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Phytoremediation of Hazardous Radioactive Wastes

Deepak Yadav and Pradeep Kumar

Abstract

Phytoremediation technology incorporates living plants for in situ remediation of contaminated soils, sediments, tailings and groundwater. These practices integrates the removal, or degradation of toxic wastes that is capable of cleaning up an area with low to moderate levels of contamination. Phytoremediation has been studied widely for metals, pesticides, solvents, explosives, crude oil, etc. These studies and research are advanced, especially in small-scale operations. Phytoremediation has been successfully tested to decontamination of radioactive sites. The chapter initiates with possible remediation methods used for radioactive wastes where we will discuss types and nature of radioisotope contamination. Then we discuss discusses the classifications of phytoremediation techniques to treat radioactive contaminated waste. Phytoremediation performance depends on numerous factors such as soil composition, level of toxicity, suitable plant species, etc. Conversely, phytoremediation prospects low cost, practical and ecologically viable approach for low-level radiation waste clean-up.

Keywords: phytoremediation, plants, radioactive pollutants, radioisotope, low-level radiation waste

1. Introduction

The term “Phytoremediation” derived from Greek and Latin words. The word “Phyto” from Greek “phutón” meaning plants, while the word “remediation” from Latin “remedium” meaning a remedy or cure or correct evil. Phytoremediation is a fairly new technology introduced in 1980s that use plants to clean/partly clean contaminated locations, or reduce the contaminants less harmful [1–4]. It is also named as green remediation, agro-remediation, botano-remediation, and vegetative remediation [4, 5]. Therefore, the word is relating the technology for the management of environmental problems using plants and their allied microorganisms.

Many observes, phytoremediation, especially when very toxic materials are in request (e.g., radioactive waste). Phytoremediation is a general term refers to a set of plant–contaminant interactions, and a precise application procedure involved in remediation of radioactively contaminated locations. Most of these practices involve applying information known for decades in agriculture and ecology to environmental problems. Basic information of phytoremediation comes from several research areas; containing ecotoxicology, plant ecophysiology, agriculture, toxicity and translocation of toxic radioactive isotopes.

Mitigation of the environmental pollutant challenges with excavating the contaminants, dispose them off somewhere else with a cost-effective and an environmentally

friendly technique in waters and soils purification even in heavy metals [2, 3]. The conventional remediation techniques like chemical, thermal, physical and other treatment methods are costly, and may cause more contaminations to the environments [4].

The International Atomic Energy Agency (IAEA) has clearly defined radioactive waste as those materials that emits radioactive particles comprise intensities greater than the prescribed benign on national and international standards, and no additional use is expected [5–7]. For instance, hazardous radioactive waste is produced at each stage of the nuclear (uranium) fuel cycle with no nuclear waste facility. So, there is an immediate need of permanent storage facilities as well as repositories for the high-level nuclear wastes. Radioactive waste can be solid, liquid or gas from a diverse group of operations and activities (mining to nuclear power) and accidents poses health risks and has the potential to interrupt ecosystems.

Phytoremediation of radioactive waste is a method that uses plants to remove, transfer, or immobilize radionuclides present in the contaminated soil, water, or sludge, and it is a useful method for treating large-scale but low-level radionuclide pollution. Radioactive materials provide numerous applications (scientific, medical, agricultural, industrial and energy generation) and play a significant role in daily life in human society. Consequently, it is predictable that such diverse actions lead to radioactive waste generation. The nuclear accident at Chernobyl, Ukraine alone has been calculated to have increased the risk of cancer to humans by 0.1% [2, 8].

Radioactive uranium (U), caesium (Cs), strontium (Sr), and plutonium (Pu) are the main radioactive isotopes present in the environment as a consequence of nuclear activities, and are the radionuclides of most concern (for a list of radionuclides of environmental and health concern. Sometime the radioactive wastes have military applications, e.g., depleted uranium is used in weaponries, and the spent nuclear fuel (from reactors) comprise weapons-usable plutonium. Nuclear waste containing short radiation, generally of little concern as it fades quickly by natural radioactive decay. Conversely medium-level long-lived and high-level radioactive nuclear waste is more challenging and benign disposal of this waste is essential. Most of the nuclear waste produced in nuclear power plants, (half-life and effects of environmentally dangerous radioactive isotopes are listed in **Table 1**).

In specific, the prerequisite for the concern is for spent (used) radioactive fuel recently removed from nuclear reactors. Moreover, there is an alarming accumulation of radioactive material cast in glass or ceramics, shielded in stainless steel containers which is held in dry storage across the world [10, 11]. So, radioactive waste needs to be managed in a safe and must be remote from people till it remains dangerous.

Radionuclide	Half-life	Uses	Effects
Uranium (238)	4.5 billion years	Bombs, weapons, nuclear fuel	Mutations, cancer, birth defects
Plutonium (244)	80.8 million years	Explosives, mixed oxide fuel, power and heat sources. Example atomic bombings of Hiroshima and Nagasaki	Fire hazard, radioactivity and the heavy metal poison, radiation sickness, genetic damage, cancer, and death
Thorium (232)	14 billion years	Alloying agent, nuclear fuel	Carcinogenic
Radium (226)	1601 years	Luminous paints, dials of watches	Lymphoma, leukaemia, bone cancer

Table 1.
Phytoremediation of radioactive metals [9].

Radionuclides waste sources are transported in soil, sediments, or sludges can be reduced over and done with absorption and accumulation by the plant roots; adsorption onto roots; precipitation, or reduction in soil with root zone; or binding to humic (organic) matter by the process of humification. Before phytoremediation of the concerned radioactive waste, the appropriate natural plant should be wisely selected. The ways for selection the right plant species for phytoremediation of the radioactive waste are as follow:

1. Primarily, the features of radioactive waste should be examined.
2. Next, the plant class and its composition should be recorded.
3. Then, the concentration of a concerned radionuclide in the plant should be determined.
4. The plant biomass should be considered, and
5. Lastly, the concentration of a goal radionuclide in the remediated radioactive waste should be restrained.

Phytoremediation of radioactive waste is a worthwhile technique for treating large-scale, but low-level radionuclide waste. However, from the above mentioned criteria we can screen out the right plant types proficient to remediate the concerned radioactive waste. In the present chapter, significant features prompting the choice of natural plant to remediate radioactive waste. The concentration and features of radioactive waste, the plant type and plant structure, deposited area are detected, and the standards based on the phytoremediation factor (PF) have been anticipated for the selection of natural plant to phytoremediate radioactive waste.

2. Classification of radioactive wastes

Radioactive waste is distinct radioactive material for which no further use is foreseen in gaseous, liquid or solid form and controlled by a regulatory organization. According to international law governed by IAEA, spent nuclear fuel is not defined as wastes are well-defined by the accountable country. The wastes are categorized by the type and concentration of radioactive particles emitted (α , β and γ), energy and heat generation. The latest waste classification system for radioactive waste has been approved in universal standards established by the IAEA and are explained as follows [7]:

Exempt waste (EW): It comprises such a low concentration of radionuclides that create negligible radiological hazards and it can be excluded from nuclear regulatory control.

Very short lived waste (VSLW): These types of wastes are often treated to achieve volume reduction and/or conditioned, stored for decay over a limited period of few years, prior to disposal. These are disposed of as regular industrial waste and consequently cleared of regulatory control [12, 13]. Further, various safe and effective treatment routes are open, with chemical precipitation as well as incineration.

Very low level waste (VLLW): It does not require isolation and a high level of containment, and disposal is done in near-surface landfill. VLLW wastes are always cured to attain liquidity (volume) reduction and waste is immobilized prior to its

disposal [13, 14]. Several safe and effective additional treatments are available, e.g., chemical precipitation and incineration.

Low level waste (LLW): It covers limited amounts of long-lived radionuclides with a very wide variety of radioactive waste. Waste that does not need shielding for handling or transportation, and isolation ages of a few 100 years. LLW may be slightly contaminated with radiation; for example, paper, glassware, tools and clothing. A wide range of disposal and storage alternatives are available, from simple to complex engineered facilities, e.g., landfills or incineration.

Intermediate level waste (ILW): ILW (reactor components, chemical residues, used metal fuel cladding) contains long-lived radionuclides alpha (α) emitters and isolation blocks. It does not need facility of heat dissipation during storage and disposal. ILW requires special handling and shielding of radioactivity. This waste is destined for disposal in deep geological repositories (the Waste Isolation Pilot Plant in USA).

High level waste (HLW): HLW covers high intensities of radiations that produce major amounts of heat by radioactive degeneration. It demands the design of removal in very deep, even geological layers, typically several hundred meters below the surface. The two primary categories are: (1) used fuel rods from nuclear plants and (2) waste from reprocessing the fuel rods. The waste contains both short-lived and long-lived high radiation nucleotides (half-lives of many thousands of years) which comprises high concentrations of radioactivity and requires cooling and special shielding, handling and storage.

3. Treatment methods

Conventional remediation techniques e.g., chemical, thermal and physical treatment methods are too costly, and may end of causing more contamination to the environment. Internationally acclaimed phytoremediation has an over 300-year old history of wastewater discharges, but the concept of using plants for the remediation of heavy metals and other pollutants was first reported in 1983 [15]. The concentration of a target element governs the degree to the widespread phytoremediation. Phytoremediation might be best suited for positions with the levels of radionuclide pollution which are only slightly advanced than the cleanup board levels because the subsequent sum of time for cleaning becomes reasonable (<10 years) and as probable plant toxicity effects are avoided [16].

Once the action is finished, an inorganic deposit remains that must be disposed of carefully, this residue has no fiscal significance. There are five varieties for positioning hazardous waste:

1. Hazardous wastes are dumped by force and under pressure by underground instillation bores (steel- and concrete-encased channels under earth crust).
2. Surface impoundment (engineered or natural depressions) can be recycled to treat, store, or dispose of hazardous waste, in pits or diked spaces.
3. Land-fills are discarding facilities where hazardous waste is located in, properly planned and lined landfills to prevent leakage.
4. Land treatment is a disposal process in which natural microbes in the soil break down (immobilize) the hazardous constituents.
5. Waste piles, non-flowing hazardous waste are used for provisional loading till it is moved to final removal and final disposal.

The hazardous waste disposed of on land, ~60% (underground injection wells), ~35% (surface impoundments), 5% in landfills, and <1% in waste piles/land application.

Radioactive waste control involves reducing radioactive residues, manage waste-packing carefully, safe storage and disposal along with protect sites of radioactivity origin clean. Underprivileged practices may lead to future complications. Therefore, selection of sites where radioactivity is to be managed safely is equally important other than technical expertise and investment, to result in safe and ecologically sound results. IAEA is endorsing recognition of some basic tenets by all countries for radioactive waste management which include:

- i. Acquiring adequate level of human safety.
- ii. Facility of a standard level of environment protection.
- iii. Although predicting (i) and (ii), guarantee of insignificant properties past national boundaries.
- iv. Tolerable impact on future groups, and
- v. No unnecessary liability on future generations. There are other legal, control, generation, safety and management characteristics likewise.

The following decisions have been declared stress staid studies and technical assessments:

- Deep geological sources.
- Ocean dumping Seabed burial.
- Sub-seabed disposal.
- Subductive waste disposal method.
- Transforming radioactive waste to non-radioactive stable waste.
- Dispatching to the Sun.

4. Radioactive waste uptake phytoremediation mechanisms

Phytoremediation is well accepted in literature [17, 18], and favored due to its in-situ/ex-situ applicability. Further additional benefits comprise fairly easy to handle and apply, proficient extraction bioavailable shares of pollutants, adaptable to a range of organic and inorganic complexes and energy generation. While the use of plants as environmental rehabilitation agents has gained wide acceptability in multidisciplinary research fields. Bramley-Alves et al. [19] proposed that phytoremediation involves a multi-skill technique for example phyto-oxidation, volatilization, and microbial remediation to improve the efficacy of pollutants' control [19]. Furthermore, phytoremediation is favored to former chemical methods because it could be useful in locations contaminated by inorganic (e.g., heavy metals) contaminants and organic (e.g., pesticides, polycyclic aromatic hydrocarbons (PAH), and polychlorinated biphenyls) [20].

Over the previous years, several methods have been used to deal with the radioactive waste from contaminated sites. Though, these methods are costly and inefficient in their concert. The chemical methods generate large volumes of sludge and increase the cost of maintenance. Thermal methods are technically difficult and adversely affect the valuable component of soil by degrading it [21]. Two major procedures that are conventionally used to remediate the radioactive contaminated sites are: [22].

1. **Ex-situ methods:** This method requires the removal of contaminated soil for treatment on/off site and then returning the treated soil to the site. The example of ex-situ methods are; soil leaching, solidification, immobilization, vitrification, heap leaching, ground disposal, sea disposal, incineration, and or destruction etc.
2. **In-situ methods:** In this method excavation of contaminated location is not needed. The examples are; de-chlorination, bottom sealing, electromagnetic heating, etc.

Phytoremediation is a novel resolution that effectively and inexpensively extracts out the contaminants from the site and scrubs up the wasteland [23]. Phytoremediation makes use of green plants to clean up and treat radioactive contaminated sites for example soil, water and sediments. Plants have notable features that help them absorb contaminants into their systems with their endorsement capabilities such as translocation, bioaccumulation and contaminant degradation. Many plant species have been successful in efficiently accumulating the radionuclides in their stems and leaves and hence remediating the contaminated site [21]. This chapter evaluates some of the research that has been done on phytoremediation of radioactive metals and aims to discuss the potential of phytoremediation, highlight the general mechanisms of plant uptake, give a brief overview on radioactive metals (especially: Uranium-238, Thorium-232, Radium-226) uptake by plants, and report the advantages and limitations associated with this method.

5. Six main subgroups in phytoremediation

1. **Phytoextraction:** Plants degrading pollutants from the soil (tailings) and concentrating the contaminants in the harvestable portions of plants; i.e., in all organs of the plant—leaves, stems and roots [24, 25].
2. **Phytodegradation:** Plants removing pollutants by using hydrolytic enzymes and metabolites in plants; however, this method may be limited only to degradation of organic contaminants [26, 27].
3. **Phytostabilization:** Plants reducing mobility and bioavailability of pollutants in the soil either by immobilization and precipitation, or by preventing contaminant migration [28, 29].
4. **Phytovolatilization:** Volatilization of pollutants into the air directly or indirectly via plant uptake into tissues and organs, and then transformation of the products into volatile compounds [25, 30].
5. **Rhizofiltration:** Plant roots strongly absorbing, accumulating and/or precipitating contaminants from aqueous waste streams or soil water almost exclusively into the root system [31, 32].

6. **Rhizodegradation:** Enhancement of naturally occurring biodegradation and destruction of contaminants in the soil through mineralization and transformation of pollutants by plant roots and associated microbes [33–35].

6. Factors affecting the uptake mechanisms

There are several factors which can affect the uptake mechanisms of radioactive metals and are discussed as below:

6.1 Plant species

Plant species with superior remediation ability of the concerned radioactive waste are screened and carefully chosen. The success of phytoremediation technique depends upon the ability of the plant to accumulate [36].

6.2 Properties of medium

Factors such as temperature, moisture content, pH, organic matter affect the rate of uptake by plants [37].

6.3 The root zone

It can absorb contaminants and store or metabolize it inside plant tissue. An increase in root diameter and reduced root elongation as a response to less permeability of the dried soil [38].

6.4 Addition of chelating agents

The increase of the uptake by crops can be influenced by increasing the bioavailability of radionuclides through addition of biodegradable physiochemical factors such as chelating agents, and micronutrients [39].

In a stressed environment, the application of plants to remediate sites governed by mainly on the persistence capacity of the plant. All through phytoremediation, plants absorb pollutant from the soil, and mineralized it, thus preventing infection of groundwater and retaining system shield for human habitation. Efe and Elenwo reported that plants (e.g., *Axonopus compressus*) used as phytoremediation means, should have the capacity to adapt properly to the climatic condition and soil of the polluted sites, and retain high patience under stressed environments [40]. Several phytoremediation plant types have technologically advanced adaptive features for absorption, acceptance, transfer and degradation of pollutants for example heavy metals, crude oil, explosives, and radionuclides [41].

The efficiency of the process is also dependent on the soil properties, type of contaminants and its bioavailability. Plant roots usually serve as interlinks providing enormous surface area for the absorption and accumulation of essential growth nutrient along with contaminants [42]. In metal contaminated sites, characterization of eco-toxicity (e.g., oxidative stress) is mostly determined through the formation of free radicals [43]. Some of the advantages of phytoremediation include risk containment, extraction of valuable metals (phytomining) and increased soil fertility/quality.

Baker and Brooks [44] recommended that the metal hyperaccumulator must fulfill a standard that the concentration of an element stored in a plant can be higher than the soil [44]. Based on their classification, the transfer factor (TF)

can be defined as the ratio of target element concentration in the plant to that in the tailings.

$$\text{Transfer factor} = \frac{(\text{target element concentration in the plant})}{(\text{target element concentration in the tailings})}. \quad (1)$$

TF can be used as an index for the growth of a target element in the plant and its transfer from the tailings to the plant. If TF for a plant is greater than 1 and the amount of the target element collected in the plant is relatively small, the elimination competence of the plant for that target element can be further improved by a number of breeding practices, and can further implemented in phytoremediation [45].

Different TF values for the plants tissues may be resulted in part from metabolic rate differences between plant species and cultivations [46]. The factors for example the concentration of a radionuclide, pH, plant age, and ecotype may adjust the uptake and ratio of the content of the element present in the plant shoot to that in its root [47]. About 91 tissues of plant species had the TF values of <1, only 9 tissues of plant species had the TF values of more than 1. Overall, it was found that most of the plant species inspected had low experiences of removing U, Th, and ^{226}Ra from the stakeouts to the plant tissues. The results were friendly with the earlier research results [48–52].

In summary, phytoremediation of goal radionuclides from the followings largely depends primarily on three parameters with the radionuclide concentration in the plant, the plant biomass, and the target radionuclide concentration in the investigations. In order to assess the potential of a plant for phytoremediation more broadly, a novel coefficient was anticipated and named as phytoremediation factor [53]. This factor is the ratio of the total amount of a target radionuclide accumulated in the plant shoot to the concentration in the tailings at the site where the plant grows.

$$\begin{aligned} &\text{Phytoremediation factor (PF)} \\ &= \frac{(\text{target radionuclide concentration in the plant shoot})}{(\text{biomass of the plant shoot Target radionuclide concentration in the tailings})}. \end{aligned} \quad (2)$$

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

The results indicated that PF was agreeable with the plant removal capability. PF extends the conventional definition of hyperaccumulator, and it can easily be obtained. Although the concentration of a target radionuclide in a plant does not fulfill the criteria for a hyperaccumulator, if the plant has relatively high biomass, the plant may also be deliberated as the candidate for phytoremediation. Keeping in view the phytoremediation factor, *P. australis* and *M. cordata* were designated as the contenders for phytoremediation of uranium-contaminated soils [53, 54]. *Azolla imbricata* was selected as the candidate for phytoremediation of uranium-contaminated water [55, 56]. *P. australis* was selected as the candidate for phytoremediation of thorium-contaminated soils [53]. *P. multifida* was selected as the candidate for phytoremediation of ^{226}Ra -contaminated soils [54–56]. While PF offers a unique place for identification of a plant proficient in remediating the contaminated by the radioactive nuclides on a large scale, except the plant biomass per unit area. It is essential to consider further research should be executed to improvise this factor.

7. Phytomanagement

Waste disposal is dumping waste with no objective of retrieval. Waste management means the whole structure of operations starting with generation of waste and ending with disposal. The per capita use of electricity is correlated to the living standard of a country, whereas, the electricity generation by nuclear resources can be viewed as a least degree of radioactive waste that is produced and the allied scale of radioactive waste management of the country. On the gauge of electricity generation by nuclear fuel, India need to improve a lot. In 2000, India's stake of nuclear electricity generation compared to total electricity generation was 2.65% related to 75% of France which ranks first according to IAEA Report. Hence the magnitude of radioactive waste management in India could be miniscule compared to that in other countries.

As more power reactors come on stream and as weaponization takes profounder routes the needs of radioactive waste management increase. Radioactive waste management has been a crucial degree in the whole nuclear fuel cycle. Low and intermediate-level radioactive wastes rise from operations in reactors retained as sludge after chemical treatment and fuel reprocessing practices.

Solid radioactive waste is compressed, incinerated are subject to the nature of the waste. Underground drains in disposal facilities are applied for solid waste disposal under continuous surveillance and monitoring.

High efficiency particulate air (HEPA) filters are used to reduce air-borne radioactivity. From the last four decades radioactive waste management facilities have been set up at Trombay, Tarapore, Rawatbhata, Kalpakkam, Narora, Kakrapara, Hyderabad and Jaduguda, accompanied by the growth of nuclear power and fuel-reprocessing plants [57–63]. Numerous barrier methodology is monitored in solid waste handling in the next flow process are given below (eq. (3)):

$$\text{Source reduction} \rightarrow \text{Recycling} \rightarrow \text{Treatment} \rightarrow \text{Disposal.} \quad (3)$$

Flow process for management of waste reduction [57].

8. Conclusion and future directions

For the phytoremediation of radioactive waste, screening of the appropriate plant type is the utmost important. Diverse factors such as radioactive waste characteristics, the concentration of a target radionuclide in the radioactive waste, the biomass of the plant, the plant species and plants composition in the radioactive waste dumped area, the concentration of a target radionuclide in the plant, and should be examined thoroughly.

The PF concern the concentration of a goal element in a plant, the shoot biomass, and the concentration of the target element in the tailings or tailing (root) of the plant, was planned for the target element to specify the removal capability of the plant from the radioactive waste. Using the PF as the criteria, *P. australis*, *M. cordata*, and *Azolla imbricata* were selected as the contenders for phytoremediation of uranium-contaminated soil, *P. multifida* was particular as the aspirant for phytoremediation of ^{226}Ra -contaminated soil, and *P. australis* was designated as the contestant for phytoremediation of thorium-contaminated soil.

Further advances must be made in the application of environmental remediation to selectively eradicate materials, the concentrations of chemicals present in the contaminated water, have a higher resistance to changes in pH, greater stability for a longer period of time and cost effectiveness.

Sensors have been established for detecting gases, chemicals and volatile organic compounds (VOCs), and the detection and identification of radiations. Further growth is essential in the functional properties of nanomaterials to meet the requisite for trace detection and the treatment of pollutants in soil, water and air and important fundamental and mechanistic studies are required in order to fully explore their real potentials. The CNTs/metal oxide are promising constituents in ecological pollution management at a bigger prospective for practical applications.

Conflict of interest

The authors declare that there is no conflict of interests regarding the publication of this book chapter.

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