



Advances in the management of radioactive wastes and radionuclide contamination in environmental compartments: a review

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Abstract Several anthropogenic activities produce radioactive materials into the environment. According to reports, exposure to high concentrations of radioactive elements such as potassium (^{40}K), uranium (^{238}U and ^{235}U), and thorium (^{232}Th) poses serious health concerns. The scarcity of reviews addressing the occurrence/sources, distribution, and remedial solutions of radioactive contamination in the ecosystems has fueled data collection for this bibliometric survey. In rivers and potable water, reports show that several parts of Europe and Asia have recorded radionuclide concentrations much higher than the permissible level of 1 Bq/L. According to various

investigations, activity concentrations of gamma-emitting radioactive elements discovered in soils are higher than the global average crustal values, especially around mining activities. Adsorption technique is the most prevalent remedial method for decontaminating radiochemically polluted sites. However, there is a need to investigate integrated approaches/combination techniques. Although complete radionuclide decontamination utilizing the various technologies is feasible, future research should focus on cost-effectiveness, waste minimization, sustainability, and rapid radionuclide decontamination. Radioactive materials can be harnessed as fuel for nuclear power generation

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to meet worldwide energy demand. However, proper infrastructure must be put in place to prevent catastrophic disasters.

Keywords Environment

Nuclear power · Radioactive waste · Radionuclides · Remediation

Introduction

Radioactive wastes are generated from nuclear reactions, nuclear power generation, mining activities, and nuclear by-products from medicine and scientific research (Adebisi et al., 2021; IAEA, 2019; Noor et al., 2020). There is a massive surge in the production capacity of industries around the globe; improvements from 1.2 billion tons to 2.3 billion tons between the years 2000 and 2017 have been reported (Sanganyado, 2021). With the increase in world population and exponential growth in the number of industries, there is a growing demand for power to drive industrialization, and nuclear energy has been explored as an alternative (IAEA, 2022a; Rypkema, 2018; Uhumamure et al., 2021).

Radioactive waste can be defined as substances that are made or polluted with radionuclides/radioisotopes at concentrations or activities higher than established permissible levels by regulatory authorities (UNSCEAR, 2008; WHO, 2016). The higher the radionuclide activity concentration, the greater the risk posed by radioactive waste to humans and the environment. Human acute/chronic radiation exposure may lead to cell damage, skin burns, cancer, respiratory diseases, and death (L'Annunziata, 2016; WHO, 2016). Radon inhalation has been associated with lung cancer, which can also be caused by smoking (Ilori & Chetty, 2020). At various biological scales, harmful effects of radiation exposure on wildlife have been documented (Kesäniemi et al., 2019). These include biodiversity loss, decreased sperm motility and reproductive problems in animals and humans, cellular damage from DNA distortion, chromosomal abnormalities, oxidative stress and mutation, and fatalities of both humans and animals (Sia et al., 2020). Due to these adverse effects, the

management of radioactive wastes became vital for health and environmental safety.

Due to scientific advancements, most nuclear/radioactive wastes emanate from nuclear power plants used for energy production and ammunition manufacturing operations, while the contribution of naturally occurring radioactive materials cannot be ruled out (Adebisi et al., 2021; IAEA, 2019; Khan et al., 2019). In terms of the volume of radioactive waste in existence, 95% is very low-level or low-level radioactivity, 4% has intermediate-level radioactivity, and high-level waste is less than 1% (IAEA, 2022b). Improper handling of radioactive wastes/radiochemicals and accidental release of technologically enhanced naturally occurring radioactive materials (TENORMs) have resulted in environmental pollution/contamination. Radioactive contamination and high activity have been reported in different environmental compartments such as water, soil, and atmosphere, and this has raised enormous public health concerns (Adeola et al., 2021a; Akingboye et al., 2021, 2022; Momoh et al., 2020). The public health impact of improper radioactive waste management is experienced in both developed and developing countries (Adebisi et al., 2021; Jasaitis et al., 2020; Kumar et al., 2022).

Furthermore, there is a need for global safety awareness on the handling and disposal of hazardous radioactive materials, and the need to establish better radioactive waste management programs. The occurrence and ecotoxicology of radioactive elements in the terrestrial and aquatic environments have been the subject of recent scientific research (Adebisi et al., 2021; Ajibola et al., 2021; Akingboye et al., 2022; Bodunrin et al., 2021; Jasaitis et al., 2020; Kang et al., 2020; Tochaikul et al., 2022; van Hullebusch et al., 2005). However, extensive literature revealed that there is a paucity of systematic reviews focused on environmental occurrence, remediation toward ensuring environmental protection, public health safety, and sustainable power generation.

Therefore, the article comprehensively reports the environmental occurrence of radionuclide contamination (NORMs & TENORMs), sources, classes, and handling specification of radioactive waste; remediation technologies for radionuclide decontamination, and highlights challenges and prospects in the management of radionuclide pollution.

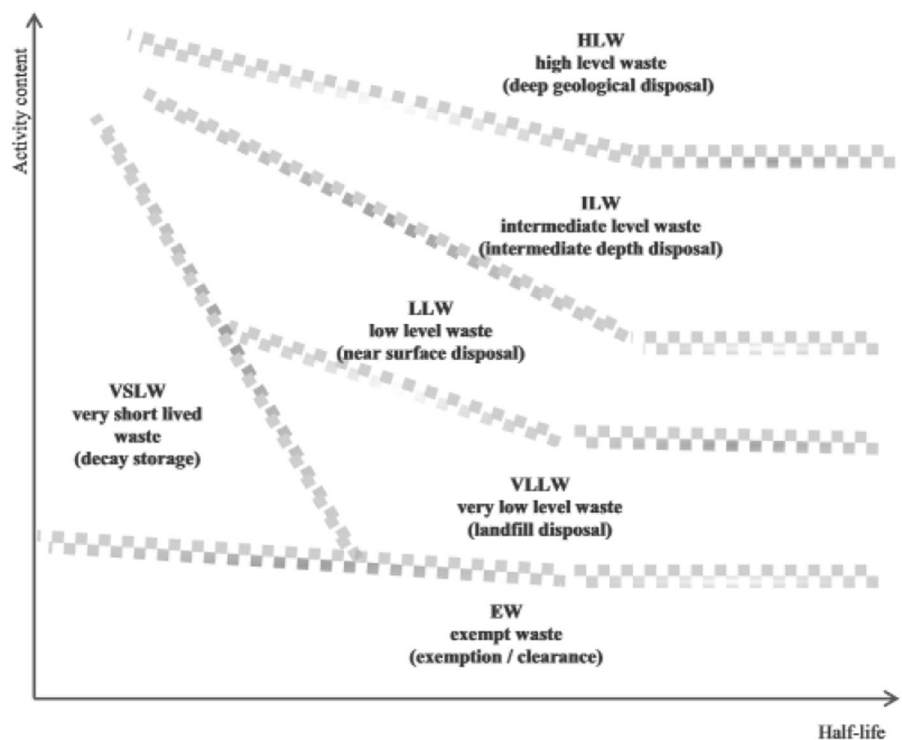
Classification of radioactive waste and sources of radionuclide contamination

Radioactive has been classified based on the decay time (half-live) and level of radioactivity. These attributes majorly determine the best form of treatment, storage, and/or disposal (Petrangeli, 2020). Radioactive waste has been classified into three broad categories, high-level, intermediate, and low-level; however, the International Atomic Energy Agency reported a broader classification (Fig. 1). These classifications are based on the amount of activity/radionuclide concentrations exhibited per volume of radioactive waste. Long-term containment for many years is a precautionary approach to handling radioactive wastes, as they cannot be neutralized like other hazardous waste (IAEA, 2022a; Rosenfeld & Feng, 2011). Due to the long decay time of radioactive wastes, they are stored to prevent radiation exposure to humans. High-level radioactive wastes are stored for a longer period (> 50 years), than low-level radioactive wastes before being disposed (Tochaikul et al., 2022; WNA, 2020).

Radioactive materials have found various applications such as in medicine (for diagnosis

and radiotherapy of health problems, i.e., hyperthyroidism, tumor, cancer, etc.), agriculture (radiological enhancement of crop yields), nuclear power production (for making nuclear reactors, fuels, and power plants), nuclear weapons, archaeology (carbon dating and estimating the age ancient materials), radio-sensors development, and other applications (Chao et al., 2018; Jeon, 2019; Pucci et al., 2019; Rosenfeld & Feng, 2011). The utilization of radionuclides for diagnostic and therapeutic purposes has improved the quality of life, especially with regard to the detection and treatment of tumors and cancerous growth. However, patient urine and excrement or hospital liquid waste discharge might release these radionuclides into the soil, surface waters, or wastewater collecting systems. Additionally, many nations have approved laws allowing hospitals to discharge their liquid waste directly into the central wastewater collecting system, opening more pathways to radiation or accidental radionuclide hazards (Hossain, 2020). The collection system for these radionuclides could deteriorate, causing leaks that would release radioactive materials into the soil, the atmosphere, or sources of drinkable

Fig. 1 International Atomic Energy Agency classification of radioactive waste (https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1419_web.pdf)



water from other point or non-point sources of radionuclides.

The annual background radiation dose people are exposed to is primarily caused by NORMs and is frequently within permissible levels. Accidental radionuclide releases and the by-products of their decay caused by mining operations, nuclear explosions, and natural disasters often have an acute effect, such as death from exposure to high radiation doses in a short amount of time. Several fatal accidents and radiation incidents have occurred around the World, notably the Three Mile Island accident (1979), the Chernobyl disaster (1986), and Fukushima Daiichi nuclear disaster (2011) (Hossain, 2020). Therefore, strict and effective treatment methods are sacrosanct to prevent the accidental release of radionuclides/radioisotopes in the environment from those plants. Groundwater around the Chernobyl NPP (ChNNP) Sarcophagus was severely polluted after the Chernobyl accident by ^{137}Cs (highest concentration was 50 MBq/L), ^{134}Cs , ^{131}I , ^{90}Sr , ^{239}Pu , ^{240}Pu , ^{106}Ru , and ^{241}Am . ^{137}Cs , ^{90}Sr , ^{239}Pu , and ^{240}Pu had maximum groundwater concentrations of 200, 3800, 7, and 7 Bq/L, respectively, as of 2001. Radioisotope fallout, discharge of highly contaminated wastewater, damage to the Sarcophagus, and cooling pond of ChNNP were the leading causes of radionuclide pollution (Bugai, 2014). However, the extent of geo-distribution and the fate of the radionuclides in that area are still relatively unknown.

Coal contains uranium, thorium, potassium-40, and the by-products of their decay (WNA, 2020). Depending on the geochemical nature of the source of the coal, the total concentrations of radionuclides usually are not high. They are generally comparable to those found in rocks close to coal. Higher sulfur content and other heavy metals are frequently linked to increased radioactive concentration in coal (Font et al., 1993). Up to 4 ppm of uranium is present in coal from the USA, Australia, India, and the UK; up to 13 ppm is present in coal from Germany; and up to 20 ppm is present in coal from Brazil and China (WNA, 2020). Therefore, coal processing and combustion may lead to the release of airborne radionuclides, which are bound to particulate matter and soot, as well as radionuclide residues that may contaminate the soil. Similarly, nuclear waste from power plant operation, decommissioning, and spent fuel storage may contribute to the environmental

burden of radioactive contamination (Uhunamure et al., 2021).

Mining practices include both open-pit and underground operations, with on-site ore processing. The ore is treated using crushing, grinding, acid treatment, and finally, sodium hydroxide is used to precipitate the radionuclide (Ramadan et al., 2022). A significant amount of slurry waste, debris, and residue from mine tailings are generated and, if not handled properly, may result in radionuclide contamination of the environment. Aborisade et al. (2018) reported the activity concentration of ^{40}K , ^{238}U , and ^{232}Th in samples collected from eight mining sites in Nigeria. Results showed that for all the sampling locations, ^{40}K ranged from <15.44 to 13,035.99 Bq/kg, ^{238}U ranged from <8.09 to 26.77 Bq/kg, and ^{232}Th ranged from <3.09 to 17.32 Bq/kg, respectively. Furthermore, radionuclides may not be mobilized from the geological formations that contain them (Brown, 2014). However, during the extraction of oil and gas, ^{224}Ra , ^{226}Ra , ^{228}Ra , and ^{210}Pb are mobilized and primarily found in the wastewater that is also generated. Significant radionuclides are released during hydraulic fracturing for the production of gas in some geological conditions both in drill cuttings and water (Ouyang et al., 2019).

Following the Fukushima accident, approximately 18,000 teraBq of ^{137}Cs was discharged into the Pacific Ocean. Radionuclide concentrations in the area as of July 2013 were 11 and 22 kBq/L for ^{134}Cs and ^{137}Cs , respectively. A sizable amount of the radioisotopes is still in the ocean and groundwater. The Three Mile Island accident also led to the discharge of a considerable amount of radionuclide into the atmosphere and soil (between 481 and 629 GBq of ^{131}I) (Kim et al., 2019; Hossain, 2020). Naturally occurring radioactive materials (NORMs) also contribute to radionuclide concentrations in different environmental compartments; however, they are often non-catastrophic with regard to activity concentrations (Adebiyi et al., 2021). These radionuclides may adversely affect people and ecosystems, regardless of the exposure mechanisms.

Ionizing and non-ionizing radiations

Ionizing radiations are regarded as radiation (consisting of subatomic particles or electromagnetic,

EM, waves) that possesses energy capable of liberating electrons from atoms or molecules, after which they become ionized. On the other hand, non-ionizing radiation refers to electromagnetic radiation that does not possess enough photon energy that can ionize atoms/molecules—and excite them in the process (Adebisi et al., 2021; UNSCEAR, 2008). Ionizing radiation that consists of energetic subatomic particles, ions, or atoms travels faster than 1% of the speed of light (an EM wave). Ionizing radiation includes Alpha (α), Beta (β), and photon radiations (Gamma [γ] & X-rays), and exposure to these radiations often causes damage to living tissue and can lead to cancer, genetic mutation, and death (WHO, 2016).

Alpha radiation is made up of alpha particles that include two protons and two neutrons and have a double positive charge (Eq. 1) and cannot permeate the outer layer of the skin. Examples of radioactive elements that emit alpha radiation include radon, uranium, radium, and thorium (Khan, 2017). When alpha-emitting compounds are ingested or breathed into the body, bodily tissues may absorb alpha radiation, which may pose an internal hazard (Adebisi et al., 2021; Khan, 2017)

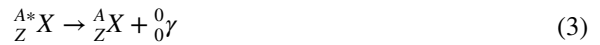


Beta radiation consists of charged particles similar to electrons that are released from the atomic nucleus. Beta particles are small, negatively charged (Eq. 2), and have higher penetrating power than alpha particles.



Exposure to beta-emitting substances can be harmful to the body; however, beta-emitting substances can be shielded by sheets of plastic, glass, or metal. Beta radiation can pass through the top layer of skin and release energy within active skin cells, but it cannot pass into the body’s tissues and organs. Beta emitters include sulfur-35, hydrogen-3 phosphorus-33, phosphorus-32, and carbon-14 (Khan, 2017).

Photon radiations are electromagnetic radiations of two types: gamma (γ) and X-ray. Gamma radiation ejects photons from the nucleus of an atom, while X-ray radiation releases photons of lower energy than gamma from outside the nucleus (Eq. 3)



Photon radiation can travel further than alpha and beta radiations and has very high penetrating power, and only dense materials such as lead or steel can offer protection. Photon radiation can penetrate body tissues and organs (Adegunwa et al., 2019). Electrically neutral, gamma particles have a great speed and penetration power and can be stopped by a thick sheet of lead, steel, concrete, or many meters of water. Cobalt-60, zinc-65, cesium-137, and radium-226 are all gamma emitters (Adebisi et al., 2021; Khan, 2017).

Naturally occurring radioactive materials (NORMs)

The prevalence of primeval radionuclides in the earth’s crust, as well as the interaction of cosmic rays with the atmosphere, causes harmful radiation exposure (Ajibola et al., 2021). These radionuclides include ${}^{232}\text{Th}$, ${}^{238}\text{U}$, ${}^{235}\text{U}$, and ${}^{40}\text{K}$, while the cosmogenic radionuclides include ${}^3\text{H}$, ${}^7\text{Be}$, ${}^{10}\text{Be}$, ${}^{14}\text{C}$, ${}^{32}\text{Si}$, and ${}^{36}\text{Cl}$ (Adebisi et al., 2021). These radioactive materials possess half-lives that are deducible from their disintegration products and can be used to extrapolate the age of the earth (Mahamood et al., 2020). It is assumed that the occurrence of NORMs in the environment does not significantly distort the ecosystem because non-cosmogenic radionuclides are expected to decay to an undetectable level (Akpanowo et al., 2020; L’Annunziata, 2016; Liu & Lin, 2018). Nonetheless, elevated levels of NORMs due to biomagnification and their redistribution in the environment may pose a threat to humans and the ecosystem. Table 1 presents the half-lives, isotopic abundance, and decay information of selected long-lived NORMS, while a representative decay pattern of uranium (U), thorium (Th), and neptunium (Np) is presented in Fig. 2. Most radionuclides in NORM (i.e., radium and radon) are generated by the decay of larger radioactive materials (i.e., uranium and thorium).

Industrial processes involving natural resources often release concentrated radionuclides that may be hazardous to humans and the environment (Alnabhani et al., 2018; IAEA, 2022a). Radionuclide-containing natural resources, whose radioactive levels

Table 1 Naturally occurring radioactive materials (NORMs) with long half-lives (Lide, 2010)

Radionuclide	Half-life (years)	Isotopic abundance (%)	Decay mode	Decay products
$^{40}_{19}K$	1.26×10^9	0.0117	β^- , EC	$^{40}_{20}Ca(\beta^-)$, $^{40}_{18}Ar(EC)$
$^{50}_{23}V$	1.4×10^{17}	0.25	β^- , EC	$^{50}_{24}Cr(\beta^-)$, $^{50}_{22}Ti(EC)$
$^{87}_{37}Rb$	4.88×10^{10}	27.835	β^-	$^{87}_{38}Sr$
$^{113}_{48}Cd$	9×10^{15}	12.22	β^-	$^{113}_{49}In$
$^{115}_{49}In$	4.4×10^{14}	95.71	β^-	$^{115}_{50}Sn$
$^{123}_{52}Te$	1.3×10^{13}	0.908	EC	$^{123}_{51}Sb$
$^{232}_{90}Th$	1.4×10^{10}	100	α	$^{228}_{88}Ra$
$^{235}_{92}U$	7.04×10^8	0.72	α	$^{231}_{90}Th$
$^{238}_{92}U$	4.46×10^9	99.27	α	$^{234}_{90}Th$
$^{144}_{60}Nd$	2.1×10^{15}	23.8	α	$^{140}_{58}Ce$

EC electron capture

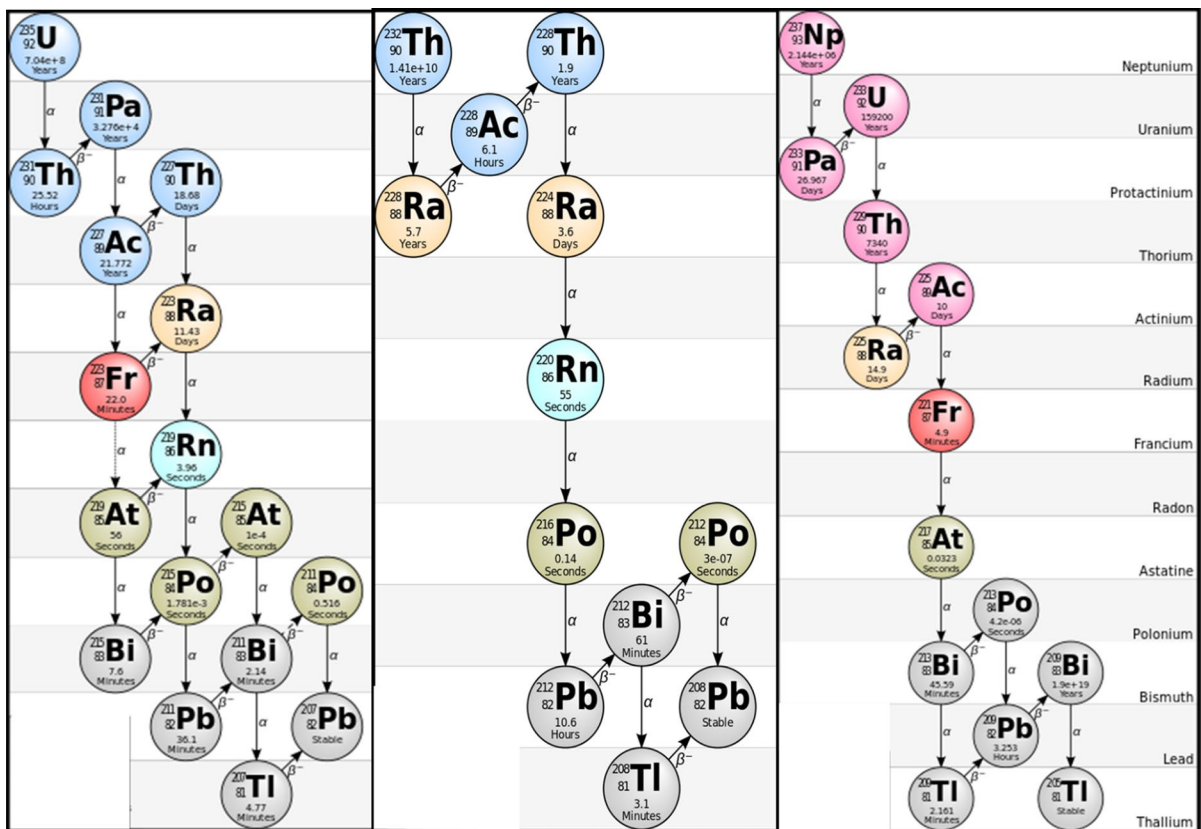


Fig. 2 Radioactive decay series for thorium and uranium. Adapted with modification from the decay chains at https://en.wikipedia.org/wiki/Decay_chain

are concentrated due to technological processes, are called technologically enhanced naturally occurring

radioactive materials (TENORM) (Ojovan & Lee, 2014). TENORM are large-volume, low-activity

radioactive waste generated from hospitals, nuclear power plants, mining, ore beneficiation, fertilizer manufacturing, borehole drilling and water treatment, paper and pulp production, oil and gas exploration and refining, combustion of coal, waste metal recycling and incineration, catalysts manufacturing, etc. (Adebiyi et al., 2021; Hossain, 2020; Valković, 2019). Upon release to the environment, they may pose a severe threat. Their fate, behavior, and activity (emission of ionizing or non-ionizing radiation) are mainly controlled by their chemistry and the nature of their host environment (Siegel & Bryan, 2014).

Radionuclide concentrations in soils

The earth’s crust and the aquifer are composed of mineral and organic components, and they serve as a major source of radiation emanating from anthropogenic contaminants such as radionuclides/radioactive

waste (Adebiyi et al., 2021). NORMs are part of several types of rocks and soils and are often a result of weathering and disintegration of rocks, a process that may also facilitate the release of radionuclides. The characteristics of soils control the behavior, concentration, and transport of radionuclides (Kang et al., 2020). Several reports suggest that radionuclides can be taken up by plants depending on the soil’s physicochemical properties, plant species, and agricultural practices (Ibikunle et al., 2019; Ilori & Chetty, 2020). The translocation of radionuclides from soil to edible plants presents a major risk of human exposure to hazardous radionuclides (El-Gamal et al., 2019a). Dust from mining activities containing radionuclides can be carried by the wind and poses an inhalation risk due to ionizing radiation generated that destroys body cells and tissues (Castillo et al., 2013; Dudu et al., 2018). Furthermore, radioactive wastes in household trash of nuclear medicine patients are being detected in municipal landfills, which may

Table 2 Selected radionuclides concentration reported in soils in different parts of the world

Location	Radionuclides	Concentration (Bq/kg)	References
Lahore, Pakistan	²²⁶ Ra, ²³² Th, and ⁴⁰ K	25.8, 49.2, and 561.6	Akhtar et al. (2005)
Ordu, Turkey	²²⁶ Ra, ²³² Th, ⁴⁰ K, and ¹³⁷ Cs	34.5, 26.9, 378.4, and 275.3	Celik et al. (2010)
Japan	²²⁶ Ra, ²³² Th, and ⁴⁰ K	320, 200, and 1100	Hassan et al. (2010)
Gulf Aqaba, Jordan	²²⁶ Ra, ²³² Th, and ⁴⁰ K	9.5, 10, and 734	Ababneh et al. (2010)
Vietnam	²²⁶ Ra, ²³² Th, and ⁴⁰ K	2.7, 59.8, and 411.9	Huy et al. (2012)
Tehran city, Iran	²²⁶ Ra, ²³² Th, and ⁴⁰ K	45.4, 57.1, and 768.5	Asgharizadeh et al. (2013)
Sithonia Peninsula, Greece	²³⁸ U, ²³² Th, ²²⁶ Ra, and ⁴⁰ K	62, 80, 69, and 777	Papadopoulos et al. (2014)
Sungai Petani, Malaysia	²²⁶ Ra, ²³² Th, and ⁴⁰ K	51.06, 78.44, and 125.66	Ahmad et al. (2015)
South Sinai, Egypt	²³⁸ U, ²³² Th, and ⁴⁰ K	46.39, 65.76, and 1186.45	Darwish et al. (2015)
Rajasthan, India	²²⁶ Ra, ²³² Th, and ⁴⁰ K	24, 55, and 549	Rani et al. (2015)
Western Regions of Ghana	²³⁸ U, ²³² Th, and ⁴⁰ K	25.51, 28.04, and 238.98	Adukpo et al. (2015)
Punjab, India	²²⁶ Ra, ²³² Th, and ⁴⁰ K	46, 98, and 756	Bangotra et al. (2016)
Quseir Harbor, Egypt	²²⁶ Ra, ²³² Th, and ⁴⁰ K	26, 19, and 458	El-Taher et al. (2018)
Kızılırmak Deltas, Turkey	²³⁸ U, ²³² Th, ⁴⁰ K, and ¹³⁷ Cs	28.59, 17.48, 150.53, and 5.32	Arıman and Gümüş (2018)
Richards Bay, South Africa	²³⁸ U, ²³² Th, ²²⁶ Ra, and ⁴⁰ K	28.26, 29.64, 32.18, and 146.77	Masok et al. (2018)
Rio de Janeiro, Brazil	²²⁶ Ra, ²²⁸ Ra, and ⁴⁰ K	29.7, 67.1, and 111.1,	Ribeiro et al. (2018)
Chittagong, Bangladesh	²³⁸ U, ²³² Th, and ⁴⁰ K	65.9, 83.2, and 946.9	Yasmin et al. (2018)
Delta Abyan, Yemen	²²⁶ Ra, ²³² Th, and ⁴⁰ K	33.15, 77.25, and 1220.59	El-Gamal et al. (2019a)
Khrami Massif, Georgia	²³⁸ U, ²³² Th, and ⁴⁰ K	38.57, 53.18, and 879.76	Kapanadze et al. (2019)
Plateau, Nigeria	²²⁶ Ra, ²³² Th, and ⁴⁰ K	242.13, 1776.08, and 374.01	Adesiji and Ademola (2019)
Uttarakhand, India	²²⁶ Ra, ²³² Th, and ⁴⁰ K	76, 69, and 549	Anamika et al. (2020)
Jeju Island, Korea	²²⁶ Ra, ²³² Th, ⁴⁰ K, and ¹³⁷ Cs	33.3, 40.6, 421, and 5.67	Kang et al. (2020)
Sao Paulo, Brazil	²³⁸ U, ²³² Th, and ²²⁶ Ra	37, 91, and 66	Gonçalves et al. (2021)
Perak, Malaysia	²²⁶ Ra, ²³² Th, and ⁴⁰ K	10, 25, and 5.8	Rahmat et al. (2022)

contribute to environmental exposures via leaching, the action of wind and rainfalls (Siegel & Bryan, 2014; Siegel & Sparks, 2002).

According to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the world average for ^{238}U , ^{232}Th , ^{226}Ra , and ^{40}K is 35, 45, 32, and 420 Bq/kg (UNSCEAR, 2008). According to Table 2, it is evident that while some radionuclide average activity concentrations reported in soils are below the world average, many of the activity concentrations obtained exceeds one or more world average activity concentration, especially those reported in Asia (El-Gamal et al., 2019a; Hassan et al., 2010; Rani et al., 2015). The locations with high radionuclide activity concentrations (such as Japan and Plateau Nigeria) have a history of volcanic eruption, earthquakes, nuclear accident, nuclear bombing (Hiroshima and Nagasaki), construction, and mining activities, which suggest that a significant amount of primordial radioactive materials is exposed to the biosphere from underground sources (Abella et al., 2019; Adesiji and Ademola 2019; Kang

et al., 2020; Khandaker et al., 2012; UNSCEAR, 2016).

Furthermore, advanced research must focus on the risk evaluation of radioactive waste pollution of soils under varying environmental conditions. The impact of radionuclides on geochemistry, soil biodiversity, and agriculture should be investigated under various climatic conditions in the light of the Sustainable Development Goals (SDGs).

Radionuclide concentrations in water and sediments

The exposure of aquatic systems to radioactive waste may cause ecotoxicological impacts, such as cellular mutation, malignant growth/tumor, cancer, death of marine species, and disruption of food chains (Adebiyi et al., 2021). The biomagnification tendency and food chain led to human exposure and risk, especially in coastal communities that source food and potable water from the marine systems. Table 3 summarizes recent research that reveals radioactive amounts in water and sediments around the world. Aquatic systems contribute significantly to the distribution and transport of NORM, TENORM, and other radioactive

Table 3 Activity concentrations of radioactive materials reported in water and sediments

Location	Sample type	Radionuclide concentration (Bq/L)				Reference
		^{238}U	^{232}Th	^{40}K	^{226}Ra	
Kadugli, Sudan	Groundwater	1.720	0.039	–	0.014	Osman et al. (2008)
Serbia	Drinking water	–	<50	<250	<70	Janković et al. (2012)
Slovenia	Mineral water	–	–	–	<33	Benedik & Jeran, (2012)
Ass-Alh, Yemen	Groundwater	–	2.93	–	6.55	El-Mageed et al. (2013)
Tamilnadu, India	Sediment (Bq/kg)	3.67	37.23	387.17	–	Ravisankar et al. (2014)
Ghana	Surface water	–	0.0012	–	0.0014	Kpeglo et al. (2014)
Žirovski Vrh, Slovenia	Tap water	0.362	–	–	0.017	Benedik et al. (2015)
Malaysia	Mineral water	–	3.39	25.39	3.30	Khandaker et al. (2017)
Saronikos Gulf, Greece	Sediment (Bq/kg)	29	7.8	360	25	Papaefthymiou et al. (2017)
Chittagong, Bangladesh	Sediment (Bq/kg)	94.4	121.9	498.0	114.0	Yasmin et al. (2018)
Assiut, Egypt	Drinking water	–	0.107	0.836	0.192	El-Gamal et al. (2019b)
Delta state, Nigeria	Water	5.67	2.86	1.67	–	Iwetan et al. (2019)
	Sediment (Bq/kg)	302.15	8.66	11.66	–	
Crimea, Russia	Sediment (Bq/kg)	–	1.872	1.440	1.620	Shadrin et al. (2020)
Lagos, Nigeria	Water	1.96	2.42	0.4	–	Adedokun et al. (2020)
Dnieper river, Ukraine	Sediment (Bq/kg)	69.9	55.6	350	22.4	Semerikov et al. (2021)
Calabria, Italy	Sediment (Bq/kg)	–	1266.12	6551.94	4329	Caridi et al., (2016, 2021)
Russia	Sediment (Bq/kg)	–	9.98	235.7	7.52	Menshikova et al. (2021)
Ogun, Nigeria	Sediment (Bq/kg)	–	128.7	453.9	42.3	Adewoyin et al. (2022)

waste residues (Novikov, 2010). The physicochemical, biogeochemical properties and mobility of radionuclides contribute to their fate in the hydroecosystem (Adebiyi et al., 2021; Caridi et al., 2021). The amount of biomass, natural organic matter, and aquatic species all contribute to the adsorption, accumulation, and half-life of radionuclides in sediments, as well as the volume and depth of the water column, the flow rate, sediment composition, sedimentation intensity, and the presence of geochemical (Ravisankar et al., 2014; Semerikov et al., 2021).

Sediment acts as a sink and diffuse source of pollutants including radioactive elements in the water bodies, partly due to input from marine systems (Jibiri & Okeyode, 2012). Higher concentrations of radionuclides have been reported in sediments than in water Table 3. Furthermore, when primary radionuclide sources are depleted, resuspension and remobilization of radioactive materials from pre-contaminated deposits become a vital diffuse/secondary source (Jibiri & Okeyode, 2012; Salbu & Lind, 2020). Secondary sources of aquatic contamination by radioactive materials also include leaching/seepage from contaminated terrestrial areas. Surface run-off and erosion from terrestrial systems may also lead to aquatic contamination, and episodic occurrences such as flooding and the transport of contaminated sediments trapped in “dirty” ice are all routes to radionuclide contamination of water bodies (Hong et al., 2012; Landa et al., 1998). These events lead to the transport of freshwater sediments to marine waters, which contributes to the mobility of associated radionuclides (Vives i Batlle, 2012).

The distribution coefficient or partition coefficient (K_d (L/g)) of radionuclides between sediment and water is given below (Eq. 4) (Kumar et al., 2020):

$$K_d = \frac{\frac{\text{Bq}}{\text{g}} \text{ Sediment}}{\frac{\text{Bq}}{\text{L}} \text{ Water}} \quad (4)$$

K_d is one of the major parameters controlling the distribution of radionuclides in the aquatic environment: a high value of K_d means that more radionuclides will be found in sediment (Kumar et al., 2020). This further suggests higher adsorption strength to the sediment, which limits the mobility of radionuclides in a water–sediment system (Kumar et al., 2020).

Radioactive elements can adhere to sediment phases from the aqueous phase by physical processes (e.g., sedimentation), chemical (e.g., polymerization, colloidal clustering/aggregation, ion exchange), and biological (e.g., detritus) processes (van Hullebusch et al., 2005; Vives i Batlle, 2012). Remobilization of NORMs and radioactive contamination from sediments to water may occur via natural or anthropogenic perturbation and resuspension, e.g., mineral or crude oil exploration, transportation, flooding, dredging or constructions, hurricane, etc. The removal of radioactive waste and landfills from coastal areas may be one of the precautionary measures needed to ensure marine and environmental protection.

Management of radioactive pollution in environmental matrices

The management approaches for radioactive pollution can be broadly categorized into the three major remediation strategies, which are physical, chemical, and biological remediation (Table 4) (Adebiyi et al., 2021; Strand et al., 2022). The physical remediation approach entails the removal of the top layer of soil of the contaminated sites, or the disposal of radioactive waste in deep geographical areas, often regarded as the best physical remediation approach (Dushenkov, 2003; Noor et al., 2020). The utilization of peroxides, citrates, carbonates, and inorganic/organic chelating agents in the cleanup of radionuclides by promoting their desorption from contaminated sites is part of the chemical remediation method (Valdovinos et al., 2014). The bioremediation technique uses algae (also called, phycoremediation), plants (phytoremediation), fungi (mycoremediation), and microbes (microremediation) in the elimination of radionuclides from a polluted environment (Galanda et al., 2014; Liu et al., 2014; Ore & Adeola, 2021).

Recent advances in the management of radioactive wastes/pollution have involved the development of methodical approaches such as natural attenuation, soil washing, adsorption, and electrochemical processes (Canner et al., 2018; Lingamdinne et al., 2017; McElroy et al., 2020; Song et al., 2015). Tables 5 and 6 provide an overview of the strategies employed in the cleanup of radioactive contaminants. The fundamental ideas and applications of the various strategies are briefly explored here.

Table 4 Broad classification of remediation techniques for radionuclide decontamination (Reddy et al. 2019)

Physical remediation	Chemical remediation	Bioremediation
Soil excavation is the process of removing contaminated soil from a pollution site and transporting it to a containment and storage facility (Kuppusamy et al., 2016)	Carbonate extraction: The use of carbonates to generate stable complexes of radioactive metals (Zhou & Gu, 2005)	Microremediation is the employment of microbes to degrade and detoxify pollutants in the environment (Psaltou & Zouboulis, 2020)
Soil flushing is the process of flushing contaminated soil with water, with or without chemicals, in situ (Song et al., 2017)	Citric acid extraction: Citrate is utilized as a complexing agent to aid in the desorption of solid matrix and the immobilization of precipitated radioactive elements (Mihalik et al., 2011)	Phycoremediation is the removal or biotransformation of radioactive contaminants using micro- and macroalgae (Galanda et al., 2014)
Solidification: The immobilization of radioactively contaminated soil in a solid matrix (Kuppusamy et al., 2016)	Sodium peroxide is an oxidizing substance that improves uranium removal by oxidation (Abdel-Sabour, 2007)	Mycoremediation: Environmental pollutants are degraded and detoxified by fungus in mycoremediation (Coelho et al., 2020a, 2020b)
Permeable reactive barrier: With the help of several adsorbents, an underground wall was built to clean up contaminated groundwater (Blowes et al., 2000; Noor et al., 2020)	Organic chelating compounds are the most effective at removing uranium from soils (Fukuda, 2005)	Phytoremediation: Plant-based solutions for radioactive contamination in soil and water (Mani & Kumar, 2014)
	Inorganic chelating agents: Polyphosphates and other inorganic cultures have been used to decontaminate radioactive metals (Wuana et al., 2010)	

Table 5 Radionuclide decontamination using electroremediation techniques

Technique	Sample type	Radio-nuclide targeted	Electrode types	Optimum process condition and removal performance (%)	References
Electrocoagulation	Mine water (16.7 °C)	Uranium	Stainless steel and iron	Time: 2 h; CD: 70 mA/cm ² ; 99.7% Time: 2 h; CD: 40 mA/cm ² ; 98.0%	Nariyan et al. (2018)
Electroactive film	Wastewater (25 °C)	Cesium	Stainless steel–aluminum Copper hexacyanoferrate with stainless steel–platinum	Time: 2 h; CD: 70 mA/cm ² ; 97.7%	Chen et al. (2017)
Iron-electrocoagulation and organic ligands	Water (25 °C)	Uranium	Sheets of pure iron and graphite	Time: 24 min; CD: 0.6 mA/cm ² ; 99.7%	Li et al. (2017)
Electrodeposition	Water (25 °C)	Uranium	Poly(3,4-ethylene-dioxythiophene) poly(styrenesulfonate) modified platinum	Time: 8 h; 94%	Agarwal and Sharma (2018)

CD current density

Electroremediation

Electrochemical remediation is also known as electrokinetics or electroreclamation (Reddy & Cameselle, 2009; Reddy et al., 2006; Saichek & Reddy, 2005). Electroremediation is a science that involves passing a low-intensity electric current through polluted soil between the cathode and anode. Electromigration and electro-osmosis are core mechanisms driving electroremediation (Cameselle & Reddy, 2012). The introduction of direct current moves water and ions toward the electrodes and has been used to decontaminate radioactive elements present in aquatic matrices. The well of the electrode accumulates the contaminants driven toward it via the movement of water and ions, and a circulation system ensures the removal of pollutants from the electrode wells. This continuous process is only discontinued when the desired removal efficiency is achieved (Cameselle & Gouveia, 2019).

The utilization of electroremediation for the treatment of radionuclide-polluted soils, water, and sediments has been limited, but few recent investigations in the literature have reported its usefulness. The electrochemical recovery of uranium in an aqueous solution was evaluated in

0.1 M KCl on poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate) modified platinum (PEDOT: PSS/Pt) electrode (Agarwal & Sharma, 2018). The presence of uranium on the electrode was confirmed by ICP-MS data that showed a 94% recovery rate. Similarly, batch electrocoagulation has been used to remove uranium from mine water under various reaction times and electrode combinations (Nariyan et al., 2018). Using electrode combinations made of aluminum–stainless steel and iron–stainless steel, the best elimination of uranium from mine water was 97.69 and 99.73%, respectively. The first-order kinetics model best described the process, implying a physical or non-bonding interaction involving the coagulant and the uranium.

Uranium contamination in groundwater was addressed using a novel direct electro-reductive technique (Liu et al., 2019). It was observed that U(VI) was reduced to U(IV)O₂ which resulted in reduction of the pollutant accumulation on Ti electrode surface with electric current efficiency > 90%. Uranium recovery of 98% was obtained dipping the Ti electrode in dilute HNO₃. Another study investigated the permeable reactive barrier-assisted electrokinetic treatment of uranium-contaminated soil utilizing a composite electrolyte of citric acid and ferric chloride

Table 6 Various techniques for remediation of radionuclide contamination in aqueous media

Remediation technique	Radionuclide	Removal efficiency (%)	Reference
Electroremediation	Uranium	94	Agarwal and Sharma (2018)
Electroremediation	Uranium	97.7 and 99.7	Nariyan et al. (2018)
Electroremediation	Uranium	98	Liu et al. (2019)
Electroremediation	Uranium	80.6	Xiao et al. (2020a)
Electroremediation	Uranium	61.6	Xiao et al. (2020b)
Bioremediation	Uranium	47	Shukla et al. (2020)
Bioremediation	Uranium	> 60	Coelho et al. (2020a)
Bioremediation	Uranium	90	Vijay et al. (2020)
Bioremediation	Uranium	93.2–97.5, 38–92	Coelho et al. (2020b)
Bioremediation	Thorium and uranium	> 95	Ozdemir et al. (2020)
Adsorption	Uranium	85.3, 79.2	Zhang et al. (2021b)
Adsorption	Uranium	> 90	Zhang et al. (2021a)
Adsorption	Uranium	91.1, 86.5	Wen et al. (2021)
Adsorption	Uranium	100	Liu et al. (2021)
Adsorption	Uranium	87.5	Zhang et al. (2020)
Adsorption	Uranium	80–87	Sharma et al. (2020)
Adsorption	Uranium	69.5, 88.9, and 95.1	Wang et al. (2021)
Adsorption	Uranium	97.8	Chen et al. (2021)
Bioremediation	Uranium	118.6	Chen et al. (2020)
Adsorption	Uranium	30.71	Wei et al. (2020)
Adsorption	Uranium	99	Hu et al. (2020)
Adsorption	Uranium	> 90	Liao and Zhang (2020)
Adsorption	Uranium	99.8	Duan et al. (2020)
Adsorption	Uranium	> 90	Ma et al. (2020)
Adsorption	Cobalt	90	Sheng et al. (2012)
Adsorption	Europium	65	Song et al. (2019a)
Adsorption	Europium	100	Huang et al. (2018)
Adsorption	Radon	99	Baeza et al. (2017)
Adsorption	Cesium	55.3	Sakamoto and Kawase (2016)
Adsorption	Strontium	100	Mihara et al. (2019)
Adsorption	Strontium	48–59	Rae et al. (2019)
Adsorption	Americium	93.4–95.4	Yao et al. (2018)
Forward osmosis	Iodine	99.7	Lee et al. (2018)
Forward osmosis	Cobalt	99.9	Liu et al. (2017)
Membrane distillation	Cobalt	99.9	Wen et al. (2016)
Nanofiltration	Cesium	88	Chen et al. (2014)
Nanofiltration	Strontium	95	
Nanofiltration	Cobalt	96	
Ultrafiltration	Iodine	60	Sancho et al. (2006)
Membrane distillation	Cesium and cobalt	97.7–99.9	Zakrzewska-Trznadel et al. (1999)
Ion-exchange	Strontium	84.6–98.3	Rae et al. (2019)
Ion-exchange	Strontium, cesium, cobalt	59–100	Fang et al. (2016)
Precipitation	Strontium	99.9	Wu et al. (2014)
Precipitation	Cesium	92.7	Rogers et al. (2012)
Photocatalysis	Uranium	100	Li et al. (2019)
Photoreduction	Uranium	99.9	Zhu et al. (2019)

Table 6 (continued)

Remediation technique	Radionuclide	Removal efficiency (%)	Reference
Biominerzalization	Cesium, strontium, technetium	70, 95, 81.3	Lee et al. (2014)

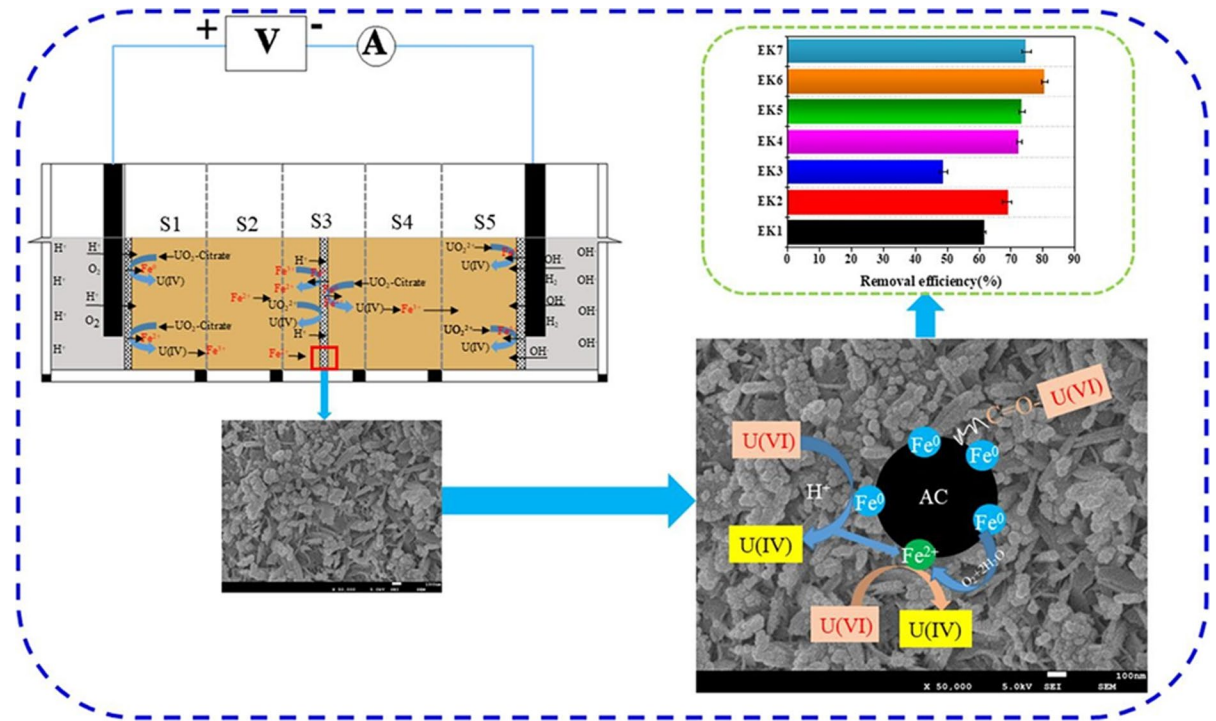


Fig. 3 A permeable reactive barrier made of iron and activated carbon for electroremediation of uranium-contaminated soil. Adapted with permission from Xiao et al. Copyright 2020, Elsevier

mixture (Fig. 3). The optimum uranium removal rate was 80.6% (Xiao et al., 2020a). Similarly, several electrolytes were used to investigate electrochemical remediation of uranium-polluted red soil. The researchers discovered that using an ideal dosage of 0.03 mol/L FeCl₃ and 0.1 mol/L citric acid increased uranium removal effectiveness to 61.6%. In addition, after electroremediation, the study found that there was less soil damage and decreased leaching toxicity (Xiao et al., 2020b).

The application of electroremediation technique in the remediation of radionuclide contamination in different environmental compartments is regarded as efficient, except for a few reports that suggested that ²³²Th and ²³⁸U are more recalcitrant in soils (Kim et al., 2003, 2012; Mohamed Johar & Embong, 2015). This trend can be attributed to

trace concentrations of radionuclides and limited electromigration due to the low permeability of the soils. The amount of radionuclide contamination in soils is proportionate to the mobile ions present for electromigration (Kim et al., 2003). Furthermore, the performance of the electrokinetic remediation is influenced by the applied voltage and the AC/DC voltage ratio; therefore, energy costs must be considered, particularly for extremely polluted locations.

A novel, portable battery-type column that sequentially removes calcium from sewage using copper hexacyanoferrate nanoparticle film (CuHCF NPs film) was reported by Chen et al. (2017). This is distinct from chemical spray, chemical bath, or electrochemical deposition. The battery-style column demonstrated electrochemical redox cesium adsorption of

CuHCF NPs screen by varying the potentials between two sandwiched electrodes. The electrochemical oxidation–reduction of Fe (II/III) and electrostatic attraction played a role in cesium removal. In another study, uranium removal from the mine water in Pyhäsalmi, Finland, was achieved via electrocoagulation. The removal efficiency, current density, and reaction time were studied. For both the iron–stainless steel and aluminum–stainless steel anode/cathode pairings, current density was found to be a determinant factor (Table 5). However, the quadratic model for the aluminum–stainless steel combination only considered

the reaction time as an essential parameter (Nariyan et al., 2018).

Bioremediation

Bioremediation involves the application of biological substances such as plants, microorganisms, and their enzymes for the decontamination of polluted environments (Arora, 2018; Gouma et al., 2014). Biological organisms such as fungi, plants, and bacteria have become choice agents of decontamination over the years, which is due to their detoxifying capabilities, and ability to trap and degrade contaminants

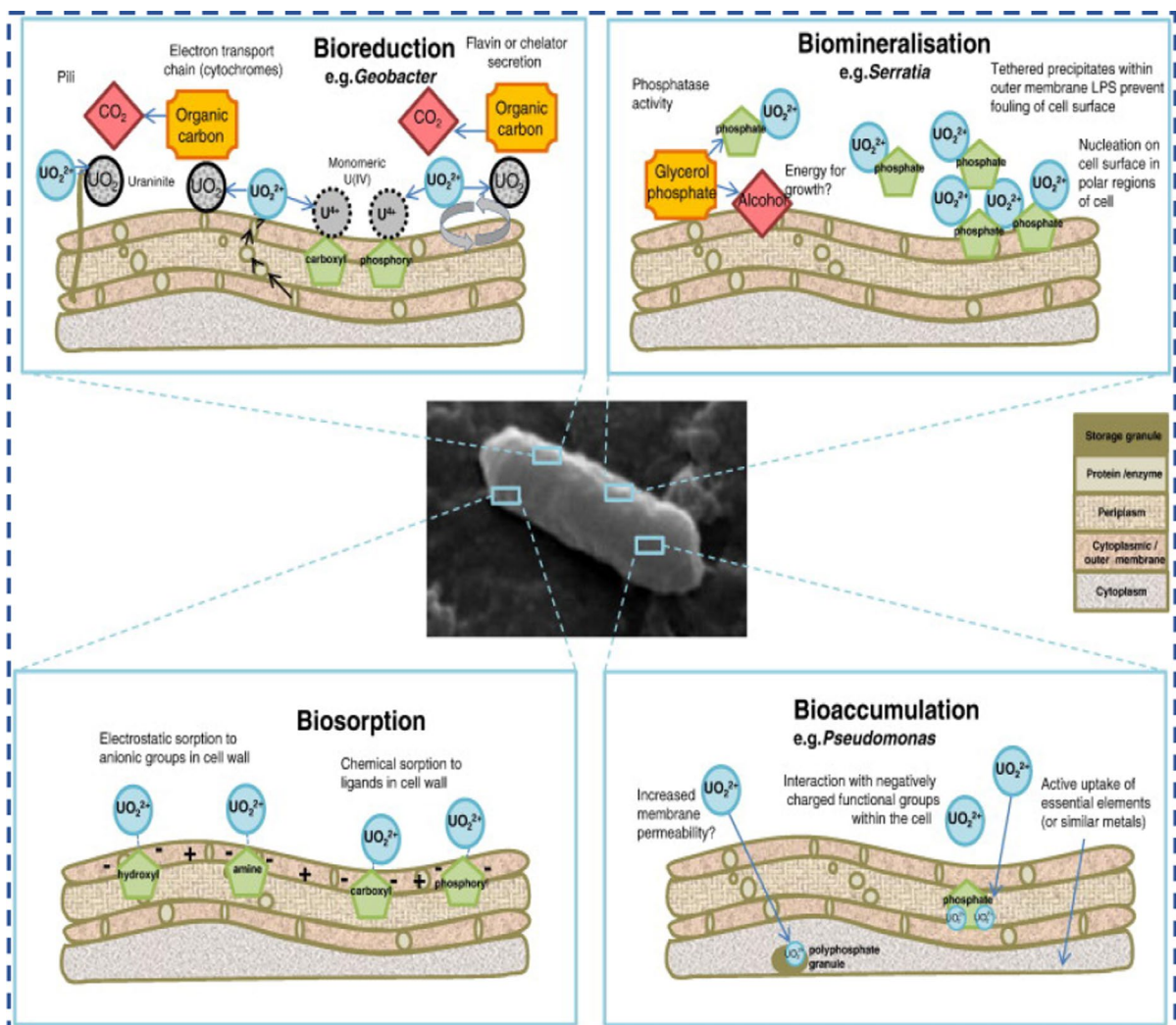


Fig. 4 Microorganism-induced remediation of uranium contamination. Adapted from Chemical Geology, Newsome et al. 363, 164–184, Copyright 2014 Elsevier

(Patel et al., 2022; Psaltou & Zouboulis, 2020). Plants that are suited for bioremediation should have an advanced root system, resistant to disease, and be able to develop quickly (Yan et al., 2020). The main mechanisms involved in bioremediation are—bioaccumulation, bioreduction, biomineralization, and biosorption, and these are features of the interaction between radioactive elements and microorganisms (Fig. 4) (Newsome et al., 2014). Phytoremediation has created environmentally benign and reasonably inexpensive methods for removing radioactive pollutants. Phytostabilization (immobilization of pollutants), phytoaccumulation (sorption and bioaccumulation in plant tissues), phytovolatilization (conversion of contaminants to volatile form to potentially trapping them in the air), and phytofiltration are some of the different strategies of bioremediation (recovery of dissolved contaminants by extra- and intra-cellular accumulation) (Sharma et al., 2015; Yan et al., 2020).

Staphylococcus aureus biofilms have been investigated for the bioremediation of uranium contamination, regardless of its pathogenicity (Shukla et al., 2020). The study reported that the addition of phosphate enhanced the efficiency of *Staphylococcus aureus*, upon treatment with uranyl nitrate solution, and an efficiency of 47% was recorded for U(VI) removal. A related study reported the isolation of fifty-seven fungi and investigated bioremediation potential against uranium. Over 60% of uranium was removed from an aqueous media by eleven fungi (Coelho et al., 2020a). The application of *Penicillium piscarium* was evaluated in the remediation of radioactive waste-polluted sites. The fungi exhibited between 93.2 and 97.5% decontamination efficiency of uranium at pH 3.5, whereas between 38 and 92% removal efficiency was obtained at pH 5.5, according to the study (Coelho et al., 2020b).

A consortium of denitrifying bacteria was employed by Vijay et al. (2020) to investigate the performance of microbial fuel cells. To manufacture insoluble uranyl phosphate, mineral phosphate produced from glycerol 3 phosphate is coupled successfully with uranium (VI). The uranium was extracted as uranyl phosphate, which resulted in a 90% removal efficiency. (Vijay et al., 2020). Thorium and uranium were targeted in a similar investigation by Ozdemir et al. (2020), a novel thermophilic bacterium was created to preconcentrate radionuclides in environmental matrices. *Bacillus*

cerus SO-14 was utilized as a biosorbent for solid-phase extraction, with the process parameters and detection limits optimized (LOD). The thorium and uranium extraction recoveries in this investigation were both better than 95%.

Although bioremediation is thought to be effective in the treatment of polluted soil and water (Adeola & Forbes, 2021; Azubuike et al., 2016). Bioremediation's limitations include low efficacy in highly contaminated locations, a lack of suitable environmental conditions for microbe development, the existence of communities of metabolically active microbes, and a detrimental effect on biodiversity (Kuppusamy et al., 2015, 2016; Patel et al., 2022). Furthermore, substantial remediation is time-consuming since microbial culture, process implementation, and optimization all take time. Furthermore, using plants demands special management procedures and safeguards, as herbivores like sheep, cattle, and other livestock may consume the plants, providing a risk of human exposure through the food chain.

Adsorption

Chemical pollutants are moved from the liquid phase to the surface or pores of solid material during the mass transfer process known as adsorption (Fig. 5) (Adeola et al., 2021b; Ibigbami et al., 2022; Ore & Adeola, 2021). To remove and recover radionuclides from various waste sources, a variety of technologies have been developed and studied. Adsorption, on the other hand, has several benefits over other types of cleanups. Some of these benefits include easy regeneration and reusability of spent adsorbent, ease of operation, and a lower risk of sludge and/or secondary pollutants (Adeola & Forbes, 2021). The primary mechanisms driving the adsorption of radionuclides in water include an amalgam of Lewis' acid–base interaction, electrostatic interaction, ion exchange, hydrogen bonding, and coordination interactions, as well as adsorption–reduction (Feng et al., 2018; Huang et al., 2018; Sukatis & Aris, 2021).

Zhang et al. (2021a) studied how quartz sand coated with zero-valent iron (ZVI-S) can be used to remove uranium from groundwater. Experiments were carried out to see how concentration, contact time, and solution pH affected the results. The hydraulic loads and particle sizes used by the ZVI-S

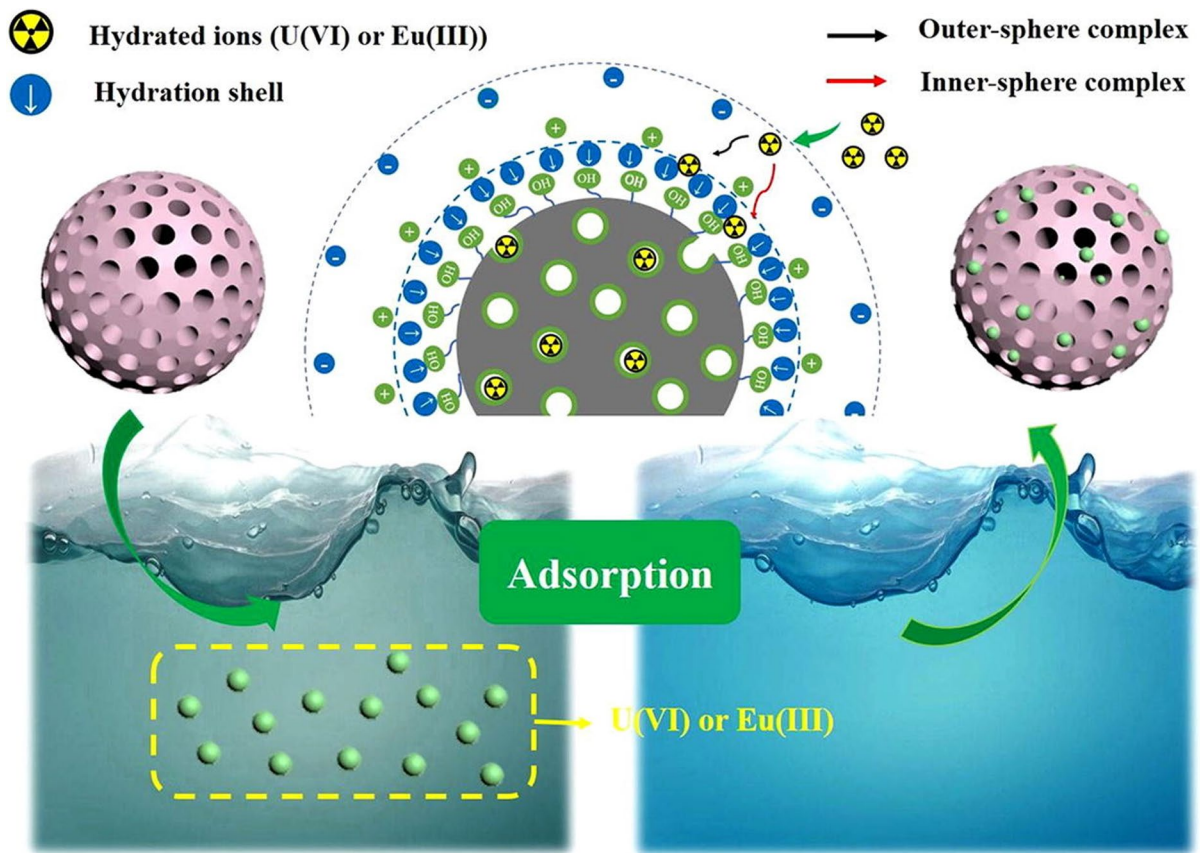


Fig. 5 Adsorption of U(VI) and Eu(III) through the formation of strong surface complexes in an aqueous solution. Reprinted from Chemical Engineering Journal, 353, Huang et al., Unex-

pected ultrafast and high adsorption of U(VI) and Eu(III) from solution using porous Al₂O₃ microspheres derived from MIL-53, 157–166, 2018, with permission from Elsevier

were changed. In batch tests, the removal efficiency of uranium was found to be 85.3%, while in column experiments, it was shown to be 79.2%. Similarly, a novel supramolecular poly(amidoxime) (PAO)-loaded macroporous resin (PLMR) adsorbent for the removal of uranium from seawater and wastewater was investigated by Wen et al. (2021). After immersion, the PAO was loaded onto the microporous resin through hydrophobic interaction. In wastewater and seawater, the PLMR adsorbent showed 91.1 and 86.5% efficiency, respectively. The efficiency of photocatalysis-assisted uranium sorption was investigated with the aid of CN550, a new carbon nitride made by heating a combination of ZnCl₂ and melamine in an inert atmosphere. After 390 min of irradiation, nearly all of the uranium in the solution had been removed (Liu et al., 2021).

For uranium removal from sewage water, Zhang et al. (2021b) developed an activated biochar-loaded nano zero-valent iron (A-BC-NZVI). The A-BC-NZVI composite was synthesized using aqueous phase reduction in a nitrogen environment at 800 °C. The investigations used factors like temperature, time, concentration, and solution pH. The effectiveness of uranium's adsorption was still greater than 90% after five cycles of sorption–desorption experiments. This demonstrated the possibility of employing A-BC-NZVI as an environmentally friendly adsorbent in uranium-polluted water restoration. Nitro-oxidized carboxycellulose nanofibers (NOCNF) were generated utilizing the nitro-oxidation process in a work by Sharma et al. (2020). The NOCNF obtained had a high surface charge and a high carboxylate content. The uranium removal

mechanism of negatively charged NOCNF showed maximum removal efficacy at neutral pH (80–87%).

Table 6 revealed that the adsorption method is the most widely utilized technique for the treatment of radionuclide contamination in water/water. However, various factors must be considered before selecting an appropriate adsorbent for the treatment of radiochemical-related pollution, including the material's efficiency, availability, non-toxicity, adaptability, robustness, reusability, and so on. Following the treatment of extremely polluted sites, a routine post-remediation check is required.

Integrated techniques and other remediation methods for radionuclide decontamination

Several treatment techniques often have shortcomings or limitations relating to stability, reusability, operational cost, sustainability, and treatment efficiency. Therefore, hyphenated methods or integrated techniques are considered viable alternatives to address these challenges (Adeola & Forbes, 2021). These integrated methods may involve chemical–physical (such as adsorption and photocatalysis), biological–physical (e.g., bioremediation and precipitation), biological–chemical (such as bioremediation and photocatalytic reduction), physical–physical or chemical–chemical processes (Table 7).

Coagulation, flocculation, and integration of both techniques have been developed and utilized to eliminate pathogens, colloidal particles, metals, and other organics from contaminated water (Sharma & Bhat-tacharya, 2017). According to Rout et al. (2006), the rate of radioactive removal from chemical sludge was consistently greater and faster when flocculant was included. In addition, bridging between a substrate (i.e., BaSO₄), radioisotopes, and flocculants was improved by minimizing repulsive forces in the double layer. The choice of coagulant and flocculant is often determined by the desired rate of settlement, decontamination efficiency, and volume of sludge/wastewater to be treated.

Photocatalytic degradation involves the remediation of organic chemicals, radionuclides, and heavy metals in environmental compartments with the aid of ultraviolet (UV) or solar light irradiation (Li et al., 2019; Zhu et al., 2019). To photoreduce U(VI), Zhu et al. (2019) reported the synthesis of a nanocomposite comprising hybridized graphene oxide nanosheets and K₂Ti₆O₁₃ nanohybrid. Due to the reduction of surface oxygen-related defects and the creation of a Schottky-like barrier at the interface between GO and KTO, it has been discovered that the combination of GO and KTO can significantly increase the separation ability of photo-electrons and holes. This can effectively reduce the recombination of electrons and

Table 7 Integrated/combined techniques for radionuclide decontamination

Integrated techniques	Radionuclide	Removal efficiency (%)	Reference
Bioremediation–co-precipitation	Cobalt	85	Lack et al. (2002)
Ultrafiltration–reverse osmosis	Iodine	80	Sancho et al. (2006)
Flocculation–microfiltration	Americium	81–99.9	Yong et al. (2004)
Coagulation–flocculation	Manganese, antimony, ruthenium, cobalt	99.25	Kim et al. (2019)
Coagulation–flocculation	Antimony, cesium, ruthenium, cobalt, iodine	75–100	Kim et al. (2016)
Coagulation–flocculation	Strontium, cesium	65–95	Rout et al. (2006)
Adsorption–photocatalytic reduction	Uranium	88	Liu et al. (2018)
Biosorption–biotransformation	Uranium	90	Song et al. (2019b)
Biosorption–Bioremediation	Cesium	95	Lee et al. (2019)
Biosorption–biomineralization	Uranium	98	Zheng et al. (2018)
Phytoremediation–bioaccumulation	Cobalt	98	Soudek et al. (2004)
Adsorption–photocatalysis	Uranium	97.6	He et al. (2020)

holes, thereby optimizing the overall performance of the photoreduction process.

Chemical precipitation is a treatment method where co-precipitation, Ostwald ripening, and pH change mechanisms can be successfully employed to efficiently separate radionuclides in aqueous media. Wu et al. (2014) presented an integrated co-precipitation microfiltration technology for removing strontium from wastewater. The nucleation, aggregation, Ostwald ripening, and formation of new particles facilitate the precipitation and separation. The strontianite formation and strontium sorption on or within the CaCO_3 crystal strengthened the removal of strontium (SrCO_3). The membrane filtration procedure was used to improve strontium's stable separation.

On the contrary, Rae et al. (2019) employed commercially available resins for strontium ion-exchange separation/recovery. A removal efficiency ranging from 84.6 to 98.3% was recorded without interference by competing ions. Zeolite was reported to effectively remove strontium, cesium and cobalt from wastewater with removal efficiency ranging from 59 to 100% (Fang et al., 2016). The presence of organics and clay had no discernible effects on the ion-exchange process for Cs^+ and Sr^{2+} , but both had a considerable impact on the adsorption of Co^{2+} .

Challenges, prospects, and opportunities

The utilization of radioactive materials in various sectors of the economy has implications for the environment, health, and safety, not to mention ethical considerations. Nuclear power has enormous potential to serve as an alternative to fossil fuels with competent engineering and monitoring. Still, public confidence in nuclear facilities is naturally low following the disasters at Three Mile Island (1979), Chernobyl (1986), and Fukushima (2011). However, nuclear power has the highest capacity factor of all energy sources (Fig. 6) and can be a viable alternative to fossil fuels. Nuclear power systems generate high-capacity base-load electricity while emitting very few pollutants (Muth et al., 2021; Piro & Duffey, 2019). Concerns about the proliferation of weapons-grade nuclear materials, the implications of accidents, and the difficulties of long-term storage of radioactive waste are all challenges that hinder the complete transition to nuclear energy and nuclear research and development (Brook et al., 2014; Hannah, 2022).

Due to the vast application of radioactive materials in various sectors such as medicine, agriculture, energy, industry, archaeology/mining activities, and radio-sensors development, there is a need for multiple management strategies for incidental and accidental environmental pollution. The creation of fast and inexpensive hybrid or integrated decontamination techniques requires urgent attention due to the proliferation of radioactive waste pollution. Various adsorbents have been developed for the rapid decontamination of radioisotopes, but challenges such as the difficulty in ion recovery from sorbents, adsorbent cost, reusability, and scalability, remain a challenge to field applications. The development of nanocomposites with the enhanced specific surface area from cheap materials such as biomass or abundant geosorbents may promote the application of the adsorption process for large-scale radionuclide decontamination.

Bioremediation/phytoremediation is often slow and requires a carefully controlled environment to prevent the death or non-performance of microorganisms or plants. Furthermore, specific radionuclides are recalcitrant/resistant to microbial remediation, but this can potentially be addressed by genetically enhancing the effectiveness of carefully selected microorganisms to prevent the adverse

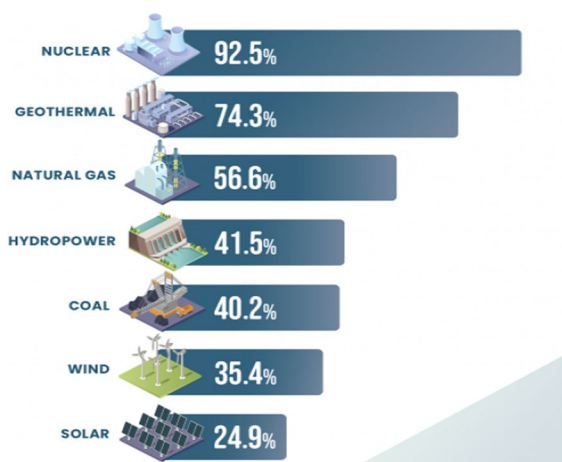


Fig. 6 The capacity factor of different energy sources in 2020. Adapted with slight modification from US Energy Information Administration, 2021

anthropogenic impact of the genetically modified agents. Although membrane techniques have shown excellent filtration properties and rapid treatment of large volumes of water, biological and chemical fouling remains a challenge. Reducing sludge during coagulation–flocculation, filtration, and biological treatment is critical. Chemical sludge must be handled carefully since it is challenging to separate coagulants and radionuclides for recycling and reuse. Reducing sample volume, aeration, and powering operations using solar or other renewable energy may reduce operational process costs.

Conclusion

For environmental monitoring and protection, understanding the distribution of radionuclides in the environment is critical. An increase in radioactive waste and accompanying environmental pollution may result from anthropogenic activities such as mining, agriculture, crude oil exploration, and nuclear power plant decommissioning. The redistribution of radioactive materials in the environment poses health and environmental concerns. Nuclear power is not renewable, but it is virtually inexhaustible due to the vast amount of source materials accessible. It emits no greenhouse gases, making it a great energy source from the standpoint of limiting climate change.

This bibliometric survey identifies hot spots of radioactive pollution from numerous sources, as well as potential health risks associated with radionuclide exposure. The type of remediation approach that might be used is influenced by environmental sustainability as well as economic costs. Future studies should concentrate on improving the efficiency of remediation procedures, particularly in densely populated residential areas. For the long-term and efficient remediation of extremely polluted sites, an integrated method such as adsorption-photocatalysis, coagulation–flocculation, and so on is required.

To find potential hot spots and protect the environment, it is important to analyze additional radionuclides, such as alpha- and beta-emitting radionuclides, globally in water and sediments. To conduct a full risk assessment and build effective radioactive waste management systems, a collaborative effort between worldwide and

regional regulatory organizations, in collaboration with universities, is required. Furthermore, national government talks should focus on implementing regulations aimed at reducing the health concerns connected with the indiscriminate disposal of radioactive wastes. Radioactive materials can serve as fuel for nuclear power generation to meet global demands due to increased population and industrialization. However, adequate infrastructure must be put in place to avert catastrophic disasters.

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