plant's vascular system to facilitate their subsequent transportation to other plant tissues, finally culminating in their deposition within leaf cells [14]. Thlaspi demonstrates an exceptional capacity to store metals within its shoots at remarkably elevated concentrations. A common plant can be subject to toxicity when exposed to low concentrations of zinc, as low as 1000 parts per million (ppm), or cadmium, ranging from 20 to 50 ppm, in its shoots. Furthermore, the research proposes a cost-effective approach for the extraction of these metals. The extraction of zinc and cadmium from contaminated soil can be achieved by harvesting the shoots of plants [11].

Various strategies have been proposed to improve the efficacy of phytoextraction in the context of radionuclides

First, select radionuclides-accumulating plant species, then genetically manipulate transporters and rhizosphere microorganisms to improve phytoextraction [7, 13, 36]. The utilization of organic acids and synthetic chelators has been found to enhance the process of phytoextraction by facilitating the desorption of radionuclides from the soil matrix and transferring them into the soil solution [35, 36]. Citric acid has been found to have significant efficacy as a chelating agent in the process of uranium desorption and subsequent plant accumulation. This phenomenon has been observed in the shoot remediation of *B. juncea* and *Brassica chinensis*, whereby the citric acid treatment has resulted in a substantial increase in uranium concentration from levels below 5 mg kg^{-1} to above 5000 mg kg^{-1}. The presence of citric and oxalic acids resulted in an increase in the uptake and translocation of uranium to the aerial parts of the plant. The utilization of S, S-ethylenediamine disuccinic acid a soil amendment that is biodegradable, resulted in a significant 18-fold rise in uranium concentrations in the soil solution. Additionally, the application of S, S-ethylenediamine disuccinic acid led to a substantial 19-fold increase in the growth of *B. juncea* shoots. Agronomic management practices can potentially boost radionuclide phytoextraction from contaminated soils. In pot tests by Singh et al. [27] increasing ambient CO_2 concentration increased Cs absorption and biomass and improved rhizosphere microbe community composition and soil microbial C and N. Poultry litter as organic fertilizer maximized ^{137}Cs and ^{90}Sr accumulation in *Sorghum halpense* in greenhouse research by Saleh et al. [39]. Stojanović et al. [36] also showed that applying NH_4NO_3 to soil boosted shoot ^{137}Cs accumulation. In rice fields, delayed drainage during grain-filling stage and/or missed midsummer drainage increased ^{137}Cs and ^{133}Cs uptake [27].

Conclusion

Radionuclide phytoremediation is a global trend. This cheap, eco-friendly remediation process is projected to be commercialized and utilized to dispose of contaminated areas, especially in underdeveloped nations. Genetic engineering, soil supplements like citric acid, and optimized agronomic management practices like CO_2 regulation and water management promote phytoextraction. To accelerate plant taxonomic selection, molecular biotechnology-assisted breeding programmes should be studied to phytoremediate. Field experiments should also assess greenhouse plant phytoextraction of radionuclides. Although phytoextraction works, eliminating radionuclides from contaminated locations, biological mechanisms are unknown. Additional investigation is needed to explore the molecular and proteomic mechanisms involved in the transport of radionuclides across membranes and their sequestration within vacuoles throughout the uptake, translocation, and accumulation processes in plant tissues. These transporters facilitate the enhancement of phytoremediation in transgenic plants. The utilization of synthetic chelating agents in the phytoremediation of radionuclides is a concern due to their non-biodegradable nature, which may result in their potential infiltration into subterranean water systems, hence posing significant environmental risks. Optimizing agronomic management practices is needed to make these revolutionary solutions commercially viable. Assessing the risks associated with radionuclide contamination in the food chain is necessary to implement appropriate mitigation measures. This includes evaluating the potential pathways of radionuclide transfer from soil to plants to animals and humans. Phytoremediation efforts must comply with relevant regulations and guidelines regarding food safety and environmental protection. Working closely with regulatory agencies ensures that remediation strategies meet established standards and requirements.

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Conflict of Interest

The authors declared that they have no conflict of interest with respect to this work.

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