Journal of Life Sciences & Biomedicine, vol. 8(81), No 1, p. 68-82 (2026)

Plants and radioactivity

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Received: May 12, 2026; Received in revised form: June 12, 2026; Accepted: June 24, 2026

Plants are continuously exposed to different sources of radiation and can accumulate radioactive elements from the soil and air. This unique characteristic makes them valuable indicators of radioactive pollution. This can be indicated by the mechanisms via which plants interact with radioactive contaminants and the subsequent changes in their physiological, biochemical and genetic attributes. Various plant responses to radiation exposure, such as alterations in optical properties, cell structure and gene expression, can be measured and analyzed to provide insights into the extent and impact of radioactive pollution. This study presents an overview of role of plants as silent observers of radioactive pollution, highlighting their significance in environmental monitoring and the potential applications of plant-based technologies in the field of radiation assessment and remediation.

Keywords: *Biomonitoring, bioindicators, radioactivity, plants, phytoremediation-extraction*

INTRODUCTION

Plants are also subjected to numerous ecosystem pollutants and hence often appear to be worthy biological indicators (Ozturk et al., 1987, 2017, 2019, 2023; Zaghloul et al., 2020; Candan et al., 2023). As stationary organisms, plants encounter radionuclides that are discharged and dispersed in the environment through wet or dry deposition onto water or soil. The regular and accidental introduction of nuclear waste into ecosystem leads to the ingestion of radionuclides, and this process facilitates the travelling of such materials from soil to vegetation (Gupta and Walther, 2014). The effect of pollutants on plants can be noticed from morphological fluctuations, biochemical or cellular alterations and through overall impacts on plant growth, performance and intensity of population. External vegetative symptoms are considered the first biological indicator of pollution (Saber et al., 2015).

The radionuclides uptake by plants and their subsequent entry into the food chain is typically considered undesirable. Numerous plants have been recognized as potential accumulators of radioactive pollution (Singh et al., 2023). For instance, *Eleutherococcus sciadophylloides*, a deciduous tree native to Japan, is capable of accumulating significant concentrations of radioactive cesium (^{137}Cs) (Kiyono and Akama, 2013). Efficient and sometimes selective intake of specific substances by plants can be beneficial in the process of remediation for contaminated soils. This approach harnesses the natural potential of plants to take up and accumulate pollutants, aiding in the purification and restoration of contaminated environments which is called phytoremediation. Phytoremediation offers a long-term and worthwhile solution for the restoration of radioactivity-contaminated areas. Utilizing plants' natural ability to accumulate and remove pollutants provides an affordable method for the treatment of such areas. This approach holds promise in mitigating the effects of radioactivity and facilitating the recovery of contaminated environments over time (Gupta and

https://doi.org/10.59849/2710-4915.2026.1.68
Available online 30 June 2026

Walther, 2014). This study highlighted the significant role of plants as silent observers of radioactive pollution and their potential as valuable tools in understanding and combating this environmental challenge.

Radioactive contamination and plants

After the fallout or waste containing radioactive materials reaches the Earth's surface, it can come into direct contact with crops before reaching the soil. This direct contamination occurs when the radioactive material adheres to the surface of the crops. In such cases, the crops themselves can become contaminated with radioactive substances. Indirect contamination of plants by radioactive substances refers to the transfer of radioactive materials to plants through intermediary pathways, rather than through direct contact with the plant surfaces, like soil and water contamination, deposition, etc. (Alharbi and El-Taher, 2013). Plants come into contact with radionuclides that are discharged into the environment through wet or dry deposition processes onto the soil surface or water. When radionuclides are present in the air, they can be washed out by precipitation. Some of these radionuclides are retained by vegetation when deposited with rain, while the remaining portion falls through the canopy and reaches the ground. The retained activity is later transferred to soil through weathering processes, and it is only temporarily present on the vegetation surface. However, the fraction of radionuclides initially grabbed by vegetation is significant in radioecological models. Direct deposition can lead to relatively high levels of radioactivity in food items (Barnett et al., 2009). Dry deposition of radioactive waste refers to the phenomenon by which radioactive contaminants settle directly onto surfaces without the presence of precipitation or moisture. During dry deposition, the radioactive particles may adhere to surfaces, including soil, vegetation, buildings, or other objects exposed to the environment. The extent of dry deposition is dependent on factors like particle size, atmospheric conditions, wind patterns and the characteristics of the affected surfaces. Once deposited, the radioactive waste can pose a threat to environment and human health. It can contaminate soil, potentially affecting plant growth and agricultural productivity (Twining and Baxter, 2012).

Mechanism of radioactive uptake

The mechanism of radioactive uptake in plants involves several processes that allow the absorption and accumulation of radionuclides from the surrounding environment. The main pathway for radioactive uptake in plants is through the roots, although foliar uptake can also play a role under specific circumstances. Radionuclides found in the soil water are absorbed by plant roots via a process known as root uptake. This mechanism involves the following steps: absorption, membrane transport, xylem transport, and distribution. Radionuclides mixed in soil water get in touch with the root surface. They can be absorbed through the root hairs and root epidermal cells. Once radionuclides enter the root, they are transported across various cell membranes. This transport occurs via passive diffusion, facilitated diffusion or active transport, influenced by the characteristics of the radionuclide and the plant species involved. After entering the root cells, radionuclides move upward within the plant through the xylem vessels. This transport mechanism relies on the plant's water uptake and transpiration process. Radionuclides are distributed to different plant tissues, including leaves, stems and fruits, through the vascular system. The extent of distribution is dependent on factors such as the mobility of radionuclide within the plant and the physiological processes occurring in different plant parts. Under certain conditions, plants can also take up radionuclides through their aerial parts, particularly through the leaves. This process, known as foliar uptake, occurs when radionuclides in the form of contaminated water droplets settle on the leaf surfaces. The radionuclides can make their way into the plant through stomata or through direct absorption across the leaf cuticle. It is beneficial to note that the efficiency and extent of radioactive uptake by plants depend on various factors, including the physicochemical attributes of radionuclides (e.g., solubility, chemical form), soil attributes (e.g., pH, organic matter content), plant species and environmental conditions. Additionally, the subsequent translocation and accumulation of radionuclides within plant tissues can vary depending on their chemical behavior and interactions with cellular components. To get the insight of radioactive uptake mechanisms in plants is crucial to assess the potential risks associated with radioactive contamination and developing strategies for phytoremediation or minimizing the radionuclides transfer to food web (Barnett et al., 2009; Oforiwaa, 2021).

Hyperaccumulating plants

Hyperaccumulating plants are a specialized group of plant species that possess the potential to accumulate high levels of heavy metals or radioactive elements in their tissues without experiencing significant negative effects (Ozturk et al., 1987, 2024, 2025a, 2025b; Li et al., 2016; Ejaz et al., 2023; Gul et al., 2025; Rafique et al., 2025). Hyperaccumulating plants present a promising solution for addressing radioactive pollution. Researchers investigated the potential of algae and aquatic plants to eliminate radioactive isotopes, specifically Cesium, Strontium and Iodine, from a culture medium. A total of 188 strains, including aquatic plants, microalgae and unidentified algal species were examined, of which six strains showed a high capacity for accumulating radioactive Cesium, three strains for Strontium and eight strains for radioactive iodine from the medium. This suggests that these specific strains have the potential to effectively remove and accumulate radionuclides (Fukuda et al., 2014). To harness the natural power of certain plants to uptake and reduce soil radioactivity caused by specific radionuclides, the researchers tested thirty-two plant species in laboratory conditions to compare their capacity to uptake radioactive Rubidium, Cobalt, Strontium and Cesium. Among the tested species, broccoli and tomato demonstrated effectiveness in absorbing Cobalt, while tomato, chard, sunflower and cucumber were effective in absorbing Rubidium. Cucumber, sunflower and turnip showed proficiency in accumulating Strontium and tomato, chard and cucumber exhibited effectiveness in absorbing Cesium. These findings suggest that these plant species have potential applications in reducing soil radioactivity through their natural uptake abilities (Gouthu et al., 1997). Catharanthus roseus bioaccumulates ^{137}Cs and ^{90}Sr and can be a consummate hyperaccumulator with the power of radionuclide elimination from the environment (Anamika et al., 2009).

Responses of plant species growing in radioactive areas

After the Fukushima nuclear plant incident, researchers conducted a comprehensive analysis of the characteristics of radioactive substances in various environmental settings, particularly in agricultural farmland. Their findings revealed that the absorption of ^{137}Cs, a radioactive isotope, by crop plants from contaminated soil was minimal, as confirmed through laboratory experiments. The downward migration rate of ^{137}Cs in soil was evaluated to be approximately 1-2 mm per year. In trees, the intake of ^{137}Cs occurred through the bark rather than roots, as the roots' active part typically lies deep in the soil where no radioactive substances are present. The spread of ^{137}Cs in the bodies of trees varied across species. Radiographic analysis of a rice grain revealed the accumulation of ^{137}Cs in both the hull and cereal germ. In contrast, in soybean plants, around half of the radiocesium accumulation in the seeds occurred during pod formation, with approximately 42% of the total absorbed radiocesium accumulating in the seeds. Interestingly, the accumulation of radiocesium in soybean seeds tended to be higher compared to that in rice grains (Nakanishi et al., 2019). During the Fukushima Daiichi nuclear tragedy in 2011, contaminants resulting from venting and hydrogen explosions were carried northwestward and settled on soil and plants through precipitation. A study conducted in Fukushima Prefecture analyzed plant foliage and surface soils from 64 chosen sites. The highest levels of ^{137}Cs (82.0 kBq/ kg) and ^{134}Cs (84.4 kBq/kg) were found in soil taken from the surface at Nagadoro (Iidate village), situated 32 km from the power plant. Additionally, other radionuclides such as 129-Tellurium, 129m-Tellurium, 131Iodine, 140-Lanthanum and 110m-Silver, were anticipated in the same obtained samples. Leaves of plants, including cabbage, grasses and bamboo, showed high contamination on their outer surfaces in areas with high-dose rates like Tsushima and Minami-Tsushima. However, mugwort leaves that grew later to contamination event had low radionuclide concentrations, but the plant/soil ratio of radiocaesium was measured at 0.023 ± 0.006. The decomposition of fallen leaves is expected to contribute to the recycling of radionuclides in the ecosystem (Tazoe et al., 2012).

Accumulation of the Chernobyl radionuclides by plants and mushrooms depends upon particular climate, soil, season, level of radioactive contamination and specific populations and species, etc. The effects of irradiation from the Chernobyl disaster have resulted in the development of structural anomalies and tumor-like changes in numerous plant species. The Chernobyl zone exhibits distinctive pathological characteristics, including a notable occurrence of abnormal pollen grains and spores. The irradiation at Chernobyl has caused genetic disorders that can persist over extended periods (Yablokov et al., 2009). The results of a study demonstrated that plants from the Chernobyl area displayed reduced germination rates in regions with higher levels of contamination, even when cultivated in controlled and uncontaminated environments (Møller and Mousseau, 2017). In a study conducted in the Chernobyl area, researchers examined the impact of radiation on fruit trees, bushes, butterflies and bumblebees. The results revealed that in highly radioactive regions, fruit-bearing plants exhibited a decrease in fruit production, which was attributed to the decline in pollinating insects and the stunted growth of trees. This reduction in fruit production had repercussions on fruit-eating birds and hindered the dispersal of seeds. These findings demonstrate a direct correlation between radiation levels, the abundance of frugivores, the populations of pollinating insects and fruit production. The study highlighted the significant influence of chronic radiation on the intricate interactions between plant and animal species, disrupting their mutual relationships (Møller et al., 2012).

Plant-based monitoring and assessment of radioactive pollution: bioindicators of radioactive pollution

Plants have proven to be valuable bioindicators of radioactive pollution in various environments. As living organisms rooted in the ground, they are directly exposed to radiation present in the air, water, and soil. Their ability to respond and accumulate radioactive substances makes them effective indicators of the presence of radioactive contamination. In plants, the impacts of radiation can be observed through changes in morphology, biochemistry, physiology and biophysics. The extent of these changes is highly influenced by factors such as the dose of exposure, soil conditions, agricultural practices and other environmental variables (Ahuja et al., 2014). Prolonged subjection to ionizing radiation has been found to induce significant modifications in the genome and epigenome of plants. These alterations can lead to changes in the overall phenotype of the affected plants. Radiation can cause various types of genetic damage, such as DNA breaks, point mutations or chromosomal rearrangements. These genetic changes can disrupt the normal functioning of genes and regulatory elements, leading to modifications in the plant's genetic information. In addition to genetic changes, ionizing radiation can also influence the plant's epigenome inducing epigenetic alterations, such as histones alterations or DNA methylation, which can influence gene activity and regulation. These epigenetic modifications can have long-lasting influence on gene expression patterns and subsequently influence the plant's phenotype. The altered genome and epigenome of plants exposed to ionizing radiation can result in phenotypic changes, including modifications in growth patterns, development, physiology or even survival. These changes can manifest as morphological variations, altered metabolic processes or changes in reproductive traits (Lancíková and Žiarovská, 2020).

A study was conducted to evaluate the impact of Assiut Thermal Power Plant (ATPP) ashes on crops, namely squash and potato. The investigation focused on both morphological and molecular changes in these plants. The findings revealed significant alterations in the morphological attributes of squash and potato, resulting in a notable decline in various growth and yield characters. The extent of these changes was proportional to the concentration of radioactive ash present in the soil. Furthermore, molecular analysis using Inter Simple Sequence

Repeats (ISSR) and Start Codon Targeted (SCoT) markers provided insights into the observed morphological abnormalities. The ISSR/SCoT bands showed the toxic and mutagenic nature of radioactive ash, affecting squash and potato crops. These results elucidate the genetic and morphometric abnormalities present in these important food crops for humans. Consequently, the increasing pollution, particularly the radioactivity directly impacting vegetation or indirectly affecting the soil, poses a potential threat to the green areas surrounding ATPP, potentially leading to their disappearance in the future (Negm et al., 2020). A field study on the biological impacts observed in plant populations residing in radioactively polluted areas with varying compositions and levels of radionuclides indicated that populations of plants exposed to radiation exhibit increased frequencies of gene and chromosome mutations, along with reduced reproductive potential compared to reference populations. Even at relatively low levels of technogenic impact, genetic diversity is enhanced and regular patterns observed in unaffected populations are disrupted. Chronic exposure to radiation acts as an ecological factor that alters the genetic makeup of wild plant populations. The data suggest the presence of adaptation processes within plant populations inhabiting technogenically impacted territories, where selection mechanisms work to improve resistance. However, the occurrence and rate of these processes can significantly differ depending on the specific radioecological conditions present (Geras'kin et al., 2010). *Oxalis corniculata* demonstrated a probable reaction to radioactive pollution in Fukushima by modulating the expression of specific metabolites, both upregulating and downregulating their levels (Sakauchi et al., 2022).

Biomonitoring techniques

Nuclear radiation can have discernible effects on the optical properties and mechanical structure of plants that can be detected and measured at a macroscopic level. This observation has led to the concept of using plants as indicators of past nuclear activities in each area. This approach involves a two-tiered methodology: Initially, a rapid survey can be conducted using simple measurements such as optical absorption or fluorescence, electrical response and mechanical strength. These measurements can help to reveal potential records of nuclear activities in the area. Once potential nuclear activity records are identified, a more detailed investigation can be conducted using molecular biology techniques. This step aims at the verification of both short and long-term nuclear activity with a low false alarm rate. Optical spectroscopic methods can be utilized to monitor the physical condition and overall health of vegetation. Numerous optical techniques can be employed to distinguish plants based on their particular spectral signatures. By measuring the absorption of light at different wavelengths, information about the pigments and chemical composition of the plant can be obtained. This can give insights into the effect of nuclear radiation on the plant's photosynthetic apparatus. Reflectance spectra capture the amount of light reflected by plant surfaces at various wavelengths. Changes in reflectance can indicate alterations in leaf structure, pigmentation or chlorophyll content, which may be linked to nuclear activity. Fluorescence spectroscopy measures the emission of light by plants after absorbing light energy. It can reveal changes in photosynthetic efficiency and stress responses caused by nuclear radiation exposure. Photoacoustic spectroscopy involves measuring acoustic waves generated by the absorption of modulated light. This technique can provide information about the plant's composition, including its pigments, photosynthetic activity and structural changes induced by nuclear radiation. By employing these optical methods, researchers can gather valuable data about the optical properties and physiological status of plants, allowing them to detect and monitor the effects of nuclear radiation on plant ecosystems (Audrey et al., 2012; Iriel et al., 2015; Jessen et al., 2013; Védrine et al., 2003). Plant bioassay is a highly reliable and efficient method for biomonitoring of genotoxicity of industrial contaminants. It allows us to detect various endpoints such as genotoxicity, mutagenicity and cytotoxicity using plants like *Tradescantia spp., Allium cepa* and *Vicia faba*. Living organisms provide a range of methods to assess the concentration and variability of toxicity resulting from pollutants.

Numerous studies have demonstrated the cytotoxic, genotoxic and mutagenic nature of industrial effluents and wastes, which can pose a negative impact on the environment. Compared to chemical tests, biological methods offer greater accuracy and reliability in monitoring the toxicity of natural resources. Plant-based systems for genotoxicity assessment are safe and have no sophisticated instrument demands, making them a sustainable monitoring solution for the emerging problem of environmental contamination (Bhat et al., 2019).

Plants for monitoring radioactive pollution

Natural electrophysiological and chemical reactions of plants can be used to develop innovative plant-based sensor networks. A study was conducted using various plant species, including Arabidopsis, Cactus, Dwarf mango (pine), Azela and Euymus, which demonstrated that Chlorophyll-a (F680) to Chlorophyll-b (F735) ratio in these plants can be modified based on the radiation dose. Furthermore, it was observed that the process of recovery and speed vary among different plant species (Islam et al., 2018). The effects of ionizing radiation on DNA result in double-strand breakage, which can be set right through illegitimate or homologous recombination. To assess genetic changes in populations of plants caused by nuclear contamination near Chernobyl, *Arabidopsis thaliana* plants with a β-glucuronidase marker gene were utilized as a recombination substrate. The study revealed a significant rise in somatic intrachromosomal recombination frequencies within a range of nuclear contamination concentration from 0.1–900 Ci/km2, indicating a hike in chromosomal aberrations. This plant-based bioindicator offers an easy and ethically accepted alternative to animal-based systems (Kovalchuk et al., 1998). Radioactive monitoring of water residing plants was done in the Yenisei River, Russia, before and after the shutdown of the MCC reactor. Six aquatic plant species were studied over several years and were seen to have a significant number of artificial radionuclides in their biomass prior to the shutdown of the reactor. However, 2 and 5 years after the shutdown, the number of detected radionuclides decreased to 3-5 and 11, respectively. The high radionuclide levels were found in *Fontinalis antipyretica*. A common aquatic plant, *Elodea canadensis* found in the Yenisei River, was used in a cytogenetic study. Cells from *Elodea canadensis* roots in the Yenisei region influenced by the radioactive discharge showed high chromosomal aberration frequency (up to 33%). In comparison, cells from plant roots in reference areas had a chromosomal aberration frequency of 5-7%. The increased frequency of chromosomal aberrations in *Elodea canadensis* from areas with higher concentrations of artificial radionuclides can be attributed to exposure to radiation. This plant can be recommended as a bioindicator for assessing radioactive contamination in aquatic ecosystems (Bolsunovsky et al., 2020). A study examined the effects of low doses of ionizing radiation on biological samples near radioactive waste deposits for environmental monitoring. *Tradescantia pallida* was selected for the study and micronucleus tests were performed to assess dose/response sensitivity in biomonitoring. The plants were exposed for 24 hours at specific locations near nuclear waste deposits in Brazil with three monitoring points at each location. The results revealed a slight elevation in micronucleus frequency per cell in the biosensor, indicating mutational effects from low-dose radiation. These findings facilitated the development of a scale to show the mutagenic effects of low-dose radiation. *T. pallida* demonstrates its value as a useful tool for environmental biomonitoring in tropical climates, providing insights into the impacts of ionizing radiation on the environment (Cristina dos Santos Leal et al., 2008).

In a study, the transfer of naturally present radionuclides, including ^{232}Th, ^{238}U, and ^{40}K as well as the fallout radionuclide ^{210}Po, to various wild plants in the Western Ghats rainforest was examined. The investigation focused on a range of physiologically diverse plants found in both the top story and understory, encompassing epiphytes and shrubs. The number of radionuclides in both soil and plants was measured utilizing a combination of gamma ray spectrometry and alpha counting techniques. The results revealed significant variations in radionuclide concentrations within the same plants and among different species. Additionally, the ratios of soil-plant varied between species, with epiphytic plants and *Elaeocarpus* *oblongus* demonstrating a preference for radionuclide uptake. Furthermore, the study identified that dust particles in the root systems of epiphytes could serve as bioindicators for assessing the presence of radionuclides in the Western Ghats region (Manigandan and Shekar, 2014).

Plants serve as reliable bioindicators of radioactive pollution due to their sensitivity and responsiveness to radiation exposure. Their visible changes, biochemical responses and ability to accumulate radioactive elements make them valuable tools in assessing the presence, extent, and impacts of radioactive contamination in the environment. Consequently, studying the responses of plants to radioactive contamination contributes to effective monitoring, management and remediation strategies. Transgenic plants have been employed as a method to monitor radiation hazards caused by the Chernobyl accident in areas of Ukraine. In this study, *Nicotiana tabacum* and *Arabidopsis thaliana* plants were genetically modified to contain a reporter gene that detects homologous recombination, a process involved in DNA repair. These transgenic plants were used to investigate the genetic impacts of low-dose radiation present in the soil of affected areas in Ukraine, where pollution levels from the accident range from 1 to 40 Ci/km^2. The study revealed a vital and dose-dependent hike in homologous recombination in cultivated plant species in the affected areas. This finding demonstrates the persistent and elevated genotoxicity of soils contaminated with radioactivity and the use of transgenic plants with the reporter gene allowed for the detection and quantification of genetic damage caused by radiation exposure in these areas. By utilizing transgenic plants as bioindicators, researchers can assess the long-term genetic effects of radiation in the environment. This information is crucial for understanding the effects of the Chernobyl incident on the genetic integrity of plant populations and the potential risks posed to human health in these inhabited areas (Kovalchuk et al., 1999).

The suitability of tobacco plants for biomonitoring radioactive wastes, specifically Po-210 and Pb-210, was investigated. Tobacco plants and soil from a remediated uranium mine in Hungary were analyzed for their isotopic concentration. The results showed a correlation between the isotope content in tobacco plants's lower leaves and the soil, indicating a potential for tracing low-level washing out. The activity level of Po-210 in tobacco and soil samples from the investigated area did not show significant radionuclide migration compared to samples from another part of Hungary. This research highlights the potential use of tobacco plants as bio-monitors in assessing and monitoring radiological wastes, particularly in mining environments (Máté et al., 2013). Wild plant species can serve as effective bio-indicators for monitoring radioactive contamination in areas surrounding the Jaslovské Bohunice nuclear power plant in the Slovak Republic. The use of wild plants in bio-indication studies allows assessment of radiation levels and the distribution of radioactive elements in the ecosystem. In studies conducted in this region, different plants have been investigated for their potential to accumulate and reflect the presence of radioactive isotopes. By analyzing the concentration of radionuclides in plant tissues, researchers can estimate the extent of contamination and assess the potential risks to ecosystems and human health. Wild plants found in the locality of the nuclear power plant can provide valuable information about the radioactive elements' dispersion. These plants accumulate radionuclides from the soil via their roots and transport them to various organs, including leaves and stems. By analyzing the radionuclide content in different plant tissues, scientists can determine the degree of contamination and identify hotspots within the contaminated sites. Furthermore, certain plant species have a high affinity for specific radionuclides, making them excellent indicators of the presence of certain radioactive elements. The plant species choice for bioindication studies is dependent on their ecological characteristics, such as their growth habits, root system and ability to accumulate radionuclides. By studying the wild plants in the surrounding area of the Jaslovské Bohunice nuclear power plant, researchers can gain insights into the distribution and behavior of radioactive wastes in the environment. This information is vital for assessing the environmental impact of the power plant, implementing appropriate mitigation measures and ensuring the safety of surrounding ecosystems and human populations (Mičieta and Murín, 2007).

Plant-based solution to radioactive pollution-phytoremediation

For the past 60 years, there has been a large-scale pollution of radioactive waste due to global nuclear activity. It is mandatory to pay attention to radioactivity management to get a contamination-free environment. A wide range of chemical, biological and physical strategies are available to manage radioactive waste. Bioremediation is displayed as a powerful tool for radioactive waste treatment. Recent advancements have been made in radioactive waste treatment via microbial transformation and phytoremediation (Natarajan et al., 2020). The term "phytoremediation" encompasses a range of remediation approaches that utilize plants to completely wash or partially clean the polluted sites, thereby reducing the presence of toxic substances and minimizing associated hazards. Phytoremediation is also referred to by alternative names such as botano-remediation, green remediation, vegetative remediation and agro-remediation. Plants possess a remarkable ability to absorb contaminants from the environment through their root systems, which gives a larger surface area to interact. They can efficiently mobilize and detoxify contaminants using various mechanisms, including elimination, containment, and degradation. These unique characteristics of plants have been successfully utilized in the removal of radioactive waste (De Filippis, 2015). In the phytoremediation field, plants employ various mechanisms to absorb and eliminate plenty of pollutants, including organic and inorganic contaminants as well as radionuclides. These mechanisms include phytostabilization, phytoextraction, phytodegradation, rhizofiltration and phytovolatilization. Phytoextraction involves the use of plants with high biomass that can accumulate radionuclides from the soil. To enhance this process, appropriate soil amendments are often used. The radionuclides are transported and concentrated in aerial parts of plants, which can then be cut off using conventional agricultural methods. Rhizofiltration utilizes the roots of plants to concentrate and precipitate radionuclides from polluted effluents. The plant roots act as filters, extracting and retaining the radionuclides from the contaminated water or other liquid media. Phytovolatilization occurs when volatile radionuclides are extracted by plants from the soil and released into the atmosphere through the foliage. This process helps in removing the radionuclides from the contaminated soil. Phytostabilization is a mechanism in which radionuclides in the soil are stabilized by plants, preventing their migration. The plants' roots and associated microorganisms play a significant role in immobilizing the radionuclides, reducing their bioavailability and potential risks (Cheema, 2023; Dushenkov, 2003).

It is foreseen that the utilization of phytoremediation techniques for managing radioactive pollution will become an integral component of ecosystem management practices, contributing to the reduction of risks associated with radioactive waste. Various plants are used to clean radionuclides, of which some examples are shown in Table 1.

Phytoremediation of radioactive contaminants

Various plants have shown potential for radioactive materials remediation in contaminated areas. The epiphytic plant *Tillandsia brachycaulos* demonstrated effective reduction of airborne Radon (Rn) through its leaves. When *Tillandsia* plants were used in the Rn chamber, the concentrations of Rn decreased more significantly compared to natural conditions. This reduction can be attributed to foliar trichomes that cover the leaves of *Tillandsia*. These trichomes enhance Rn progeny particles deposition due to the increased rough surface area of leaves. Additionally, the powdery epicuticular layer of wax on the foliar trichomes facilitates the uptake of liposoluble Rn. These findings present a novel ecological way for controlling Rn pollution, suggesting that movable *epiphytic Tillandsia* plants can be employed in Rn removal systems (Li et al., 2018). A study was carried out to demonstrate the potential of *Ludwigia stolonifera* as an effective local aquatic plant to Phyto remediate hazardous radioactive substances in aqueous waste. *Ludwigia stolonifera* was exposed to single and binary solutions containing two radioactive elements (^{137}Cs and ^{60}Co).

Table 1. Mechanisms of phytoremediation of various radionuclides.

Radionuclides	Plants	Mechanism of remediation	References
99Tc	*Mixed grass species, Deciduous Forest, Lolium, Triticum*	Phytoextraction	Echevarria et al., 1997
222Rn, 226Ra	*Festuca, Helianthus, Zea mays*		Lewis and MacDonell, 1990
90Sr	*Pinus radiata, Vitis, ponderosa pine, Sorghum, Agrostis, Panicum, Salix, Calotropis, Chromolaena, Vetiveria, Cannabis*		Entry et al., 1993; Veresoglou et al., 1996
90Co	*Sorghum, Melilotus, Trifolium*		Rogers and Williams, 1986
238,235U	*Amaranthus, Helianthus, Brassica, Phaseolus, Beta, Pisum*		Ebbs et al., 1998; Huang et al., 1998; Salt et al., 1997
210Po	*Nicotiana tabaccum*		Kovács et al., 2004
137Cs	*Brassica, Calotropis, Spinacia, Lactuca, Raphanus, Salix, Pisum, Soya, Avena mycorrhizal association*		Chou et al., 2005; Dutton and Humphreys, 2005; Eapen et al., 2006; Goncharova, 2009; Singh et al., 2008
90Sr	*Helianthus, Catharanthus, Eichhornia, Brassica*	Rhizofiltration	Salt et al., 1997; Singh et al., 2009
238,235U	*Brassica, Eichhornia, Chenopodium*		Dushenkov et al., 1997a; Eapen et al., 2003
137Cs	*Eichhornia, Catharanthus, Helianthus*		Prasad and De Oliveira Freitas, 2003; Salt et al., 1997
239,240Pu	*Soya bean*		Cataldo et al., 1988

The researchers investigated the specific rate of uptake of the plant under varying conditions, including different contents of activity of radionuclides, exposure to lightning, masses of the plant and pH levels. The results indicated that ^{137}Cs and ^{60}Co accumulation in the plant was higher than 65% and 95%, when exposed to the binary mixture. This suggests that *Ludwigia stolonifera* is highly efficient in removing these radioactive elements from the aqueous environment (Saleh et al., 2017).

Initial experiments in laboratory and treatability studies demonstrated the effective use of land plant roots for uranium (U) removal from water through rhizofiltration. Specifically, sunflower plants exhibited a strong liking for U and were chosen for treating polluted water. Most of the U removed during laboratory experiments was concentrated in the roots, with bioaccumulation coefficients up to 30,000 based on the U levels in roots compared to the aqueous phase. Field testing of rhizofiltration technology was conducted at a former U processing facility in Ashtabula, OH, using U-contaminated water. The pilot-scale rhizofiltration system successfully treated the source water, reducing U concentrations to below 20 µg/L, meeting the water quality standards according to the EPA Water Quality Standard, before releasing into the environment (Dushenkov et al., 1997b).

Phytoremediation is a promising approach to treat radioactive wastes containing radionuclides, including 60Co and ^{137}Cs. This study focuses on the use of the water hyacinth plant as a potential tool for the phytoremediation of radioactive contaminated streams. Water hyacinth has shown the ability to bioaccumulate radionuclides from these waste streams. The research investigates various factors that influence the bioaccumulation of ^{137}Cs and ^{60}Co using floating plants. These factors may include environmental conditions, plant physiology and waste characteristics. Understanding these factors is crucial for optimizing the phytoremediation process and enhancing the efficiency of radionuclide removal. The findings of this study add up to the knowledge and potential application of phytoremediation in the treatment of radioactive wastes (Saleh, 2012). Based on the phytoremediation factor as the criterion, *Azolla imbricata, M. cordata* and *P. australis* were chosen as suitable candidates for phytoremediation of uranium-contaminated soil. *P. multifida* was specifically identified as a potential candidate to Phyto remediate ^{226}Ra-contaminated soil. *P. australis* was selected as the candidate for phytoremediation of thorium-polluted soil (Deepak and Pradeep, 2019). These and plenty of other studies suggest that various plant species can be vital to monitor and remediate radioactive contamination from the environment without posing any serious threat to any component of the environment.

Advantages and limitations

While plants have shown promise as biosensors of radioactive pollution, there are several limitations to their use in this capacity. Plants may have varying sensitivity and selectivity towards different radionuclides, making it challenging to detect and quantify specific radioactive contaminants accurately. Plant responses to radioactive pollution can be affected by environmental factors like soil composition, temperature, humidity and sunlight. These factors can introduce variability and make it difficult to establish consistent and reliable correlations between plant responses and radioactive pollution levels. Plants are exposed to a wide range of contaminants other than radioactive substances. The other pollutants can potentially interfere with plant responses and complicate the interpretation of results related to radioactive pollution. Monitoring and analyzing plant responses to radioactive pollution require dedicated resources, including time, expertise, and equipment. Conducting large-scale and long-term monitoring using plants as biosensors can be time-consuming and expensive. There is a need for standardized protocols and validation methods to ensure the accuracy, reproducibility, and comparability of results obtained from different plant-based biosensing studies. Lack of standardized approaches can hinder the wider adoption and integration of plant biosensors into environmental monitoring programs. Extensive research has been conducted on phytoremediation, particularly in small-scale operations, but the application of this technique on a large scale is currently restricted due to technological constraints, insufficiency of comprehensive knowledge and limited success. Phytoremediation has not yet been implemented commercially or industrially for the decontamination of radioactive sites (De Filippis, 2015).

Future directions

There are several key possibilities that can further enhance the role of plants in monitoring radioactive pollution. Research can focus on identifying plant species that exhibit high sensitivity and specificity to specific radionuclides. By studying the response of these plants to radioactive contamination, we can develop reliable bioindicators and biomonitoring systems. This can involve monitoring changes in plant physiology, gene expression, or biochemical markers in response to radiation exposure. Transcriptomic and proteomic studies can provide a comprehensive understanding of the molecular mechanisms underlying plant responses to radioactive pollution. Analyzing changes in gene expression and protein profiles can identify key pathways and biomarkers associated with radiation stress. This information can be used to develop molecular tools for assessing radiation exposure in plants. Investigating the interactions of microorganisms and plants in radioactive environments can provide insights into the mechanisms of plant adaptation and responses to radiation stress. Understanding the function of beneficial microbial communities in facilitating plant nourishment and tolerance to radioactivity can contribute to the development of microbial-assisted phytoremediation strategies. Genetic engineering approaches can be employed to improve the plants' ability to tolerate and remediate radioactive contamination. By introducing genes associated with metal uptake, detoxification or DNA repair, plants can be engineered to better cope with radiation stress and accumulate radionuclides more efficiently for phytoremediation purposes. Advancements in remote sensing and imaging technologies can enable non-invasive and large-scale monitoring of radioactive pollution using plants as indicators. Techniques such as hyperspectral imaging and fluorescence imaging can be utilized to detect changes in plant health and spectral signatures associated with radiation stress. Evaluating the ecological risks associated with radioactive pollution and the long-term impacts on plant communities is crucial. Assessing the effects of radiation on plant population dynamics, biodiversity, and ecosystem functions can help inform decision-making and remediation strategies. Long-term monitoring research is needed to track the persistence and fate of radioactive contaminants in plant systems over extended periods. This can provide valuable data on the effectiveness of phytoremediation approaches, the potential for contaminant transfer through the food chain, and the long-term ecological impacts of radioactivity on plant ecosystems. By focusing on these future perspectives and research directions, we can harness the capabilities of plants as silent observers of radioactive pollution. As we deepen our knowledge of the different biological mechanisms involved in phytoremediation, we can continually improve and optimize the technology. Further research and knowledge expansion in this field can lead to better outcomes and increased success in using phytoremediation for environmental cleanup.

CONCLUSIONS

It is evident that plants exhibit physical, biochemical, and physiological responses to radiation exposure, making them reliable indicators of radioactive contamination. The use of bioindicators and sentinel plants, along with techniques for measuring radionuclide concentrations, offers an effective means of monitoring radioactive pollution. However, further research in this field is crucial. There is a dire need to explore the long-term impacts of radiation on plant populations, understand the genetic and molecular reactions of plants to radioactive contamination and assess the potential of different plants for the phytoremediation process. In conclusion, plants are capable of contributing significantly to a sustainable and healthier environment in the context of radioactive pollution. By harnessing the power of plants as silent observers, we can gain valuable insights and develop strategies for monitoring, mitigating and remediating radioactive pollution in our ecosystems.

DECLARATIONS

Author Contributions

Munir Ozturk: Conceptualization, study design, literature review, supervision, manuscript preparation, and final approval of the manuscript.

Alvina Gul: Literature review, data collection, drafting of the manuscript, and reference management.

Volkan Altay: Data interpretation, critical revision of the manuscript, and scientific validation.

Tuba Arjumend: Literature review, manuscript editing, and contribution to the discussion and conclusions.

Iqra Siddique: Data organization, manuscript formatting, reference checking, and proofreading.

All authors have read and approved the final version of the manuscript.

Funding

The authors received no specific funding for this research.

Data Availability Statement

No new datasets were generated or analyzed during the current study. All information used in this article was obtained from published scientific literature and publicly available sources.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgments

The authors express their gratitude to their respective institutions for providing academic support and access to scientific resources that facilitated the completion of this study.

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Computer design:	*Ravana Ilmangizi*
Artistic design:	*Shalale Mammad*

Paper size 60x84 $^{1}/_{8}$
Volume 10,5
Circulation

Printing in "Elm" EPPC *(Istiglaliyyat str. 28)*