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

[1]**Adeola, A.O.,** [2,*]**Iwuozor, K.O.,** [3,4]**Akopmie, K.G.,** [5]**Adegoke, K.A.,** [6]**Oyedotun, K.O.,** [7]**Ighalo, J.O.,** [8]**Amaku, J.F.,** [9]**Olisah, C.,** [3]**Conradie, J.**

[1] Department of Chemical Sciences, Adekunle Ajasin University, Akungba-Akoko, Ondo State, Nigeria.

[2] Department of Pure & Industrial Chemistry, Nnamdi Azikiwe University, Awka, Nigeria.

[3] Department of Chemistry, University of the Free State, Bloemfontein, 9300, South Africa.

[4] Department of Pure & Industrial Chemistry, University of Nigeria, Nsukka, Nigeria.

[5] Department of Chemical Sciences, University of Johannesburg, Doornfontein, 2028, South Africa.

[6] Department of Physics, Institute of Applied Materials, SARCH1 Chair in Carbon Technology and Materials, University of Pretoria, Pretoria, 0028, South Africa.

[7] Department of Chemical Engineering, Nnamdi Azikiwe University, P.M.B. 5025, Awka, Nigeria.

[8] Department of Chemistry, Michael Okpara University of Agriculture, Umudike, Nigeria.

[9] Department of Botany, Institute for Coastal and Marine Research (CMR), Nelson Mandela University, Port Elizabeth, South Africa

* Correspondence to A.O. Adeola. e-mail: adedapo.adeola@aaua.edu.ng

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 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 (Adebiyi 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; Uhunamure 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 (Adebiyi 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 (Adebiyi 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 (Adebiyi 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).

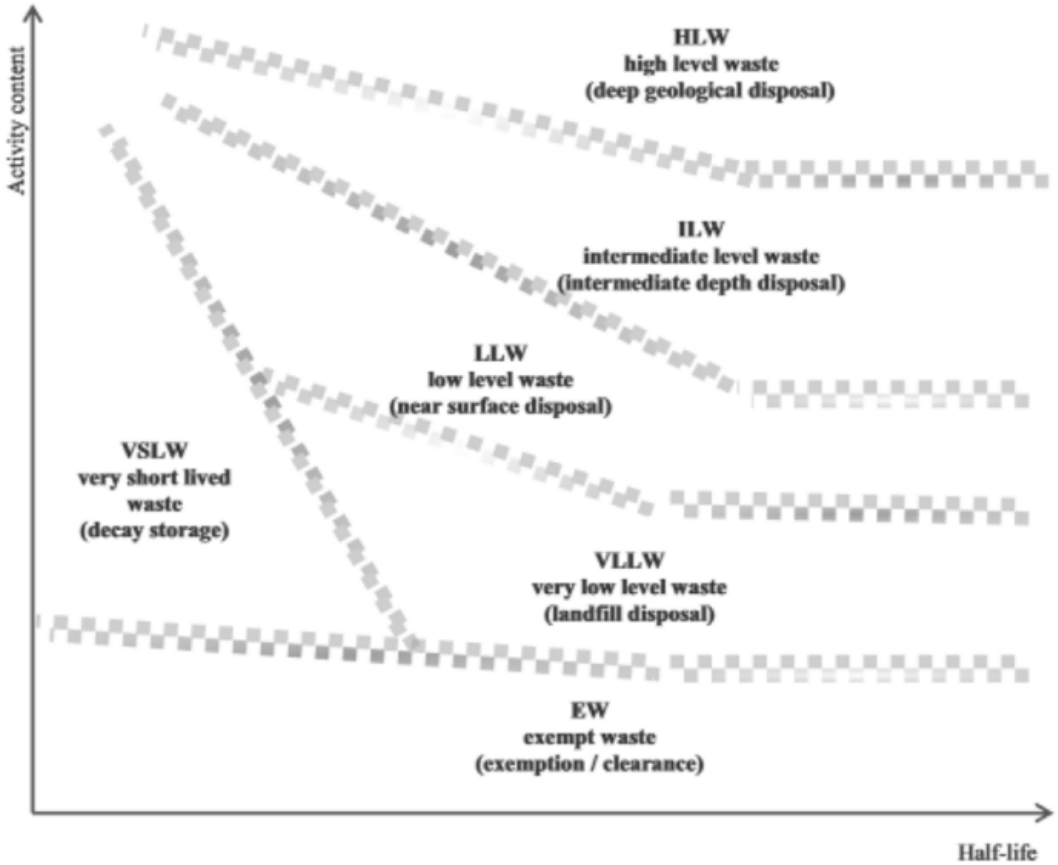

Fig. 1. International Atomic Energy Agency classification of radioactive waste (https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1419_web.pdf)

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 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 Chornobyl 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 131I) (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 (Adebiyi 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 (Adebiyi et al., 2021; Khan, 2017)

$$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha \tag{1}$$

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.

$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}e^{+} + {}^{0}_{0}\nu \tag{2}$$

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)

$$^{A*}_{Z}X \rightarrow {}^{A}_{Z}X + {}^{0}_{0}\gamma \tag{3}$$

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 (Adebiyi 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}Th, ^{238}U, ^{235}U, and ^{40}K, while the cosmogenic radionuclides include ^{3}H, ^{7}Be, ^{10}Be, ^{14}C, ^{32}Si, and ^{36}Cl (Adebiyi 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).

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	$^{140}_{58}Ce$

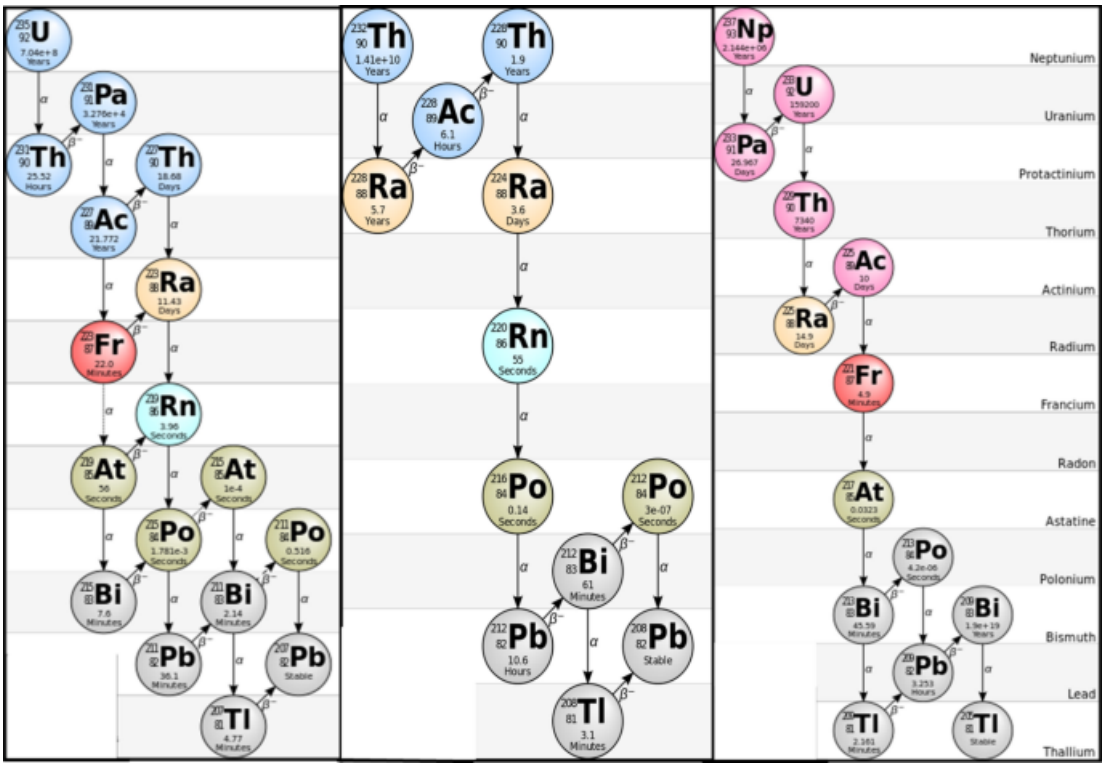

Fig. 2. Radioactive decay series for thorium and uranium. Adapted with modification from the decay chains at https://en.wikipedia.org/wiki/Decay_chain

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 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 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).

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, Jordon	^{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)

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 waste residues (Novikov, 2010). The physicochemical, biogeochemical properties and mobility of radionuclides contribute to their fate in the hydro-ecosystem (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).

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)

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).

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)	

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):

$$K_d = \frac{\frac{\text{Bq}}{\text{g}}\ \text{Sediment}}{\frac{\text{Bq}}{\text{L}}\ \text{Water}} \tag{4}$$

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.

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)
			Stainless steel–aluminum	Time: 2 h; CD: 70 mA/cm^2; 97.7%	
Electroactive film	Wastewater (25 °C)	Cesium	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

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,

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)
Biomineralization	Cesium, strontium, technetium	70, 95, 81.3	Lee et al. (2014)

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.

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 $U(IV)O_2$ 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 HNO_3. Another study investigated the permeable reactive barrier-assisted electrokinetic treatment of uranium-contaminated soil utilizing a composite electrolyte of citric acid and ferric chloride 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 $FeCl_3$ 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).

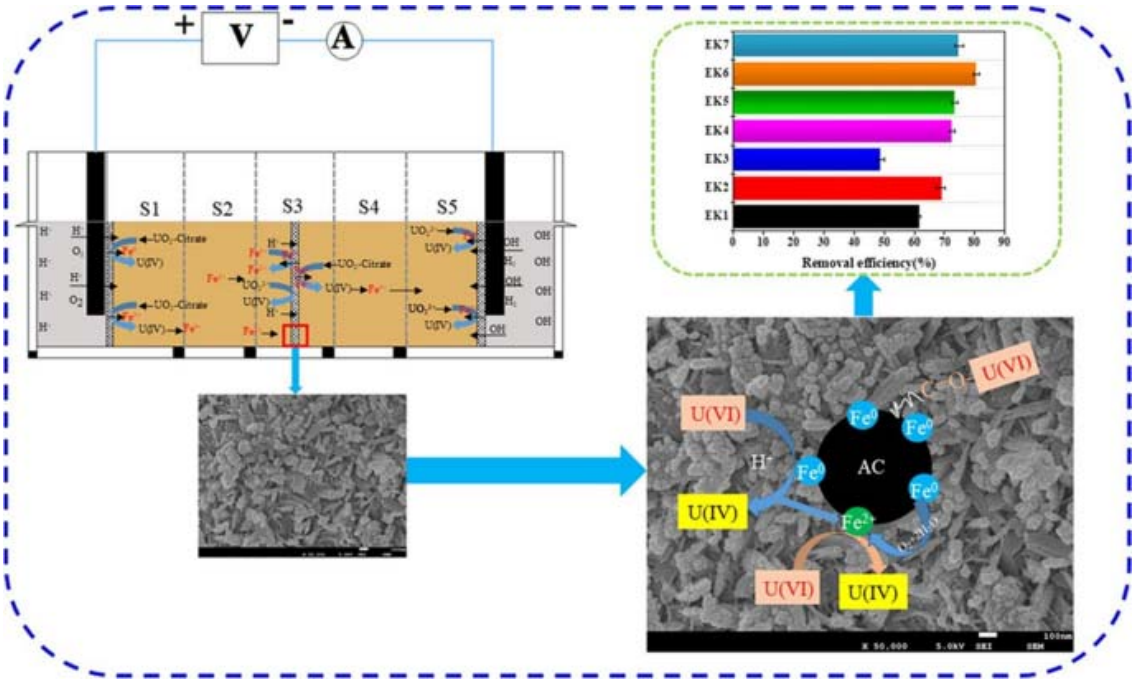

Fig. 3. A permeable reactive barrier made of iron and activated carbon for electroremediation of uranium-contaminated soil.
Adapted with permission from Xiao et al. Copyright 2020, Elsevier

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 ^{232}Th and ^{238}U 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 (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).

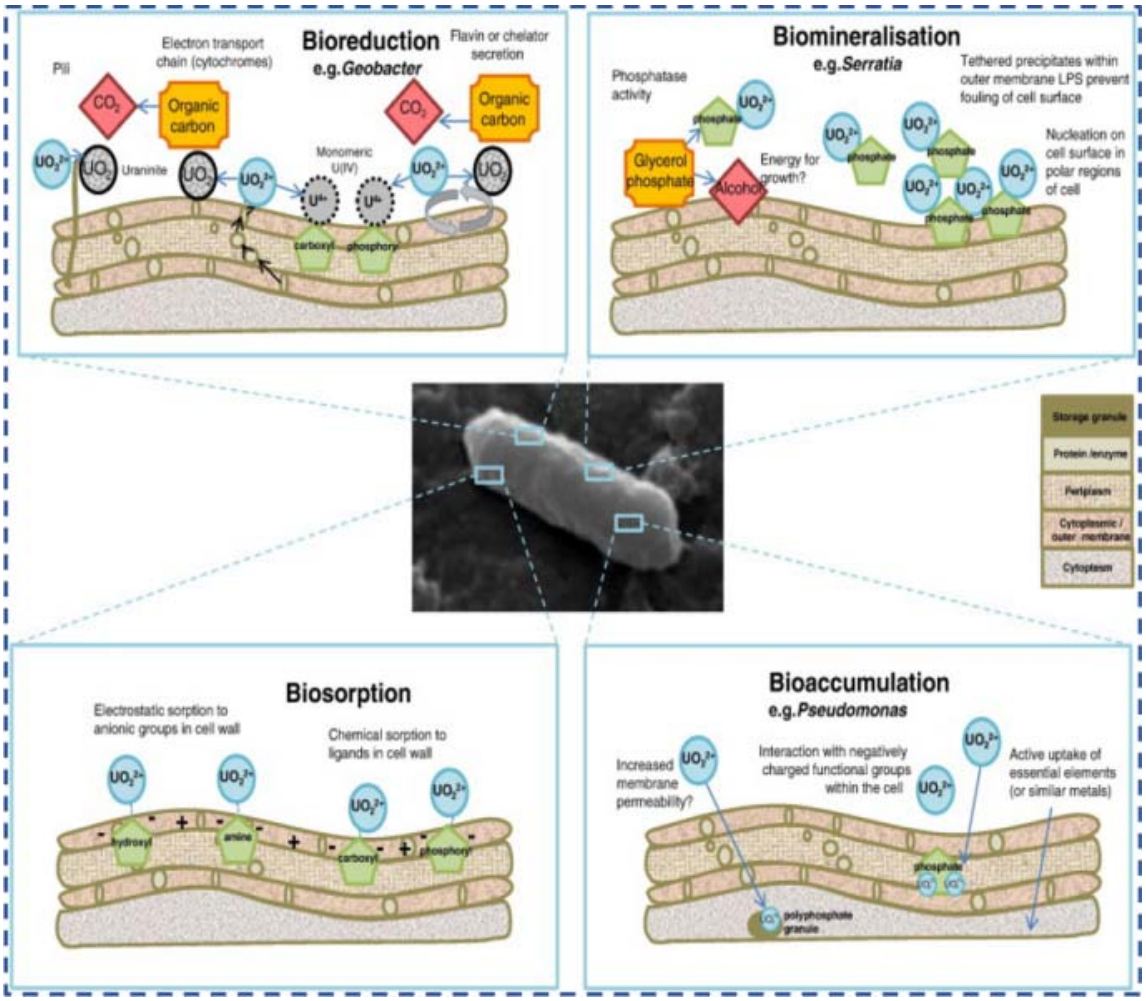

Fig. 4. Microorganism-induced remediation of uranium contamination.
Adapted from Chemical Geology, Newsome et al. 363, 164–184, Copyright 2014 Elsevier

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 cereus* 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).

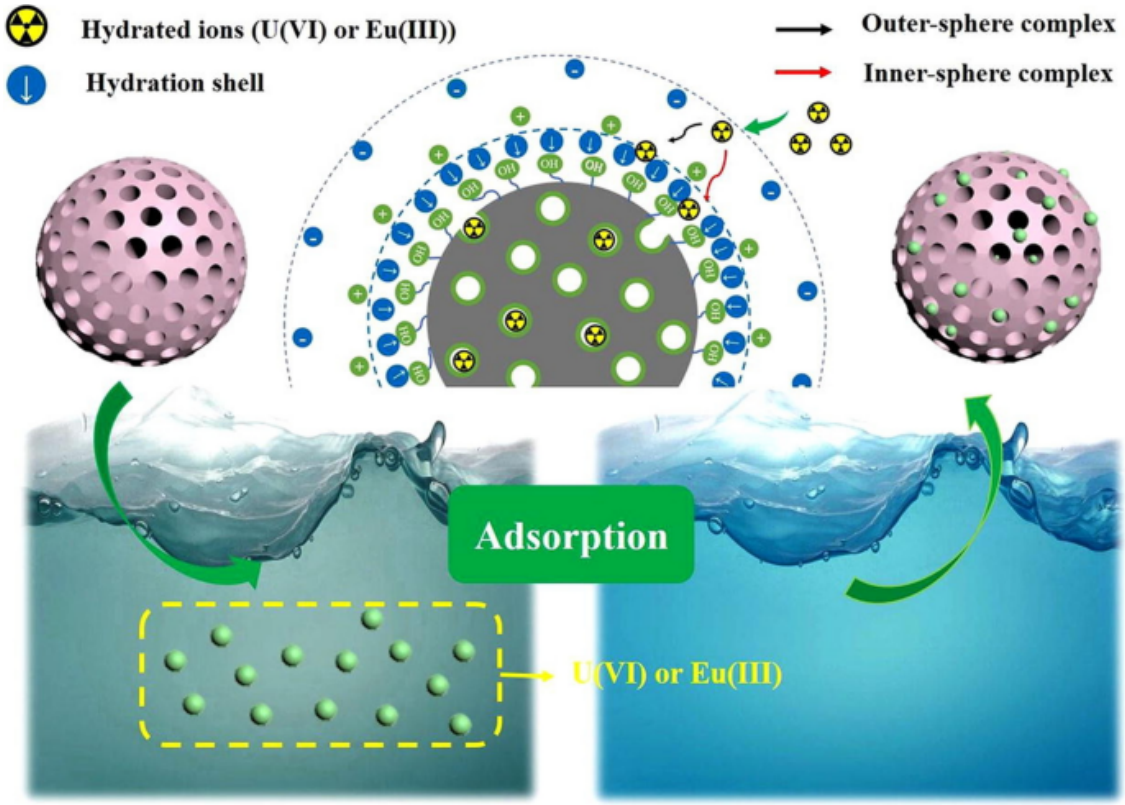

Fig. 5. Adsorption of U(VI) and Eu(III) through the formation of strong surface complexes in an aqueous solution.
Reprinted from Chemical Engineering Journal, 353, Huang et al., Unexpected ultrafast and high adsorption of U(VI) and Eu(III) from solution using porous Al_2O_3 microspheres derived from MIL-53, 157–166, 2018, with permission from Elsevier

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 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 $ZnCl_2$ 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).

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)

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 & Bhattacharya, 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 $K_2Ti_6O_{13}$ 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 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 baseload electricity while emitting very few pollutants (Muth et al., 2021; Pioro & 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).

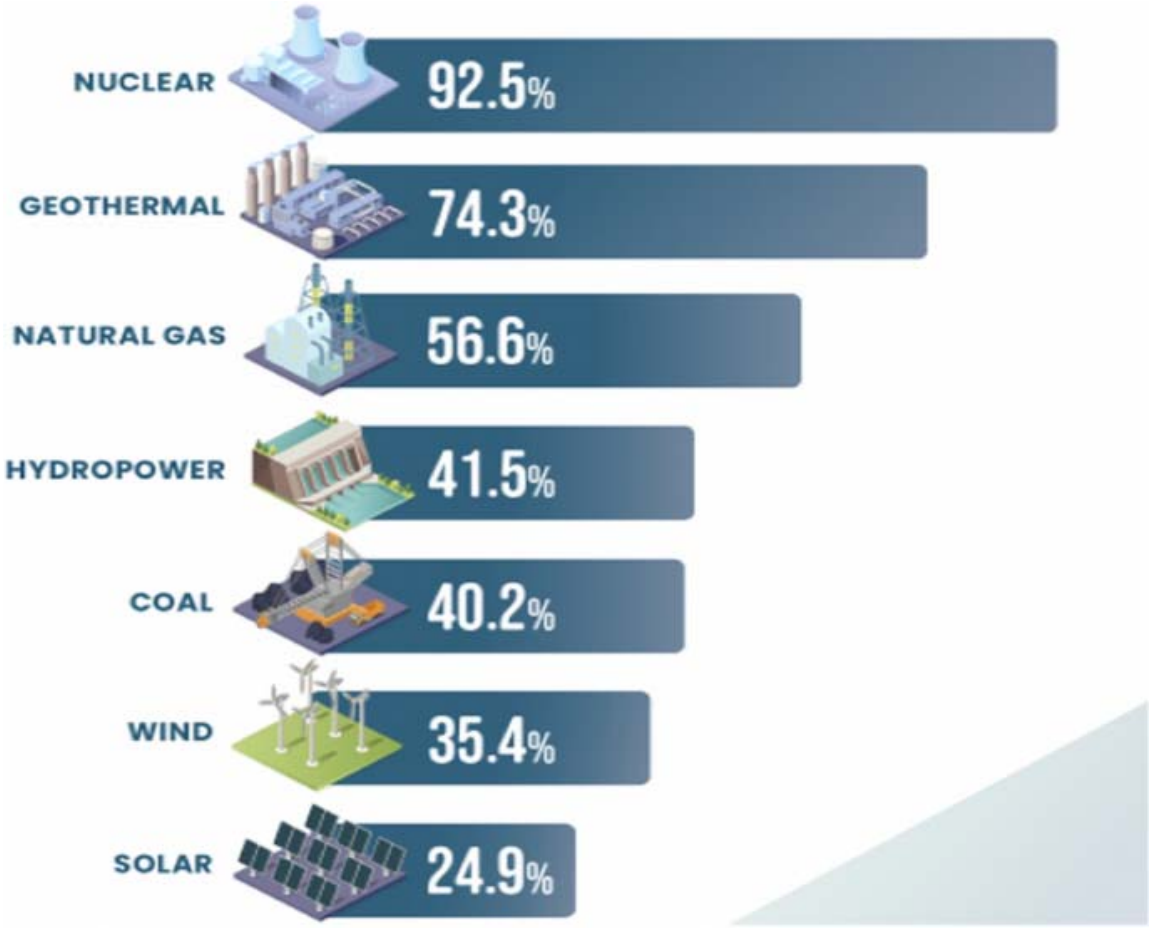

Fig. 6. The capacity factor of different energy sources in 2020.
Adapted with slight modification from US Energy Information Administration, 2021

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 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.

Funding

There was no external funding for the study.

Contributions

AOA was involved in conceptualization; methodology; writing—original draft; writing—review and editing; supervision; validation; project administration. KOI, KGA, KOO, JFA, KAA, JOI, CO, and JC helped in writing—review and editing; validation.

Conflict of interest

The authors declare that there are no conflicts of interest.

Ethical standards

This article does not contain any studies involving human or animal subjects.

References

Ababneh, Z. Q., Al-Omari, H., Rasheed, M., Al-Najjar, T., & Ababneh, A. M. (2010). Assessment of gamma-emitting radionuclides in sediment cores from the Gulf of Aqaba, Red Sea. *Radiation Protection Dosimetry, 141*, 289–298.

Abdel-Sabour, M. F. (2007). Remediation and bioremediation of uranium contaminated soils. *Electronic Journal of Environmental, Agricultural and Food Chemistry, 6*, 2009–2023.

Abella, M., Molina, M. R., Nikolic-Hughes, I., Hughes, E. W., & Ruderman, M. A. (2019). Background gamma radiation and soil activity measurements in the northern Marshall Islands. *Proceedings of the National Academy of Sciences United States of America, 116*(31), 15425–15434. https://doi.org/10.1073/pnas.1903421116

Aborisade, M. A., Gbadebo, A. M., Adedeji, O. H., Okeyode, I. C., & Ajayi, O. A. (2018). Excess lifetime cancer risk and radiation pollution hazard indices in rocks and soil of some selected mining sites in Nasarawa State, Nigeria. *Aegean Journal of Environmental Sciences, 3*, 1–18.

Adebiyi, F. M., Ore, O. T., Adeola, A. O., Durodola, S. S., Akeremale, O. F., Olubodun, K. O., & Akeremale, O. K. (2021). Occurrence and remediation of naturally occurring radioactive materials in Nigeria: A review. *Environmental Chemistry Letters, 19*, 3243–3262.

Adedokun, M. B., Aweda, M. A., Maleka, P. P., Obed, R. I., & Ibitoye, A. Z. (2020). Evaluation of natural radionuclides and associated radiation hazard indices in soil and water from selected vegetable farmlands in Lagos, Nigeria. *Environmental Forensics, 23*, 301–313.

Adegunwa, A. O., Awojide, S. H., & Ore, O. T. (2019). Investigation of radionuclide levels in groundwater around transmission company of Nigeria for environmental impact assessment. *Radiation Science and Technology, 4*(4), 66.

Adeola, A. O., Akingboye, A. S., Ore, O. T., Oluwajana, O. A., Adewole, A. H., Olawade, D. B., & Ogunyele, A. C. (2021a). Crude oil exploration in Africa: Socio-economic implications, environmental impacts, and mitigation strategies. *Environment Systems and Decisions, 42*, 26–50.

Adeola, A. O., de Lange, J., & Forbes, P. B. C. (2021b). Adsorption of antiretroviral drugs, efavirenz and nevirapine from aqueous solution by graphene wool: Kinetic, equilibrium, thermodynamic and computational studies. *Applied Surface Science Advances, 6*, 100157.

Adeola, A. O., & Forbes, P. B. C. (2021). Advances in water treatment technologies for removal of polycyclic aromatic hydrocarbons: Existing concepts, emerging trends, and future prospects. *Water Environment Research, 93*, 343–395.

Adesiji, N. E., & Ademola, J. A. (2019). Soil-to-cassava plant transfer factor of natural radionuclides on a mining impacted soil in a tropical ecosystem of Nigeria. *Journal of Environmental Radioactivity, 201*, 1–4.

Adewoyin, O. O., Maxwell, O., Akinwumi, S. A., Adagunodo, T. A., Embong, Z., & Saeed, M. A. (2022). Estimation of activity concentrations of radionuclides and their hazard indices in coastal plain sand region of Ogun state. *Scientific Reports, 12*, 2108.

Adukpo, O. K., Faanu, A., Lawluvi, H., Tettey-Larbi, L., Emi-Reynolds, G., Darko, E. O., Kansaana, C., Kpeglo, D. O., Awudu, A. R., Glover, E. T., Amoah, P. A., Efa, A. O., Agyemang, L. A., Agyeman, B. K., Kpordzro, R., & Doe, A. I. (2015). Distribution and assessment of radionuclides in sediments, soil and water from the lower basin of river Pra in the Central and Western Regions of Ghana. *Journal of Radioanalytical and Nuclear Chemistry, 303*, 1679–1685.

Agarwal, R., & Sharma, M. K. (2018). Selective electrochemical separation and recovery of uranium from mixture of uranium(VI) and lanthanide(III) ions in aqueous medium. *Inorganic Chemistry, 57*, 10984–10992.

Ahmad, N., Jaafar, M., & Alsaffar, M. (2015). Natural radioactivity in virgin and agricultural soil and its environmental implications in Sungai Petani, Kedah, Malaysia. *Pollution, 1*, 305–313.

Ajibola, T. B., Orosun, M. M., Lawal, W. A., Akinyose, F. C., & Salawu, N. B. (2021). Assessment of annual effective dose associated with radon in drinking water from gold and bismuth mining area of Edu, Kwara, North-central Nigeria. *Pollution, 7*, 231–240.

Akhtar, N., Tufail, M., Ashraf, M., & Mohsin Iqbal, M. (2005). Measurement of environmental radioactivity for estimation of radiation exposure from saline soil of Lahore, Pakistan. *Radiation Measurements, 39*, 11–14.

Akingboye, A. S., Ademila, O., Okpoli, C. C., Oyeshomo, A. V., Ijaleye, R. O., Faruwa, A. R., Adeola, A. O., & Bery, A. A. (2022). Radiogeochemistry, uranium migration, and radiogenic heat of the granite gneisses in parts of the southwestern Basement Complex of Nigeria. *Journal of African Earth Sciences, 188*, 104469.

Akingboye, A. S., Ogunyele, A. C., Jimoh, A. T., Adaramoye, O. B., Adeola, A. O., & Ajayi, T. (2021). Radioactivity, radiogenic heat production and environmental radiation risk of the Basement Complex rocks of Akungba-Akoko, southwestern Nigeria: Insights from in situ gamma-ray spectrometry. *Environmental Earth Sciences, 80*, 228.

Akpanowo, M., Umaru, I., Iyakwari, S., Joshua, E. O., Yusuf, S., & Ekong, G. B. (2020). Determination of natural radioactivity levels and radiological hazards in environmental samples from artisanal mining sites of Anka, North-West Nigeria. *Scientific African, 10*, e00561.

Alnabhani, K., Khan, F., & Yang, M. (2018). Dynamic modeling of TENORM exposure risk during drilling and production. *Journal of Petroleum Exploration and Production Technology, 8*, 175–188.

Anamika, K., Mehra, R., & Malik, P. (2020). Assessment of radiological impacts of natural radionuclides and radon exhalation rate measured in the soil samples of Himalayan foothills of Uttarakhand, India. *Journal of Radioanalytical and Nuclear Chemistry, 323*, 263–274.

Arıman, S., & Gümüş, H. (2018). Radioactivity levels and health risks due to radionuclides in the soil and sediment of mid-Black Sea: Kızılırmak Deltas-Turkey. *Radiochimica Acta, 106*, 927–937.

Arora, N. K. (2018). Bioremediation: A green approach for restoration of polluted ecosystems. *Environmental Sustainability, 1*, 305–307.

Asgharizadeh, F., Ghannadi, M., Samani, A. B., Meftahi, M., Shalibayk, M., Sahafipour, S. A., & Gooya, E. S. (2013). Natural radioactivity in surface soil samples from dwelling areas in Tehran city, Iran. *Radiation Protection Dosimetry, 156*, 376–382.

Azubuike, C. C., Chikere, C. B., & Okpokwasili, G. C. (2016). Bioremediation techniques–classification based on site of application: Principles, advantages, limitations and prospects. *World Journal of Microbiology and Biotechnology, 32*, 180.

Baeza, A., Salas, A., Guillén, J., Muñoz-Serrano, A., Ontalba-Salamanca, M. Á., & Jiménez-Ramos, M. C. (2017). Removal naturally occurring radionuclides from drinking water using a filter specifically designed for Drinking Water Treatment Plants. *Chemosphere, 167*, 107–113.

Bangotra, P., Mehra, R., Kaur, K., & Jakhu, R. (2016). Study of natural radioactivity (^{226}Ra, ^{232}Th and ^{40}K) in soil samples for the assessment of average effective dose and radiation hazards. *Radiation Protection Dosimetry, 171*, 277–281.

Benedik, L., & Jeran, Z. (2012). Radiological of natural and mineral drinking waters in Slovenia. *Radiation Protection Dosimetry, 151*, 306–313.

Benedik, L., Rovan, L., Klemenčič, H., Gantar, I., & Prosen, H. (2015). Natural radioactivity in tap waters from the private wells in the surroundings of the former Žirovski Vrh uranium mine and the age-dependent dose assessment. *Environmental Science and Pollution Research, 22*, 12062–12072.

Blowes, D. W., Ptacek, C. J., Benner, S. G., McRae, C. W. T., Bennett, T. A., & Puls, R. W. (2000). Treatment of inorganic contaminants using permeable reactive barriers11Disclaimer: The U. S. Environment Protection Agency through its Office of Research and Development partially funded and collaborated in the research described here under assistance agreement number CR-823017 to the University of Waterloo. It has not been subjected to Agency review and therefore does not necessarily reflect the views of the Agency, and no official endorsement should be inferred. Mention of trade names or commercial products does not constitute endorsement or recommendation. *Journal of Contaminant Hydrology, 45*, 123–137.

Bodunrin, J. O., Ajayi, O. S., & Oke, J. A. (2021). Human exposure levels to ionizing radiation in Agbara Industrial Estate: An impact of Industrial activities in Nigeria. *Environmental Monitoring and Assessment, 193*, 34.

Brook, B. W., Alonso, A., Meneley, D. A., Misak, J., Blees, T., & van Erp, J. B. (2014). Why nuclear energy is sustainable and has to be part of the energy mix. *Sustainable Materials and Technologies, 1–2*, 8–16.

Brown, V. J. (2014). Radionuclides in fracking wastewater: Managing a toxic blend. *Environmental Health Perspectives, 122*, A50–A55.

Bugai, D. A. (2014). Groundwater contamination following the chernobyl accident: Overview of monitoring data, assessment of radiological risks and analysis of remedial measures. In *IAEA TM conference on groundwater contamination following Fukushima accident, Vienna, Austria*.

Cameselle, C., & Gouveia, S. (2019). Physicochemical methods for the remediation of radionuclide contaminated sites. In D. K. Gupta & A. Voronina (Eds.), *Remediation measures for radioactively contaminated areas* (pp. 31–49). Springer.

Cameselle, C., & Reddy, K. R. (2012). Development and enhancement of electro-osmotic flow for the removal of contaminants from soils. *Electrochimica Acta, 86*, 10–22.

Canner, A. J., Pepper, S. E., Hayer, M., & Ogden, M. D. (2018). Removal of radionuclides from a HCl steel decontamination stream using chelating ion exchange resins—Initial studies. *Progress in Nuclear Energy, 104*, 271–279.

Caridi, F., D'Agostino, M., Marguccio, S., Belvedere, A., Belmusto, G., Marcianò, G., Sabatino, G., & Mottese, A. (2016). Radioactivity, granulometric and elemental analysis of river sediments samples from the coast of Calabria, south of Italy. *The European Physical Journal plus, 131*, 136.

Caridi, F., Paladini, G., Venuti, V., Crupi, V., Procopio, S., Belvedere, A., D'Agostino, M., Faggio, G., Grillo, R., Marguccio, S., Messina, G., & Majolino, D. (2021). Radioactivity, metals pollution and mineralogy assessment of a beach stretch from the Ionian Coast of Calabria (Southern Italy). *International Journal of Environmental Research and Public Health, 18*, 12147.

Castillo, S., de la Rosa, J. D., Sánchez de la Campa, A. M., González-Castanedo, Y., Fernández-Caliani, J. C., Gonzalez, I., & Romero, A. (2013). Contribution of mine wastes to atmospheric metal deposition in the surrounding area of an abandoned heavily polluted mining district (Rio Tinto mines, Spain). *Science of the Total Environment, 449*, 363–372.

Celik, N., Damla, N., & Cevik, U. (2010). Gamma ray concentrations in soil and building materials in Ordu, Turkey. *Radiation Effects and Defects in Solids, 165*, 1–10.

Chao, Y., Liang, C., Yang, Y., Wang, G., Maiti, D., Tian, L., Wang, F., Pan, W., Wu, S., Yang, K., & Liu, Z. (2018). Highly effective radioisotope cancer therapy with a non-therapeutic isotope delivered and sensitized by nanoscale coordination polymers. *ACS Nano, 12*, 7519–7528.

Chen, C., Zhang, X., Jiang, T., Li, M., Peng, Y., Liu, X., Ye, J., & Hua, Y. (2021). Removal of uranium(VI) from aqueous solution by $Mg(OH)_2$-coated nanoscale zero-valent iron: Reactivity and mechanism. *Journal of Environmental Chemical Engineering, 9*, 104706.

Chen, D., Zhao, X., & Li, F. (2014). Treatment of low level radioactive wastewater by means of NF process. *Nuclear Engineering and Design, 278*, 249–254.

Chen, L., Long, C., Wang, D., & Yang, J. (2020). Phytoremediation of cadmium (Cd) and uranium (U) contaminated soils by *Brassica juncea* L. enhanced with exogenous application of plant growth regulators. *Chemosphere, 242*, 125112.

Chen, R., Tanaka, H., Kawamoto, T., Wang, J., & Zhang, Y. (2017). Battery-type column for caesium ions separation using electroactive film of copper hexacyanoferrate nanoparticles. *Separation and Purification Technology, 173*, 44–48.

Coelho, E., Reis, T. A., Cotrim, M., Mullan, T. K., & Corrêa, B. (2020a). Resistant fungi isolated from contaminated uranium mine in Brazil shows a high capacity to uptake uranium from water. *Chemosphere, 248*, 126068.

Coelho, E., Reis, T. A., Cotrim, M., Rizzutto, M., & Corrêa, B. (2020b). Bioremediation of water contaminated with uranium using Penicillium piscarium. *Biotechnology Progress, 36*, e30322.

Darwish, D. A. E., Abul-Nasr, K. T. M., & El-Khayatt, A. M. (2015). The assessment of natural radioactivity and its associated radiological hazards and dose parameters in granite samples from South Sinai, Egypt. *Journal of Radiation Research and Applied Sciences, 8*, 17–25.

Duan, C., Zhang, Y., Li, J., Kang, L., Xie, Y., Qiao, W., Zhu, C., & Luo, H. (2020). Rapid room-temperature preparation of hierarchically porous metal-organic frameworks for efficient uranium removal from aqueous solutions. *Nanomaterials, 10*, 1539.

Dudu, V. P., Mathuthu, M., & Manjoro, M. (2018). Assessment of heavy metals and radionuclides in dust fallout in the West Rand mining area of South Africa. *Clean Air Journal, 28*, 42–52.

Dushenkov, S. (2003). Trends in phytoremediation of radionuclides. *Plant and Soil, 249*, 167–175.

El-Gamal, H., Hussien, M. T., & Saleh, E. E. (2019a). Evaluation of natural radioactivity levels in soil and various foodstuffs from Delta Abyan, Yemen. *Journal of Radiation Research and Applied Sciences, 12*, 226–233.

El-Gamal, H., Sefelnasr, A., & Salaheldin, G. (2019). Determination of natural radionuclides for water resources on the west bank of the Nile River, Assiut Governorate, Egypt. *Water, 11*, 311.

El-Mageed, A. I. A., El-Kamel, A.E.-H., Abbady, A.E.-B., Harb, S., & Saleh, I. I. (2013). Natural radioactivity of ground and hot spring water in some areas in Yemen. *Desalination, 321*, 28–31.

El-Taher, A., Zakaly, H. M. H., & Elsaman, R. (2018). Environmental implications and spatial distribution of natural radionuclides and heavy metals in sediments from four harbours in the Egyptian Red Sea coast. *Applied Radiation and Isotopes, 131*, 13–22.

Fang, X., Xu, Z., Luo, Y., Ren, L., & Hua, W. (2016). Removal of radionuclides from laundry wastewater containing organics and suspended solids using inorganic ion exchanger. *Procedia Environmental Sciences, 31*, 375–381.

Feng, M., Zhang, P., Zhou, H. C., & Sharma, V. K. (2018). Water-stable metal-organic frameworks for aqueous removal of heavy metals and radionuclides: A review. *Chemosphere, 209*, 783–800.

Font, J., Casas, M., Forteza, R., Cerda, V., & Garcias, F. (1993). Natural radioactive elements and heavy metals in coal, fly ash and bottom ash from a thermal power plant. Journal of Environmental Science and Health. *Part A: Environmental Science and Engineering and Toxicology, 28*, 2061–2073.

Fukuda, S. (2005). Chelating agents used for plutonium and uranium removal in radiation emergency medicine. *Current Medicinal Chemistry, 12*, 2765–2770.

Galanda, D., Mátel, Ľ, Strišovská, J., & Dulanská, S. (2014). Mycoremediation: The study of transfer factor for plutonium and americium uptake from the ground. *Journal of Radioanalytical and Nuclear Chemistry, 299*, 1411–1416.

Gonçalves, P. N., Damatto, S. R., Leonardo, L., & Souza, J. M. (2021). Natural radionuclides in soil profiles and sediment cores from Jundiaí reservoir, state of Sao Paulo-Brazil. *Brazilian Journal of Radiation Sciences, 9*, 18.

Gouma, S., Fragoeiro, S., Bastos, A. C., & Magan, N. (2014). 13—Bacterial and fungal bioremediation strategies. In S. Das (Ed.), *Microbial biodegradation and bioremediation* (pp. 301–323). Elsevier.

Hannah, L. (2022). Chapter 21—Mitigation: Reducing greenhouse gas emissions, sinks, and solutions. In L. Hannah (Ed.), *Climate change biology* (3rd ed., pp. 439–472). Academic Press.

Hassan, N., Ishikawa, T., Hosoda, M., Sorimachi, A., Tokonami, S., Fukushi, M., & Sahoo, S. (2010). Assessment of the natural radioactivity using two techniques for the measurement of radionuclide concentration in building materials used in Japan. *Journal of Radioanalytical and Nuclear Chemistry, 283*, 15–21.

He, S., Yang, Z., Cui, X., Zhang, X., & Niu, X. (2020). Fabrication of the novel Ag-doped SnS2@InVO4 composite with high adsorption-photocatalysis for the removal of uranium (VI). *Chemosphere, 260*, 127548.

Hong, G. H., Hamilton, T. F., Baskaran, M., & Kenna, T. C. (2012). Applications of anthropogenic radionuclides as tracers to investigate marine environmental processes. In M. Baskaran (Ed.), *Handbook of environmental isotope geochemistry* (Vol. I, pp. 367–394). Berlin: Springer.

Hossain, F. (2020). Natural and anthropogenic radionuclides in water and wastewater: Sources, treatments and recoveries. *Journal of Environmental Radioactivity, 225*, 106423.

Hu, X., Wang, Y., Yang, J. O., Li, Y., Wu, P., Zhang, H., Yuan, D., Liu, Y., Wu, Z., & Liu, Z. (2020). Synthesis of graphene oxide nanoribbons/chitosan composite membranes for the removal of uranium from aqueous solutions. *Frontiers of Chemical Science and Engineering, 14*, 1029–1038.

Huang, S., Pang, H., Li, L., Jiang, S., Wen, T., Zhuang, L., Hu, B., & Wang, X. (2018). Unexpected ultrafast and high adsorption of U(VI) and Eu(III) from solution using porous Al_2O_3 microspheres derived from MIL-53. *Chemical Engineering Journal, 353*, 157–166.

Huy, N. Q., Hien, P. D., Luyen, T. V., Hoang, D. V., Hiep, H. T., Quang, N. H., Long, N. Q., Nhan, D. D., Binh, N. T., Hai, P. S., & Ngo, N. T. (2012). Natural radioactivity and external dose assessment of surface soils in Vietnam. *Radiation Protection Dosimetry, 151*, 522–531.

IAEA, International Atomic Energy Agency. (2019). *Nuclear power reactors in the world*. Reference Data Series No. 2, Vienna, Austria. Retrieved July 28, 2022 from https://www.iaea.org/publications/13552/nuclear-power-reactors-in-the-world

IAEA, International Atomic Energy Agency. (2022b). *New IAEA report presents global overview of radioactive waste and spent fuel management*. Last updated [21 Jan 2022]. Retrieved August 1, 2022 from https://www.iaea.org/newscenter/news/new-iaea-report-presents-global-overview-of-radioactive-waste-and-spent-fuel-management

IAEA, International Atomic Energy Agency. (2022a). *What is nuclear energy? The science of nuclear power*. Last updated [8 Feb 2022]. Retrieved February, 16 2022aa from https://www.iaea.org/newscenter/news/what-is-nuclear-energy-the-science-of-nuclear-power

Ibigbami, T. B., Adeola, A. O., Olawade, D. B., Ore, O. T., Isaac, B. O., & Sunkanmi, A. A. (2022). Pristine and activated bentonite for toxic metal removal from wastewater. *Water Practice and Technology, 17*, 784–797.

Ibikunle, S. B., Arogunjo, A. M., & Ajayi, O. S. (2019). Characterization of radiation dose and soil-to-plant transfer factor of natural radionuclides in some cities from south-western Nigeria and its effect on man. *Scientific African, 3*, e00062.

Ilori, A. O., & Chetty, N. (2020). Soil-to-crop transfer of natural radionuclides in farm soil of South Africa. *Environmental Monitoring and Assessment, 192*, 775.

Iwetan, C. N., Fuwape, I. A., Aiyesanmi, A. F., & Ayorinde, T. T. (2019). Assessment of radiological parameters of river water and sediment in some oil producing communities of delta state of Nigeria. *Environmental Forensics, 20*, 251–264.

Janković, M. M., Todorović, D. J., Todorović, N. A., & Nikolov, J. (2012). Natural radionuclides in drinking waters in Serbia. *Applied Radiation and Isotopes, 70*, 2703–2710.

Jasaitis, D., Klima, V., Pečiulienė, M., Vasiliauskienė, V., & Konstantinova, M. (2020). Comparative assessment of radiation background due to natural and artificial radionuclides in soil in specific areas on the Territories of State of Washington (USA) and Lithuania. *Water, Air, & Soil Pollution, 231*, 347.

Jeon, J. (2019). Review of therapeutic applications of radiolabeled functional nanomaterials. *International Journal of Molecular Sciences, 20*, 2323.

Jibiri, N. N., & Okeyode, I. C. (2012). Evaluation of radiological hazards in the sediments of Ogun river, South-Western Nigeria. *Radiation Physics and Chemistry, 81*, 103–112.

Kang, T.-W., Park, W.-P., Han, Y.-U., Bong, K. M., & Kim, K. (2020). Natural and artificial radioactivity in volcanic ash soils of Jeju Island, Republic of Korea, and assessment of the radiation hazards: Importance of soil properties. *Journal of Radioanalytical and Nuclear Chemistry, 323*, 1113–1124.

Kapanadze, K., Magalashvili, A., & Imnadze, P. (2019). Distribution of natural radionuclides in the soils and assessment of radiation hazards in the Khrami Late Variscan crystal massif (Georgia). *Heliyon, 5*, e01377.

Kesäniemi, J., Jernfors, T., Lavrinienko, A., Kivisaari, K., Kiljunen, M., Mappes, T., & Watts, P. C. (2019). Exposure to environmental radionuclides is associated with altered metabolic and immunity pathways in a wild rodent. *Molecular Ecology, 28*, 4620–4635.

Khan, N. T. (2017). Radioactivity: An introduction to mysterious science. *Journal of Physical Chemistry & Biophysics, 7*(254), 2161–2398.

Khan, N., Kalair, E., Abas, N., Kalair, A. R., & Kalair, A. (2019). Energy transition from molecules to atoms and photons. *Engineering Science and Technology, an International Journal, 22*, 185–214.

Khandaker, M. U., Jojo, P. J., & Kassim, H. A. (2012). Determination of primordial radionuclides in natural samples using HPGe gamma-ray spectrometry. *APCBEE Procedia, 1*, 187–192.

Khandaker, M. U., Nasir, N. L. M., Zakirin, N. S., Kassim, H. A., Asaduzzaman, K., Bradley, D. A., Zulkifli, M. Y., & Hayyan, A. (2017). Radiation dose to the Malaysian populace via the consumption of bottled mineral water. *Radiation Physics and Chemistry, 140*, 173–179.

Kim, G.-N., Kim, S.-S., Park, H.-M., Kim, W.-S., Moon, J.-K., & Hyeon, J.-H. (2012). Development of complex electrokinetic decontamination method for soil contaminated with uranium. *Electrochimica Acta, 86*, 49–56.

Kim, K.-W., Baek, Y.-J., Lee, K.-Y., Chung, D.-Y., & Moon, J.-K. (2016). Treatment of radioactive waste seawater by coagulation–flocculation method using ferric hydroxide and poly acrylamide. *Journal of Nuclear Science and Technology, 53*, 439–450.

Kim, K.-H., Kim, S.-O., Lee, C.-W., Lee, M.-H., & Kim, K.-W. (2003). Electrokinetic processing for the removal of radionuclides in soils. *Separation Science and Technology, 38*, 2137–2163.

Kim, K.-W., Shon, W.-J., Oh, M.-K., Yang, D., Foster, R. I., & Lee, K.-Y. (2019). Evaluation of dynamic behavior of coagulation–flocculation using hydrous ferric oxide for removal of radioactive nuclides in wastewater. *Nuclear Engineering and Technology, 51*, 738–745.

Kpeglo, D. O., Mantero, J., Darko, E. O., Emi-Reynolds, G., Akaho, E. H. K., Faanu, A., & Garcia-Tenorio, R. (2014). Radiological exposure assessment from soil, underground and surface water in communities along the coast of a shallow water offshore oilfield in Ghana. *Radiation Protection Dosimetry, 163*, 341–352.

Kumar, A., Rout, S., Pulhani, V., & Kumar, A. V. (2020). A review on distribution coefficient (Kd) of some selected radionuclides in soil/sediment over the last three decades. *Journal of Radioanalytical and Nuclear Chemistry, 323*, 13–26.

Kumar, P., Kumar, B., & Singh, D. (2022). Chapter 11—Radioactive waste management. In D. Yadav, P. Kumar, P. Singh, & D. A. Vallero (Eds.), *Hazardous waste management* (pp. 289–301). Elsevier.

Kuppusamy, S., Palanisami, T., Megharaj, M., Venkateswarlu, K., & Naidu, R. (2016). Ex-situ remediation technologies for environmental pollutants: A critical perspective. In P. de Voogt (Ed.), *Reviews of environmental contamination and toxicology* (Vol. 236, pp. 117–192). Springer.

Kuppusamy, S., Thavamani, P., Megharaj, M., & Naidu, R. (2015). Bioremediation potential of natural polyphenol rich green wastes: A review of current research and recommendations for future directions. *Environmental Technology & Innovation, 4*, 17–28.

L'Annunziata, M. F. (2016). *Radioactivity: Introduction and history, from the quantum to quarks*. Elsevier.

Lack, J. G., Chaudhuri, S.K., Kelly, S. D., Kemner, K. M., O'Connor, S. M., Coates, J. D. (2002). Immobilization of radionuclides and heavy metals through anaerobic bio-oxidation of Fe(II). *Applied and Environmental Microbiology*, *68*, 2704–2710.

Landa, E. R., Reimnitz, E., Beals, D. M., Pochkowski, J. M., Winn, W. G., & Rigor, I. (1998). Transport of ^{137}Cs and ^{239,240}Pu with ice-rafted debris in the Arctic Ocean. *Arctic, 51*, 27–39.

Lee, K.-Y., Lee, S.-H., Lee, J. E., & Lee, S.-Y. (2019). Biosorption of radioactive cesium from contaminated water by microalgae *Haematococcus pluvialis* and *Chlorella vulgaris*. *Journal of Environmental Management, 233*, 83–88.

Lee, S. Y., Jung, K.-H., Lee, J. E., Lee, K. A., Lee, S.-H., Lee, J. Y., Lee, J. K., Jeong, J. T., & Lee, S.-Y. (2014). Photosynthetic biomineralization of radioactive Sr via microalgal CO_2 absorption. *Bioresource Technology, 172*, 449–452.

Lee, S., Kim, Y., Park, J., Shon, H. K., & Hong, S. (2018). Treatment of medical radioactive liquid waste using Forward Osmosis (FO) membrane process. *Journal of Membrane Science, 556*, 238–247.

Li, P., Zhun, B., Wang, X., Liao, P., Wang, G., Wang, L., Guo, Y., Zhang, W. (2017). Highly efficient interception and precipitation of Uranium(VI) from aqueous solution by iron-electrocoagulation combined with cooperative chelation by organic ligands. *Environmental Science & Technology*, *51*, 14368–14378.

Li, P., Wang, J., Wang, Y., Liang, J., He, B., Pan, D., Fan, Q., & Wang, X. (2019). Photoconversion of U(VI) by TiO_2: An efficient strategy for seawater uranium extraction. *Chemical Engineering Journal, 365*, 231–241.

Li, P., Zhun, B., Wang, X., Liao, P., Wang, G., Wang, L., Guo, Y., Zhang, W. (2017). Highly efficient interception and precipitation of Uranium(VI) from aqueous solution by iron-electrocoagulation combined with cooperative chelation by organic ligands. *Environmental Science & Technology*, *51*, 14368–14378.

Liao, J., & Zhang, Y. (2020). Effective removal of uranium from aqueous solution by using novel sustainable porous Al2O3 materials derived from different precursors of aluminum. *Inorganic Chemistry Frontiers, 7*, 765–776.

Lide, D. R. (2010). *CRC handbook of chemistry and physics* (81st ed., p. 10e220). CRC Press.

Lingamdinne, L. P., Choi, Y.-L., Kim, I.-S., Yang, J.-K., Koduru, J. R., & Chang, Y.-Y. (2017). Preparation and characterization of porous reduced graphene oxide based inverse spinel nickel ferrite nanocomposite for adsorption removal of radionuclides. *Journal of Hazardous Materials, 326*, 145–156.

Liu, M., Dong, F., Kang, W., Sun, S., Wei, H., Zhang, W., Nie, X., Guo, Y., Huang, T., & Liu, Y. (2014). Biosorption of strontium from simulated nuclear wastewater by *Scenedesmus spinosus* under culture conditions: Adsorption and bioaccumulation processes and models. *International Journal of Environmental Research and Public Health, 11*, 6099–6118.

Liu, S., Wang, Z., Lu, Y., Li, H., Chen, X., Wei, G., Wu, T., Maguire, D.-J., Ye, G., & Chen, J. (2021). Sunlight-induced uranium extraction with triazine-based carbon nitride as both photocatalyst and adsorbent. *Applied Catalysis B: Environmental, 282*, 119523.

Liu, T., Yuan, J., Zhang, B., Liu, W., Lin, L., Meng, Y., Yin, S., Liu, C., & Luan, F. (2019). Removal and recovery of uranium from groundwater using direct electrochemical reduction method: performance and implications. *Environmental Science & Technology, 53*, 14612–14619.

Liu, X., Du, P., Pan, W., Dang, C., Qian, T., Liu, H., Liu, W., & Zhao, D. (2018). Immobilization of uranium(VI) by niobate/titanate nanoflakes heterojunction through combined adsorption and solar-light-driven photocatalytic reduction. *Applied Catalysis B: Environmental, 231*, 11–22.

Liu, X., & Lin, W. (2018). Natural radioactivity in the beach sand and soil along the coastline of Guangxi Province, China. *Marine Pollution Bulletin, 135*, 446–450.

Liu, X., Wu, J., Liu, C., & Wang, J. (2017). Removal of cobalt ions from aqueous solution by forward osmosis. *Separation and Purification Technology, 177*, 8–20.

Ma, D., Wei, J., Zhao, Y., Chen, Y., & Tang, S. (2020). The removal of uranium using novel temperature sensitive urea-formaldehyde resin: Adsorption and fast regeneration. *Science of the Total Environment, 735*, 139399.

Mahamood, K. N., Divya, P. V., Vineethkumar, V., & Prakash, V. (2020). Dynamics of radionuclides activity, radon exhalation rate of soil and assessment of radiological parameters in the coastal regions of Kerala, India. *Journal of Radioanalytical and Nuclear Chemistry, 324*, 949–961.

Mani, D., & Kumar, C. (2014). Biotechnological advances in bioremediation of heavy metals contaminated ecosystems: An overview with special reference to phytoremediation. *International Journal of Environmental Science and Technology, 11*, 843–872.

Masok, F. B., Masiteng, P. L., Mavunda, R. D., Maleka, P. P., & Winkler, H. (2018). Measurement of radioactivity concentration in soil samples around phosphate rock storage facility in Richards Bay, South Africa. *Journal of Radiation Research and Applied Sciences, 11*, 29–36.

McElroy, E., Lawter, A. R., Appriou, D., Smith, F., Bowden, M., Qafoku, O., Kovarik, L., Szecsody, J. E., Truex, M. J., & Qafoku, N. P. (2020). Iodate interactions with calcite: Implications for natural attenuation. *Environmental Earth Sciences, 79*, 306.

Menshikova, E., Perevoshchikov, R., Belkin, P., & Blinov, S. (2021). Concentrations of natural radionuclides (40K, 226Ra, 232Th) at the potash salts deposit. *Journal of Ecological Engineering, 22*, 179–187.

Mihalik, J., Tlustoš, P., & Száková, J. (2011). The influence of citric acid on mobility of radium and metals accompanying uranium phytoextraction. *Plant, Soil and Environment, 57*(11), 526–531.

Mihara, F., Shuseki, Y., Tamura, S., Ui, K., Kikuchi, K., Yasumori, A., Komaba, S., Fukunishi, M., Kogo, Y., Idemoto, Y., & Takeuchi, K. (2019). Removal of strontium from aqueous solutions using scallop shell powder. *Journal of the Ceramic Society of Japan*, *127*(2), 111–116.

Mohamed Johar, S., & Embong, Z. (2015). The optimisation of electrokinetic remediation for heavy metals and radioactivity contamination on Holyrood-Lunas soil (acrisol species) in Sri Gading Industrial Area, Batu Pahat, Johor, Malaysia. *Radiation Protection Dosimetry, 167*, 160–164.

Momoh, A. H., Ochalla, I., Ocheni, D. O., Ajibade, D. R., & Bello, A. I. (2020). Radiological status of drinking water sources around a coal mining site in Kogi State, North Central Nigeria. *Journal of Applied Sciences and Environmental Management, 24*, 903–908.

Muth, C. J., Aalto, P., Mylläri, F., Rönkkö, T., & Harsia, P. (2021). Chapter 2—Globally and locally applicable technologies to accelerate electrification. In P. Aalto (Ed.), *Electrification* (pp. 25–55). Academic Press.

Nariyan, E., Sillanpää, M., & Wolkersdorfer, C. (2018). Uranium removal from Pyhäsalmi/Finland mine water by batch electrocoagulation and optimization with the response surface methodology. *Separation and Purification Technology, 193*, 386–397.

Newsome, L., Morris, K., & Lloyd, J. R. (2014). The biogeochemistry and bioremediation of uranium and other priority radionuclides. *Chemical Geology, 363*, 164–184.

Noor, T., Javid, A., Hussain, A., Bukhari, S. M., Ali, W., Akmal, M., & Hussain, S. M. (2020). Chapter 14—Types, sources and management of urban wastes. In P. Verma, P. Singh, R. Singh, & A. S. Raghubanshi (Eds.), *Urban ecology* (pp. 239–263). Elsevier.

Novikov, A. P. (2010). Migration and concentration of artificial radionuclides in environmental objects. *Geochemistry International, 48*, 1263–1387.

Ojovan, M. I., & Lee, W. E. (2014). 4—Naturally occurring radionuclides. In M. I. Ojovan & W. E. Lee (Eds.), *An introduction to nuclear waste immobilisation* (2nd ed., pp. 31–39). Elsevier.

Ore, O. T., & Adeola, A. O. (2021). Toxic metals in oil sands: Review of human health implications, environmental impact, and potential remediation using membrane-based approach. *Energy, Ecology and Environment, 6*, 81–91.

Osman, A. A. A., Salih, I., Shaddad, I. A., El Din, S., Siddeeg, M. B., Eltayeb, H., Idriss, H., Hamza, W., & Yousif, E. H. (2008). Investigation of natural radioactivity levels in water around Kadugli, Sudan. *Applied Radiation and Isotopes, 66*, 1650–1653.

Ouyang, B., Renock, D. J., Ajemigbitse, M. A., Van Sice, K., Warner, N. R., Landis, J. D., & Feng, X. (2019). Radium in hydraulic fracturing wastewater: Distribution in suspended solids and implications to its treatment by sulfate co-precipitation. *Environmental Science: Processes & Impacts, 21*, 339–351.

Ozdemir, S., Kılınc, E., Yalcin, M. S., Soylak, M., & Sen, F. (2020). A new magnetized thermophilic bacteria to preconcentrate uranium and thorium from environmental samples through magnetic solid-phase extraction. *Journal of Pharmaceutical and Biomedical Analysis, 186*, 113315.

Papadopoulos, A., Christofides, G., Koroneos, A., & Stoulos, S. (2014). Natural radioactivity distribution and gamma radiation exposure of beach sands from Sithonia Peninsula. *Open Geosciences, 6*, 229–242.

Papaefthymiou, H., Gkaragkouni, A., Papatheodorou, G., & Geraga, M. (2017). Radionuclide activities and elemental concentrations in sediments from a polluted marine environment (Saronikos Gulf-Greece). *Journal of Radioanalytical and Nuclear Chemistry, 314*, 1841–1852.

Patel, A. K., Singhania, R. R., Albarico, F. P. J. B., Pandey, A., Chen, C.-W., & Dong, C.-D. (2022). Organic wastes bioremediation and its changing prospects. *Science of the Total Environment, 824*, 153889.

Petrangeli, G. (2020). Chapter 1—Introduction. In G. Petrangeli (Ed.), *Nuclear safety* (2nd ed., pp. 1–17). Butterworth-Heinemann.

Pioro, I., & Duffey, R. (2019). 3—Current status of electricity generation in the world and future of nuclear power industry. In T. M. Letcher (Ed.), *Managing global warming* (pp. 67–114). Academic Press.

Psaltou, S., & Zouboulis, A. (2020). Catalytic ozonation and membrane contactors—A review concerning fouling occurrence and pollutant removal. *Water, 12*, 2964.

Pucci, C., Martinelli, C., & Ciofani, G. (2019). Innovative approaches for cancer treatment: Current perspectives and new challenges. *Ecancermedicalscience, 13*, 961.

Rae, I. B., Pap, S., Svobodova, D., & Gibb, S. W. (2019). Comparison of sustainable biosorbents and ion-exchange resins to remove Sr^{2+} from simulant nuclear wastewater: Batch, dynamic and mechanism studies. *Science of the Total Environment, 650*, 2411–2422.

Rahmat, M. A., Ismail, A. F., Rodzi, N. D., Aziman, E. S., Idris, W. M. R., & Lihan, T. (2022). Assessment of natural radionuclides and heavy metals contamination to the environment: Case study of Malaysian unregulated tin-tailing processing industry. *Nuclear Engineering and Technology, 54*, 2230–2243.

Ramadan, R. S., Dawood, Y. H., Yehia, M. M., & Gad, A. (2022). Environmental and health impact of current uranium mining activities in southwestern Sinai, Egypt. *Environmental Earth Sciences, 81*, 213.

Rani, A., Mittal, S., Mehra, R., & Ramola, R. C. (2015). Assessment of natural radionuclides in the soil samples from Marwar region of Rajasthan, India. *Applied Radiation and Isotopes, 101*, 122–126.

Ravisankar, R., Sivakumar, S., Chandrasekaran, A., Prince Prakash Jebakumar, J., Vijayalakshmi, I., Vijayagopal, P., & Venkatraman, B. (2014). Spatial distribution of gamma radioactivity levels and radiological hazard indices in the East Coastal sediments of Tamilnadu, India with statistical approach. *Radiation Physics and Chemistry, 103*, 89–98.

Reddy, K. R., Ala, P. R., Sharma, S., & Kumar, S. N. (2006). Enhanced electrokinetic remediation of contaminated manufactured gas plant soil. *Engineering Geology, 85*, 132–146.

Reddy, K. R., & Cameselle, C. (2009). *Electrochemical remediation technologies for polluted soils, sediments and groundwater*. Wiley.

Reddy, P. C. O., Raju, K. S., Sravani, K., Sekhar, A. C., & Reddy, M. K. (2019). Transgenic plants for remediation of radionuclides. In: *Transgenic plant technology for remediation of toxic metals and metalloids*. London: Academic Press, pp 187–237. https://doi.org/10.1016/B978-0-12-814389-6.00010-9

Ribeiro, F. C. A., Lauria, D. D. C., Silva, J. I. R., Lima, E. S. A., Amaral Sobrinho, N. M. B. D., & Pérez, D. V. (2018). Baseline and quality reference values for natural radionuclides in soils of Rio de Janeiro State, Brazil. *Revista Brasileira de Ciência do Solo, 42*, 1–15.

Rogers, H., Bowers, J., & Gates-Anderson, D. (2012). An isotope dilution–precipitation process for removing radioactive cesium from wastewater. *Journal of Hazardous Materials, 243*, 124–129.

Rosenfeld, P. E., & Feng, L. G. H. (2011). 1—Definition of hazardous waste. In P. E. Rosenfeld & L. G. H. Feng (Eds.), *Risks of hazardous wastes* (pp. 1–10). William Andrew Publishing.

Rout, T. K., Sengupta, D. K., Kaur, G., & Kumar, S. (2006). Enhanced removal of dissolved metal ions in radioactive effluents by flocculation. *International Journal of Mineral Processing, 80*, 215–222.

Rypkema, H. A. (2018). Chapter 2.1—Environmental chemistry, renewable energy, and global policy. In B. Török & T. Dransfield (Eds.), *Green chemistry* (pp. 19–47). Elsevier.

Saichek, R. E., & Reddy, K. R. (2005). Surfactant-enhanced electrokinetic remediation of polycyclic aromatic hydrocarbons in heterogeneous subsurface environments. *Journal of Environmental Engineering and Science, 4*, 327–339.

Sakamoto, S., & Kawase, Y. (2016). Adsorption capacities of poly-γ-glutamic acid and its sodium salt for cesium removal from radioactive wastewaters. *Journal of Environmental Radioactivity, 165*, 151–158.

Salbu, B., & Lind, O. C. (2020). Analytical techniques for charactering radioactive particles deposited in the environment. *Journal of Environmental Radioactivity, 211*, 106078.

Sancho, M., Arnal, J. M., Verdú, G., Lora, J., & Villaescusa, J. I. (2006). Ultrafiltration and reverse osmosis performance in the treatment of radioimmunoassay liquid wastes. *Desalination, 201*, 207–215.

Sanganyado, E. (2021). Policies and regulations for emerging pollutants in freshwater ecosystems: Challenges and opportunities. In T. Dalu & N. T. Tavengwa (Eds.), *Emerging freshwater pollutants*. Elsevier.

Semerikov, S., Alokhina, T., Gudzenko, V., Chukharev, S., Sakhno, S., Striuk, A., Iatsyshyn, A., Klimov, S., Osadchyi, V., Vakaliuk, T., Nechypurenko, P., Bondarenko, O., & Danylchuk, H. (2021). Distribution of radionuclides in modern sediments of the rivers flowing into the Dnieper-Bug Estuary. In *E3S Web of conferences* 280.

Shadrin, N., Mirzoeva, N., Sidorov, I., Korotkov, A., & Anufriieva, E. (2020). Natural radionuclides in bottom sediments of the saline lakes. What factors determine their concentration? *Environmental Earth Sciences, 79*, 168.

Sharma, P. R., Sharma, S. K., Borges, W., Chen, H., & Hsiao, B. S. (2020). *Remediation of UO_2^{2+} from water by nitro-oxidized carboxycellulose nanofibers: Performance and mechanism. Contaminants in our water: identification and remediation methods*. American Chemical Society (pp. 269–283).

Sharma, S., & Bhattacharya, A. (2017). Drinking water contamination and treatment techniques. *Applied Water Science, 7*, 1043–1067.

Sharma, S., Singh, B., & Manchanda, V. K. (2015). Phytoremediation: Role of terrestrial plants and aquatic macrophytes in the remediation of radionuclides and heavy metal contaminated soil and water. *Environmental Science and Pollution Research, 22*, 946–962.

Sheng, G., Dong, H., & Li, Y. (2012). Characterization of diatomite and its application for the retention of radiocobalt: Role of environmental parameters. *Journal of Environmental Radioactivity, 113*, 108–115.

Shukla, S. K., Hariharan, S., & Rao, T. S. (2020). Uranium bioremediation by acid phosphatase activity of *Staphylococcus aureus* biofilms: Can a foe turn a friend? *Journal of Hazardous Materials, 384*, 121316.

Sia, J., Szmyd, R., Hau, E., & Gee, H. E. (2020). Molecular mechanisms of radiation-induced cancer cell death: A primer. *Front Cell Dev Biol, 8*, 41. https://doi.org/10.3389/fcell.2020.00041

Siegel, J. A., & Sparks, R. B. (2002). Radioactivity appearing at landfills in household trash of nuclear medicine patients: Much ado about nothing? *Health Physics, 82*, 367–372.

Siegel, M. D., & Bryan, C. R. (2014). 11.6—Radioactivity, geochemistry, and health. In H. D. Holland & K. K. Turekian (Eds.), *Treatise on geochemistry* (2nd ed., pp. 191–256). Elsevier.

Song, B., Zeng, G., Gong, J., Liang, J., Xu, P., Liu, Z., Zhang, Y., Zhang, C., Cheng, M., Liu, Y., Ye, S., Yi, H., & Ren, X. (2017). Evaluation methods for assessing effectiveness of in situ remediation of soil and sediment contaminated with organic pollutants and heavy metals. *Environment International, 105*, 43–55.

Song, S., Zhang, S., Huang, S., Zhang, R., Yin, L., Hu, Y., Wen, T., Zhuang, L., Hu, B., & Wang, X. (2019a). A novel multi-shelled Fe_3O_4@MnOx hollow microspheres for immobilizing U(VI) and Eu(III). *Chemical Engineering Journal, 355*, 697–709.

Song, W., Wang, X., Sun, Y., Hayat, T., & Wang, X. (2019b). Bioaccumulation and transformation of U(VI) by sporangiospores of *Mucor circinelloides*. *Chemical Engineering Journal, 362*, 81–88.

Song, W., Wang, X., Wang, Q., Shao, D., & Wang, X. (2015). Plasma-induced grafting of polyacrylamide on graphene oxide nanosheets for simultaneous removal of radionuclides. *Physical Chemistry Chemical Physics, 17*, 398–406.

Soudek, P., Tykva, R., & Vaněk, T. (2004). Laboratory analyses of ^{137}Cs uptake by sunflower, reed and poplar. *Chemosphere, 55*, 1081–1087.

Strand, P., Jefferies, N., Koma, Y., & Plyer, J. (2022). Methodological developments and practice in characterisation of unconventional and legacy waste. *Journal of Radiological Protection, 42*, 020501.

Sukatis, F. F., & Aris, A. Z. (2021). *Metal−organic frameworks based adsorbents for aquatic pollutants removal: Metal−organic frameworks for environmental remediation* (pp. 155–170). American Chemical Society.

Tochaikul, G., Phattanasub, A., Khemkham, P., Saengthamthawee, K., Danthanavat, N., & Moonkum, N. (2022). *Radioactive waste treatment technology: A review*. Kerntechnik.

U.S Energy information Administration. (2021). *Nuclear power plants*. Last updated April 6, 2021 from https://www.eia.gov/energyexplained/nuclear/nuclear-power-plants.php

Uhunamure, S. E., Agyekum, E. B., Durowoju, O. S., Shale, K., Nethengwe, N. S., Ekosse, G.-I.E., & Adebayo, T. S. (2021). Appraisal of nuclear energy as an alternative option in South Africa's energy scenario: A multicriteria analysis. *Applied Sciences, 11*, 10349.

UNSCEAR, United Nation Scientific Committee on the Effects of Atomic Radiation. (2008). *Sources and effects of ionizing radiation*. United Nations. Report of the United Nations Scientific Committee on the Effect of Atomic Radiation to General Assembly, New York, USA. https://www.unscear.org/docs/reports/2008/11-80076_Report_2008_Annex_E.pdf

UNSCEAR, United Nation Scientific Committee on the Effects of Atomic Radiation. (2016). *Developments since the 2013 UNSCEAR report on the levels and effects of radiation exposure due to the nuclear accident following the great east-Japan earthquake and tsunami*. https://www.unscear.org/unscear/en/publications/Fukushima_WP2016.html

Valdovinos, V., Monroy-Guzman, F., & Bustos, E. (2014). Treatment methods for radioactive wastes and its electrochemical applications. In M. C. Hernandez-Soriano (Ed.), *Environmental risk assessment of soil contamination*. IntechOpen. https://doi.org/10.5772/57445.

Valković, V. (2019). Chapter 2—Technologically modified exposure to natural radiation. In V. Valković (Ed.), *Radioactivity in the environment* (2nd ed., pp. 31–62). Elsevier.

van Hullebusch, E. D., Lens, P. N. L., & Tabak, H. H. (2005). Developments in bioremediation of soils and sediments polluted with metals and radionuclides. 3. Influence of chemical speciation and bioavailability on contaminants immobilization/mobilization bio-processes. *Reviews in Environmental Science and Bio/technology, 4*, 185–212.

Vijay, A., Khandelwal, A., Chhabra, M., & Vincent, T. (2020). Microbial fuel cell for simultaneous removal of uranium (VI) and nitrate. *Chemical Engineering Journal, 388*, 124157.

Vives i Batlle, J. (2012). Radioactivity in the marine environment. In R. A. Meyers (Ed.), *Encyclopedia of sustainability science and technology* (pp. 8387–8425). Springer.

Wang, S., Wang, L., Li, Z., Zhang, P., Du, K., Yuan, L., Ning, S., Wei, Y., & Shi, W. (2021). Highly efficient adsorption and immobilization of U(VI) from aqueous solution by alkalized MXene-supported nanoscale zero-valent iron. *Journal of Hazardous Materials, 408*, 124949.

Wei, H., Dong, F., Chen, M., Zhang, W., He, M., & Liu, M. (2020). Removal of uranium by biogenetic jarosite coupled with photoinduced reduction in the presence of oxalic acid: A low-cost remediation technology. *Journal of Radioanalytical and Nuclear Chemistry, 324*, 715–729.

Wen, S., Sun, Y., Liu, R., Chen, L., Wang, J., Peng, S., Ma, C., Yuan, Y., Gong, W., & Wang, N. (2021). Supramolecularly poly(amidoxime)-loaded macroporous resin for fast uranium recovery from seawater and uranium-containing wastewater. *ACS Applied Materials & Interfaces, 13*, 3246–3258.

Wen, X., Li, F., & Zhao, X. (2016). Filtering of low-level radioactive wastewater by means of vacuum membrane distillation. *Nuclear Technology, 194*, 379–386.

WHO: World Health Organization. (2016). *Ionizing radiation, health effects and protective measures*. World Health Organization.

WNA, World Nuclear Association. (2020). *Naturally-occurring radioactive materials (NORM)*. Updated April 2021. Retrieved February 16, 2022 from https://www.world-nuclear.org/informationlibrary/safety-and-security/radiation-and-health/naturally-occurring-adioactive-materials-norm.aspx

Wu, L., Zhang, G., Wang, Q., Hou, L., & Gu, P. (2014). Removal of strontium from liquid waste using a hydraulic pellet co-precipitation microfiltration (HPC-MF) process. *Desalination, 349*, 31–38.

Wuana, R. A., Okieimen, F. E., & Imborvungu, J. A. (2010). Removal of heavy metals from a contaminated soil using organic chelating acids. *International Journal of Environmental Science & Technology, 7*, 485–496.

Xiao, J., Pang, Z., Zhou, S., Chu, L., Rong, L., Liu, Y., Li, J., & Tian, L. (2020a). The mechanism of acid-washed zero-valent iron/activated carbon as permeable reactive barrier enhanced electrokinetic remediation of uranium-contaminated soil. *Separation and Purification Technology, 244*, 116667.

Xiao, J., Zhou, S., Chu, L., Liu, Y., Li, J., Zhang, J., & Tian, L. (2020b). Electrokinetic remediation of uranium(VI)-contaminated red soil using composite electrolyte of citric acid and ferric chloride. *Environmental Science and Pollution Research, 27*, 4478–4488.

Yan, A., Wang, Y., Tan, S. N., Mohd Yusof, M. L., Ghosh, S., & Chen, Z. (2020). Phytoremediation: A promising approach for revegetation of heavy metal-polluted land. *Frontiers in Plant Science, 11*, 359.

Yao, W., Wang, X., Liang, Y., Yu, S., Gu, P., Sun, Y., Xu, C., Chen, J., Hayat, T., Alsaedi, A., & Wang, X. (2018). Synthesis of novel flower-like layered double oxides/carbon dots nanocomposites for U(VI) and ^{241}Am(III) efficient removal: Batch and EXAFS studies. *Chemical Engineering Journal, 332*, 775–786.

Yasmin, S., Barua, B. S., Uddin Khandaker, M., Kamal, M., Abdur Rashid, M., Abdul Sani, S. F., Ahmed, H., Nikouravan, B., & Bradley, D. A. (2018). The presence of radioactive materials in soil, sand and sediment samples of Potenga sea beach area, Chittagong, Bangladesh: Geological characteristics and environmental implication. *Results in Physics, 8*, 1268–1274.

Yong, G., Jun, Z., Guanghui, Z., Dong, Z., Weiwen, C., Guoqi, Y., Xuejun, L., Bangzhong, M., Junhui, Z., & Ping, G. (2004). Treatment of the wastewater containing low-level 241Am using flocculation-microfiltration process. *Separation and Purification Technology, 40*, 183–189.

Zakrzewska-Trznadel, G., Harasimowicz, M., & Chmielewski, A. G. (1999). Concentration of radioactive components in liquid low-level radioactive waste by membrane distillation. *Journal of Membrane Science, 163*, 257–264.

Zhang, Q., Wang, Y., Wang, Z., Zhang, Z., Wang, X., & Yang, Z. (2021a). Active biochar support nano zero-valent iron for efficient removal of U(VI) from sewage water. *Journal of Alloys and Compounds, 852*, 156993.

Zhang, W., Dong, Y., Wang, H., Guo, Y., Zeng, H., & Zan, J. (2021b). Removal of uranium from groundwater using zero-valent-iron coated quartz sands. *Journal of Radioanalytical and Nuclear Chemistry, 327*, 1–12.

Zhang, W., Liu, H., Fan, X., Zhuo, Z., & Guo, Y. (2020). Removal of uranium from aqueous solution by a permeable reactive barrier loaded with hydroxyapatite-coated quartz sand: Implication for groundwater remediation. *Geochemistry, 80*, 125545.

Zheng, X. Y., Shen, Y. H., Wang, X. Y., & Wang, T. S. (2018). Effect of pH on uranium(VI) biosorption and biomineralization by *Saccharomyces cerevisiae*. *Chemosphere, 203*, 109–116.

Zhou, P., & Gu, B. (2005). Extraction of oxidized and reduced forms of uranium from contaminated soils: effects of carbonate concentration and pH. *Environmental Science & Technology, 39*, 4435–4440.

Zhu, M., Cai, Y., Liu, S., Fang, M., Tan, X., Liu, X., Kong, M., Xu, W., Mei, H., & Hayat, T. (2019). $K_2Ti_6O_{13}$ hybridized graphene oxide: Effective enhancement in photodegradation of RhB and photoreduction of U(VI). *Environmental Pollution, 248*, 448–455.