# Occurrence and remediation of naturally occurring radioactive materials in Nigeria: a review

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## Abstract

Radioactive compounds are released in the environment by several anthropogenic activities, however, studies reveal that naturally occurring radioactive materials are responsible for over 80% of human exposure to ionizing radiation. Reports suggest that there are severe health risks associated with exposure to elevated concentrations of radioactive materials, such as potassium ($^{40}$K), uranium ($^{238}$U and $^{235}$U), and thorium ($^{232}$Th). The rarity of comprehensive reviews addressing the occurrence, risk assessment, and potential remediation strategies of radioactive pollution in Nigerian environments propelled the collection of data over the last decade. Concentration as high as 2.42 ± 0.28 Bq/L has been reported in rivers in Nigeria, much higher than the radionuclide permissible level of 1 Bq/L. There are emerging concerns as activity concentrations of gamma-emitting radioactive materials found in soils are higher than worldwide average crustal values based on several reports. In many cases, the absorbed air dose rates were also greater (i.e., 86.44 nGy hr$^{-1}$) than acceptable limits (60 nGy hr$^{-1}$) except for few study areas. The level of radionuclides reported is indicative of the type of parent rocks and mineral composition of the studied area. Advances in remediation technologies suggest that electroremediation, bioremediation, and adsorption are the most efficient remedial approach for decontamination of radiochemical polluted sites. There is a need to explore an integrated synergistic approach for sustainable remediation of heavily polluted sites and in the light of environmental protection, attention must be given to areas with high levels of radioactive pollution. This review seeks to bridge information gaps towards ensuring that radioactive materials do not destroy our ecosystem.

**Keywords:** Energy; Environment; Gamma rays; Radioactive materials; Primordial radionuclides

## 1. Introduction

The radiation in the environment emanates from natural and anthropogenic sources. However, estimates revealed that more than 80% of the worldwide environmental radiation is from natural sources (WHO 2016). Environmental radiation exposure is caused by the presence of primordial radionuclides in the earth's crust and atmospheric cosmic rays' interaction (UNSCEAR 2008; Jasaitis et al. 2020). The primordial radionuclides include $^{232}$Th, $^{238}$U, $^{235}$U, and $^{40}$K while the cosmogenic radionuclides include $^{36}$Cl, $^{32}$Si, $^{7}$Be, $^{14}$C, $^{10}$Be, $^{26}$Al, and $^{3}$H (Twining and Baxter 2012; Khandaker et al. 2012). The half-lives of these radioactive materials are comparable to their decay products and the age of the earth (Primal and Narayana 2012; Mahamood et al. 2020). Due to this, it is expected that non-cosmogenic radionuclides would have undergone radioactive decay to a level that is probably undetectable (L'Annunziata 2020). The half-lives, decay modes, and isotopic abundance of these radioactive materials are presented in Table 1 while a representative diagram of the radioactive decay in thorium (Th) and uranium (U) series is presented in Figure 1. Under natural conditions, the presence of radioactive materials in the environment does not upset the dynamic balance of the ecosystem (Liu and Lin 2018). However, it is presumed that elevated levels of radioactive materials could bring about an alteration in the natural ecology of the biosphere, posing severe hazards upon exposure.

**Table 1: Long-lived naturally occurring radioactive materials (Lide 2010)**

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

Radionuclides such as radium, thorium, potassium, and uranium, are released into different environmental matrices such as soil, water, and/or air. The naturally occurring radium, thorium, and uranium are particularly associated with the release of gamma rays, with their concentrations heavily dependent on geographical and geological conditions (Pandey et al. 2017; El-Taher et al. 2018, Akingboye et al. 2021). Gamma radiation is reported to contribute significantly to the radiation dose exposed to by humans (Sanjurjo-Sánchez, and Alves 2017; Abd El-Azeem and Mansour 2020). The major exposure pathways to radionuclides include external exposure from radionuclide deposits embedded in marine sediments and freshwater, ingestion of foodstuffs and drinking water, and cloud immersion (UNSCEAR 2016). The protection of lives against potential hazards emanating from exposure to these radionuclides requires a proper understanding of their

generation, migration from source, and influential factors responsible for the entire process (Al-Jarallah et al. 2005; Somlai et al. 2006, 2008).

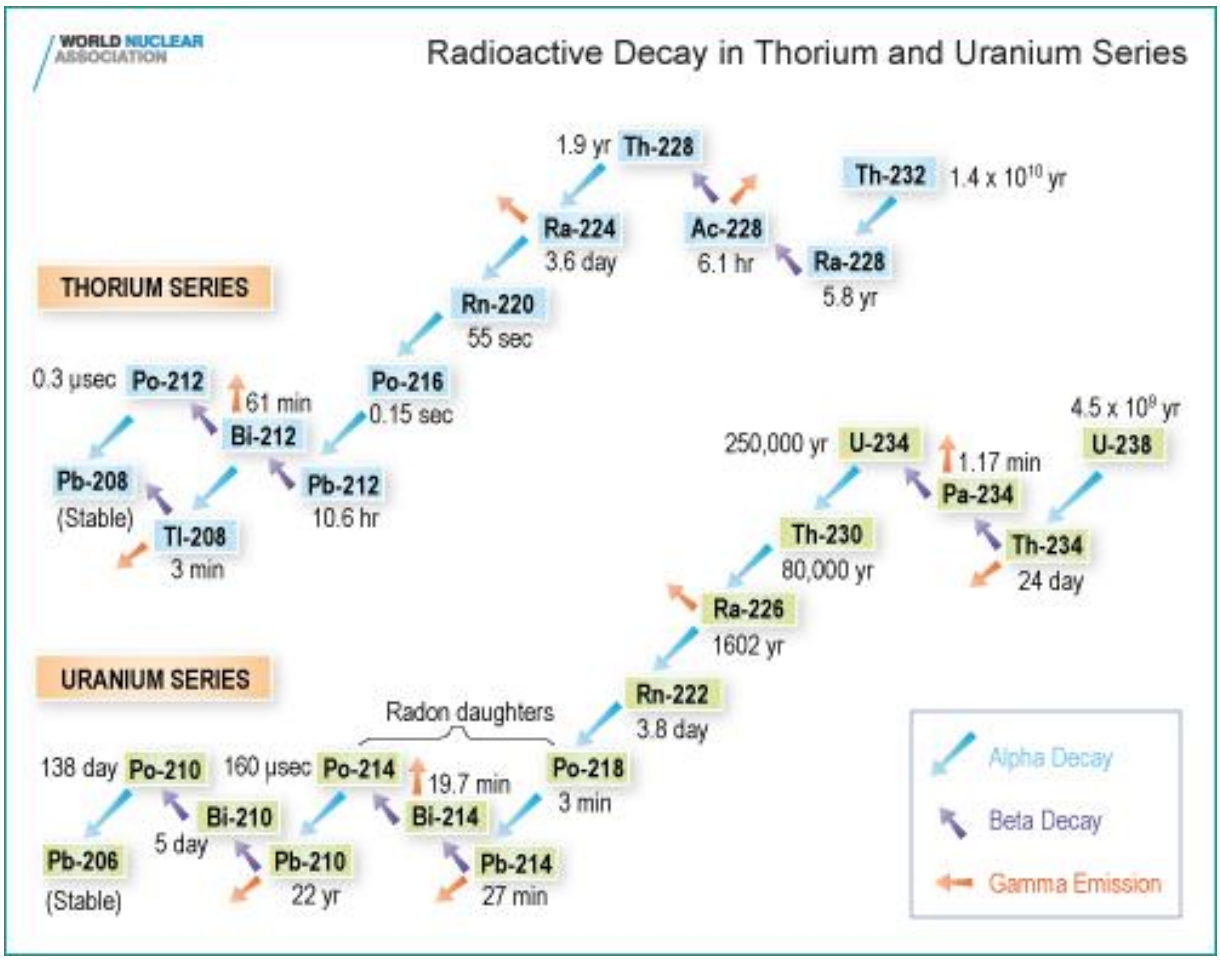


**Figure 1:** Radioactive decay in thorium and uranium series (*adapted with slight modification from WNA, 2020*).

Soil, a major sink of environmental contaminants, comprises several organic and mineral components. This accounts for the presence of some levels of radioactive elements which are primarily dependent on the parent rock type of the soil. The physicochemical properties of soils also influence the behaviour, concentration, and distribution of radioactive materials (Kang et al.

2020). Upon inhalation and/or ingestion, these radionuclides irradiate the host with gamma rays, beta, and alpha particles (Rani and Singh 2005; Anamika et al. 2020). The translocation and uptake of natural radionuclides into edible parts of plants is dependent on its composition in the soil, arising from agricultural practices, atmosphere, plant types, soil characteristics, and environmental contamination (Sunday et al. 2019; Ilori and Chetty 2020). The transfer of radionuclides from soil to food crops represents humans' major exposure pathway (El-Gamal et al. 2019). Water bodies close to phosphate ore deposits, nuclear plants, and/or agricultural farmlands where there is the predominant use of phosphate fertilizers are potential hotspots of radionuclides. For instance, the movement of groundwater through rocks and soil allows for the dissolution of some radionuclides in the water (Duggal et al. 2014). Influential factors determining the levels of these radionuclides in underground water during migration include pH, water flow, calcium content, etc. (Pandey et al. 2017).

Exposure to ionizing radiations incidentally or accidentally, over short term (acute exposure) or long term (chronic exposure), can cause skin burns, cell damage, cancer, cardiovascular disease, and death. A low level of exposure in the environment does not cause instant adverse health effects, but like most toxic environmental pollutants, consistent exposure over a long period contributes to the risk of cancer (Al-Zoughool and Krewski 2009; Ryan 2012; WHO 2016). The biological consequences of exposure to ionizing radiation have been accurately documented in the literature (WHO 2009; L'Annunziata 2016). After smoking, an increased risk of lung cancer is an adverse health issue predominantly associated with exposure to radon inhalation (Al-Zoughool and Krewski 2009; Ilori and Chetty 2020).

Many recent studies have focused on the occurrence and health risk assessment of radioactive materials in soil, sediments, and water in Nigeria (Abba and Saleh 2020; Bello et al. 2020; Momoh

et al. 2020; Ajibola et al. 2021; Bodunrin et al. 2021; Orosun et al. 2021). However, there is a paucity of comprehensive reviews simultaneously addressing the possible risks and plausible remediation strategies for these radionuclides. This review thus seeks to provide a critical assessment of the occurrence and distribution of radioactive materials in soil, sediments, and water as well as possible mitigating measures in a bid to ensuring a sustainable and eco-friendly environment. The most recent data reporting the levels of radioactive materials in Nigerian soils, sediments, and water in the last decade were obtained in order to bridge information gaps and provide an accurate assessment of the radiological risks associated with exposure, as well as identifying hotspots that may require special consideration.

## 2. Radioactivity

Radioactivity is the spontaneous decay of an unstable nucleus with excess energy. This is accompanied by the emission of radiation in the form of electromagnetic waves (gamma rays) or streams of subatomic (alpha, beta, or neutron) particles (UNSCEAR 2000). It was first discovered in 1896 by Henri Becquerel when exposing potassium uranyl sulfate to sunlight. Three different types of radioactive radiations i.e., negative, positive, and neutral were discovered during his scientific research (Khan 2017). Furthermore, Marie Curie coined the term radioactivity and along with her husband Pierre, discovered other radioactive elements such as radium and polonium from radioactive ore of uranium. In addition, another scientist Ernest Rutherford came up with the discovery of radioactive particles and named them alpha, beta, and gamma particles. The classification of these radiations was based on their ability to penetrate matter (Friedlander et al. 1982; Annunziata 2007; Khan 2017).

Radiation is defined as “the emission or transmission of energy in the form of waves or particles through space or a material medium”. This includes electromagnetic radiation (gamma radiation,

x-rays, etc.), particle radiation (neutron, alpha radiation (α), and beta radiation (β)), and acoustic radiation (seismic waves, sound, etc.). The energy of the radiated particles is the basis upon which radiation is classified. Hence, we have ionizing and non-ionizing radiation (Figure 2) (UNSCEAR 2000). Radioactive materials have found application in medicine (for detection and treatment of ailments ranging from hyperthyroidism to cancer), agriculture (for optimizing crop yields with artificial radiation sources), power generation (for manufacturing nuclear reactors and power plants), nuclear ammunitions, archeology (carbon dating and determination the ages of geological materials), radio-indicators and other applications (Figure 3) (Matucha et al. 2003; Lichfouse 2012; Chao et al. 2018, Pucci et al. 2019, Jeon 2019).

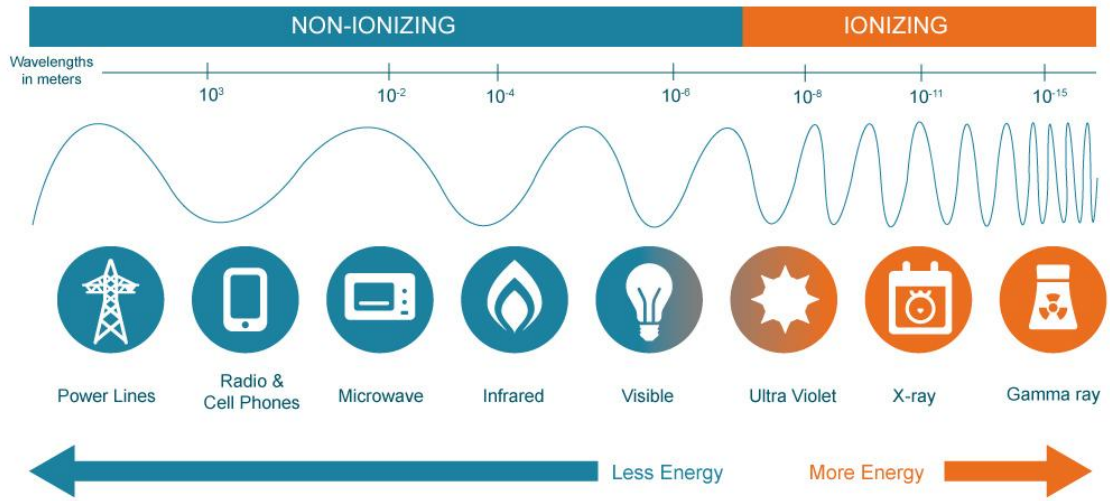


**Figure 2:** Illustration of ionizing and non-ionizing electromagnetic radiations (*https://www.mirion.com/learning-center/radiation-safety-basics/what-is-radiation*)

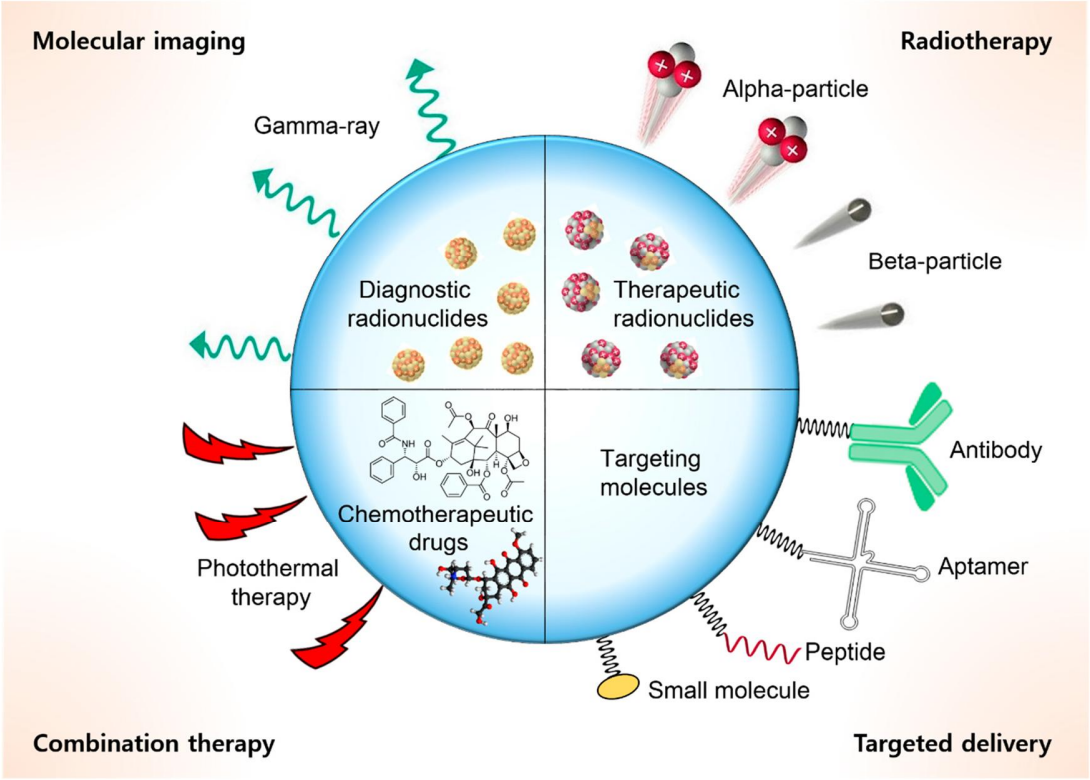


**Figure 3:** Multifunctional radionuclides and applications in the field of medicine (*adapted from International Journal of Molecular Science, Jeon J., 20(9), 2323, 2019*)

### 2.1 Non- ionizing radiation

Non-ionizing radiation can be defined as "any type of electromagnetic radiation that does not carry enough energy per quantum (photon energy) to ionize atoms or molecules—that is, to completely remove an electron from an atom or molecule" (UNSCEAR 2000). The probable biological effects associated with exposure to non-ionizing radiation are heavily dependent on their frequency in the electromagnetic spectrum. For instance, upper frequencies such as UV and visible light can induce non-thermal biological damages. In contrast, lower frequencies such as radio waves and microwave, are yet to be proven to constitute non-thermal radiation effects upon exposure (UNSCEAR 2000).

## 2.2 Ionizing radiation

Ionizing radiation is defined as “radiation that carries enough energy to liberate electrons from atoms or molecules, thereby ionizing them”. Ionizing radiation is made up of energetic subatomic particles, ions, or atoms moving at high speeds (usually greater than 1 % of the speed of light), and electromagnetic waves on the high-energy end of the electromagnetic spectrum. Gamma rays, X-rays, and the higher ultraviolet part of the electromagnetic spectrum are ionizing (WHO 2016). Ionizing radiation is radiation with enough energy so that during an interaction with an atom, it can remove tightly bound electrons from the orbit of an atom, causing the atom to become charged or ionized (WHO 2016). The presence and levels of ionizing radiation cannot be detected by human organs, hence the use of radiation detection equipment. Exposure to ionizing radiation causes damage to living tissue and can result in cancer, radiation sickness, mutation, and death (WHO 2016).

### 2.2.1 Alpha radiation (α)

Alpha radiation consists of alpha particles that are made up of two protons and two neutrons each and that carry a double positive charge (Equation 1).

$$ {}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}X + {}^{4}_{2}\alpha \qquad (1) $$

Due to their relatively large mass and charge, they have an extremely limited ability to penetrate matter. Alpha radiation can be stopped by a piece of paper or the dead outer layer of the skin. However, when alpha-radiation-emitting nuclear substances are taken into the body (for example, by breathing them in or by ingesting them), the energy of the alpha radiation is completely absorbed into bodily tissues. For this reason, alpha radiation is only an internal hazard. Alpha particles are characterized by the following features; contains two neutrons and two protons, particle carries a positive charge, the mass of each alpha-particle is 4 times that of a proton or H-

atom, it has high ionization power with low penetration power, they have strong ionizing power because they remove electrons from the atoms of gas through which they pass, they travel only a few centimeters in air and is easily stopped by a paper sheer or the outer skin layer. Examples of alpha emitters are radon, uranium, radium, and thorium (Khan 2017).

### 2.2.2 Beta radiation (β)

Beta radiation consists of charged particles that are ejected from an atom's nucleus and that are physically identical to electrons. Beta particles generally have a negative charge (Equation 2), are very small, and can penetrate more deeply than alpha particles.

$$ {}^{A}_{Z}X \rightarrow {}_{Z-1}{}^{A}Y + {}_{+1}{}^{0}e^{+} + V_e \qquad (2) $$

However, most beta radiation can be stopped by small amounts of shielding, such as sheets of plastic, glass, or metal. When the source of radiation is outside the body, beta radiation with sufficient energy can penetrate the body's dead outer layer of skin and deposit its energy within active skin cells. However, beta radiation is very limited in its ability to penetrate deeper tissues and organs in the body. Beta-radiation-emitting nuclear substances can also be hazardous on exposure to the body. Beta particles are negatively charged and possess low ionization power. Examples of beta emitters are sulphur-35, hydrogen-3 phosphorus-33, phosphorus-32, and carbon-14 (Khan 2017).

### 2.2.3 Photon radiation (gamma [γ] and X-ray)

Photon radiation is electromagnetic radiation. There are two types of photon radiation: gamma (γ) and X-ray. Gamma radiation consists of photons that originate from within the nucleus (Equation 3).

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z}X + {}^{4}_{2}\gamma \qquad (3) $$

X-ray radiation consists of photons that originate from outside the nucleus and are typically lower in energy than gamma radiation. Photon radiation can penetrate very deeply and sometimes can only be reduced in intensity by materials that are quite dense, such as lead or steel. In general, photon radiation can travel much greater distances than alpha or beta radiation, and it can penetrate bodily tissues and organs when the radiation source is outside the body. Photon radiation can also be hazardous if photon-emitting nuclear substances are taken into the body. Gamma rays have the highest penetrating power compared to alpha and beta particles within the body either through inhalation or ingestion, the effects of alpha and beta particles within the body are far more detrimental because of their ionizing power (Gruber et al. 2009; Adegunwa et al. 2019a). Gamma particles are characterized by the following features; electrically neutral, high penetration power, fast speed, could only be stopped by a thick sheet of lead, steel, concrete, or several meters of water. Examples of gamma emitters are cesium-137, cobalt-60, radium-226, and zinc-65 (Khan 2017). The interaction of gamma rays with a medium is in three ways namely pair production (high Z materials and high energy photons), photoelectric absorption (high Z materials and low energy photons), and Compton scattering (moderate energies) (Rittersdorf 2007).

## 3. Occurrence of radioactivity in environmental compartments

### 3.1 Radionuclide concentrations in soils

The characteristics of Nigerian soils vary and physicochemical properties such as soil pH, exchangeable cations, organic carbon content, minerals, etc., depending on parent rock types, historical geochemical processes, and land use/anthropogenic activities (Aleksakhin 2009; Ogunyele et al. 2020). Twelve savanna soils in Nigeria were characterized and the result showed a wide variation in texture and constituents. Most soil samples have an appreciable amount of silt (10–69%), kaolinite and smectite are the major mineral components of clay, quartz and K-feldspar

constitute a higher proportion in sands, while other minerals such as ilmenite, magnetite, extractable phosphates, organic carbon, and radioactive elements are also present in Nigerian soils (Møberg and Esu 1991; Ogunyele et al. 2020; Akingboye et al., 2021).

Soil acts as a repository for many environmental pollutants including radionuclides. A summary of previous studies carried out on radioactivity levels in Nigerian soils is presented in Table 2. Gbadamosi et al. (2017) quantified the activity concentrations of radioactive materials in waste dumpsite soils in Agbara, Ogun State, Nigeria using a properly calibrated high purity germanium (HpGe) γ-ray spectrophotometer. The mean measured activity concentrations of $^{232}$Th, $^{238}$U, and $^{40}$K are 26 ±2.2, 40.3 ±7.2, and 103±7.5 Bq kg$^{-1}$ respectively. The relatively higher activity level of $^{40}$K was ascribed to the possible predominant use of potassium-rich fertilizers on the soils. The estimated absorbed air dose rate of 40.69± 5.31 nGy hr$^{-1}$ was lower than the crustal average of 60 nGy hr$^{-1}$ (UNSCEAR 2000). The findings of the study showed that little or no immediate radiological threats are associated with exposure to the measured activity concentrations of radionuclides. However, cumulative effects emanating from frequent exposure and radiation build-up could be devastating for human health.

Ibikunle et al. (2019) reported the radiation dose of naturally occurring radionuclides in the soils of some south-western cities in Nigeria. HpGe detector was used in evaluating the activity concentrations of $^{232}$Th, $^{226}$Ra, and $^{40}$K in the soil samples. The mean activity concentrations of $^{232}$Th, $^{226}$Ra, and $^{40}$K measured in the soils are 76.79, 52.91, and 393.73 Bq kg$^{-1}$ respectively. The concentration of $^{40}$K is about five times the concentrations of the other investigated radionuclides (Ibikunle et al. 2019). The high activity levels of the radionuclides were attributed to the rocky geology of the study areas. The measured mean absorbed air dose rate (86.44) was higher than the

worldwide average value (60). This showed an upsurge in the recommended value considered safe for the environment.

**Table 2: Activity concentrations of radioactive materials reported in some Nigerian soils**

| Area | Radionuclide | Concentration ($BqKg^{-1}$) | Reference |
|---|---|---|---|
| Abeokuta, Ogun state | $^{40}K$ | 261.29 ±3 6.84 | Ekhaguere et al. 2019 |
| | $^{226}Ra$ | 30.87 ± 6.81 | |
| | $^{232}Th$ | 47.10 ± 11.95 | |
| South-western cities | $^{40}K$ | 393.73 | Ibikunle et al. 2019 |
| | $^{226}Ra$ | 52.91 | |
| | $^{232}Th$ | 76.79 | |
| Delta state | $^{40}K$ | 413.64 ± 21.22 | Ononugbo et al. 2019 |
| | $^{226}Ra$ | 54.43 ± 3.22 | |
| | $^{232}Th$ | 561.67 ± 2.21 | |
| Ile-Ife, Osun state | $^{40}K$ | 270.14 ± 61.79 | Oluyide et al. 2019 |
| | $^{226}Ra$ | 12.14 ± 4.17 | |
| | $^{232}Th$ | 23.23 ± 7.67 | |
| Coastal area, Akwa Ibom state | $^{40}K$ | 145 ± 6 | Akpan et al. 2020 |
| | $^{226}Ra$ | 23 ± 3 | |
| | $^{232}Th$ | 36 ± 2 | |
| Mangoro-Agege, Lagos state | $^{40}K$ | 403.07 ± 33.85 | Ilori and Alausa 2019 |
| | $^{226}Ra$ | 11.47 ± 0.75 | |
| | $^{232}Th$ | 10.44 ± 0.75 | |
| Asa, Kwara state | $^{40}K$ | 570.91 | Orosun et al. 2019 |
| | $^{226}Ra$ | 42.86 | |
| | $^{232}Th$ | 18.15 | |

| | | | |
|---|---|---|---|
| Elere, Oyo state | $^{40}K$ | 537.3 ± 76.51 | Alausa et al. 2017 |
| | $^{226}Ra$ | 36.55 ± 5.7 | |
| | $^{232}Th$ | 29.05 ± 3.68 | |
| Jos, Plateau state | $^{40}K$ | 374.01 ± 590.51 | Adesiji and Ademola 2019 |
| | $^{226}Ra$ | 242.13 ± 429.1 | |
| | $^{232}Th$ | 1776.08 ± 4164.89 | |
| South-western cities | $^{40}K$ | 554.2 ± 83.13 | Ajayi et al. 2018 |
| | $^{226}Ra$ | 25.53 ± 3.63 | |
| | $^{232}Th$ | 61.12 ± 8.82 | |
| Lagos state | $^{40}K$ | 19.38 ± 15.81 | Adedokun et al. 2020 |
| | $^{226}Ra$ | 10.99 ± 3.75 | |
| | $^{232}Th$ | 11.2 ± 5.36 | |
| South-western cities | $^{40}K$ | 151.72 ± 22.76 | Ajayi et al. 2017 |
| | $^{226}Ra$ | 8.27 ± 1.21 | |
| | $^{232}Th$ | 17.37 ± 2.88 | |
| Gold mining sites | $^{40}K$ | 627.58 | Dike et al. 2019 |
| | $^{226}Ra$ | 9.53 | |
| | $^{232}Th$ | 11.00 | |
| Ewekoro, Ogun state | $^{40}K$ | 285.34 ± 13.37 | Usikalu et al. 2018 |
| | $^{226}Ra$ | 1.95 ± 0.09 | |
| | $^{232}Th$ | 51.13 ± 1.86 | |
| Onikitinbi, Ogun state | $^{40}K$ | 350.75 ± 19.02 | Gbadamosi et al. 2018a |
| | $^{226}Ra$ | 30.51 ± 5.09 | |
| | $^{232}Th$ | 103.19 ± 6.54 | |
| Agbara, Ogun state | $^{40}K$ | 103 ± 7.5 | Gbadamosi et al. 2017 |

| | | | |
|---|---|---|---|
| | $^{226}$Ra | 40.3 ± 7.2 | |
| | $^{232}$Th | 26 ± 2.2 | |
| Akure, Ondo state | $^{40}$K | 51.52 ± 0.06 | Adebiyi and Ore 2020 |
| | $^{226}$Ra | 132.13 ± 0.16 | |
| | $^{232}$Th | 0.89 ± 0.08 | |
| Egbeda, Oyo state | $^{40}$K | 200 | Owoade et al. 2019 |
| | $^{226}$Ra | 30.5 | |
| | $^{232}$Th | 50.8 | |
| Agbaaru, Oyo state | $^{40}$K | 381.8 ± 16 | Ademola 2019 |
| | $^{226}$Ra | 25.3 ± 7.1 | |
| | $^{232}$Th | 26.2 ± 5 | |
| Bajoga, Gombe state | $^{40}$K | 196.11 ± 9.08 | Kolo et al. 2019 |
| | $^{226}$Ra | 7.41 ± 0.44 | |
| | $^{232}$Th | 16.27 ± 0.84 | |
| Zone A, Benue state | $^{40}$K | 113.02 ± 2.78 | Kungur et al. 2020 |
| | $^{226}$Ra | 39.10 ± 2.67 | |
| | $^{232}$Th | 29.44 ± 0.99 | |
| Bituminous sand deposit area, Ogun state | $^{40}$K | 461 ± 24.3 | Gbadamosi et al. 2018b |
| | $^{226}$Ra | 42.6 ± 6.5 | |
| | $^{232}$Th | 113 ± 10.5 | |
| South-western cities | $^{40}$K | 477.69 | Ibikunle et al. 2018a |
| | $^{226}$Ra | 52.05 | |
| | $^{232}$Th | 85.84 | |
| Bituminous sand deposit area, Ondo state | $^{40}$K | 46.46 ± 24.73 | Isinkaye et al. 2018 |
| | $^{226}$Ra | 24.13 ± 3.15 | |

| | | | |
|---|---|---|---|
| | $^{232}$Th | 20.1 ± 2.61 | |
| Ajaokuta, Kogi state | $^{40}$K | 712 ± 13 | Usikalu et al. 2017 |
| | $^{226}$Ra | 31 ± 2 | |
| | $^{232}$Th | 36 ± 3 | |
| Osogbo, Osun state | $^{40}$K | 223.59 ± 11.98 | Adegunwa et al. 2019b |
| | $^{226}$Ra | 15.39 ± 1.95 | |
| | $^{232}$Th | 4.54 ± 0.28 | |
| Owo, Ondo state | $^{40}$K | 1190.1 ± 373.62 | Aladeniyi et al. 2019 |
| | $^{226}$Ra | 64.64 ± 28.1 | |
| | $^{232}$Th | 110.18 ± 46.12 | |
| Mowe, Ogun state | $^{40}$K | 1071.85 ± 58.10 | Egunjobi et al. 2020 |
| | $^{226}$Ra | 67.28 ± 11.77 | |
| | $^{232}$Th | 11.21 ± 1.07 | |
| Esan, Edo state | $^{40}$K | 57.80 ± 1.7 | Popoola et al. 2019 |
| | $^{226}$Ra | 2.07 ± 0.09 | |
| | $^{232}$Th | 6.89 ± 0.34 | |
| Rayfield-Du, Jos, Plateau state | $^{40}$K | 346.1 ± 21.92 | Atipo et al. 2020 |
| | $^{226}$Ra | 168.83 ± 9.35 | |
| | $^{232}$Th | 436.08 ± 26.31 | |
| Ondo, Ondo state | $^{40}$K | 146.2 | Ogundele et al. 2020 |
| | $^{226}$Ra | 171.8 | |
| | $^{232}$Th | 19.8 | |
| Ile-Ife, Osun state | $^{40}$K | 131.11 ± 3.76 | Olalekan and Adebiyi 2020 |
| | $^{226}$Ra | 106.03 ± 3.68 | |
| | $^{232}$Th | 17.17 ± 1.56 | |

The radioactivity levels of soils around an iron and smelting company in Ile-Ife, Osun State, Nigeria were measured using a well-calibrated NaI (Tl) detector. Oluyide et al. (2019) reported the mean activity concentrations of $^{232}$Th, $^{238}$U, and $^{40}$K in the soils as 23.23 ± 7.67, 12.14 ± 4.17, and 270.14 ± 61.79 Bq kg$^{-1}$ respectively. The measured activity concentrations were lower than the worldwide average. Nevertheless, prolonged occupational exposure should be discouraged inorder to avert radiation build-up.

The observed variations in the activity concentrations of the radionuclides reported in this study reflect the variation in human activities and the soil types of the study areas. Many of the reviewed studies had activity concentrations of $^{40}$K higher than those of $^{232}$Th and $^{238}$U (Oluyide et al. 2019; Adedokun et al., 2019; Ibikunle et al. 2019). This observation is in tandem with the wide assertion that environmental media with high absorption activities for $^{40}$K usually have low absorption activities for $^{226}$Ra and vice versa (Adedokun et al. 2019). In stark contrast, some of the studies had relatively lower activity levels of $^{40}$K. Adebiyi and Ore (2020) reported increased levels of $^{238}$U over $^{40}$K in the measurement of radioactivity levels of oil-contaminated soils. The activity concentrations of $^{232}$Th, $^{238}$U, and $^{40}$K were 0.89 ± 0.08, 132.13 ± 0.16, and 51.52 ± 0.06 Bq/Kg, respectively. The measured mean absorbed air dose rate (63.73) was higher than the worldwide average thus indicating the susceptibility of residents to long-term health hazards. Atipo et al. (2020) measured the levels of primordial radionuclides in the soils of a tin mine in Jos, Plateau State, Nigeria using HpGe detector. The activity concentrations of $^{232}$Th, $^{238}$U, and $^{40}$K in the normal soils were 436.08±26.31, 168.83±9.35, and 346.1±21.92 Bq/kg respectively. The increased levels in thorium, uranium, and potassium were attributed to the mineral composition of the soils, which are rich in cassiterite, zirconium sand, theorite, columbite, and uranyl monazite. Radioactive elements predominant in soils are a reflection of the type of parent material. Lower levels of

potassium and thorium are usually associated with sedimentary rocks while higher levels are associated with igneous rocks (Ramola et al. 2011; Ajayi et al. 2018).

However, there is a need for further research on the risk assessment of soil radioactive pollution under different environmental conditions. Impact on agricultural practices, soil biodiversity, and environmental protection strategy should be given due consideration in future research.

### 3.2 Radionuclide concentrations in water and sediments

A summary of recent studies carried out on the concentrations of radionuclides in water and sediments in Nigeria is presented in Table 3. Adedokun et al. (2020) reported the levels of primordial radionuclides, $^{40}K$, $^{226}Ra$, and $^{232}Th$ in surface water in Lagos State, Nigeria as 1.96±0.54, 2.42±0.28, and 0.4±0.03 Bq/L respectively. The minimal variation observed in the specific activity concentrations of the radionuclides was credited to the relative uniformity of the geology of Lagos over a large area of land. The mean concentration of $^{226}Ra$ in the water samples was 142% higher than the recommended limit (1 Bq/L) while the mean concentration of $^{232}Th$ in the water samples was 60% lesser than the recommended limit (1 Bq/L). The continuous use of these water sources for domestic and irrigation purposes should not be encouraged in a bid to preventing the accumulation of radionuclides.

**Table 3: Activity concentrations of radioactive materials reported in some Nigerian water and sediments**

| Area | Sample type | Radionuclide concentration | | | Reference |
|---|---|---|---|---|---|
| | | $^{40}K$ | $^{226}Ra$ | $^{232}Th$ | |
| Erin-Oke, Osun state | Water | 61.01 ± 15.5 | 8.16 ± 2.05 | 5.24 ± 1.57 | Ibikunle et al. 2017 |
| | Sediments | 172.02 ± 35.43 | 19.28 ± 4.95 | 17.08 ± 4.37 | |
| Ikogosi, Ekiti state | Water | 56.88 ± 18.29 | 9.35 ± 3.72 | 6.91 ± 2.34 | Ibikunle et al. 2018b |
| | Sediments | 208.72 ± 29.57 | 21.63 ± 6.25 | 12.97 ± 0.96 | |
| Ndokwa east, Delta state | Water | 15.82 ± 2.03 | 2.37 ± 0.1 | 4.19 ± 0.23 | Ononugbo and Anyalebechi 2017 |
| | Sediments | 725.62 ± 21.03 | 189.62 ± 2.54 | 53.47 ± 1.21 | Ononugbo and Ofuonye 2017 |
| Andoni, Rivers state | Sediments | 29.01 | 22.64 | 8.45 | Ononugbo and Amah 2019 |
| Anka, Zamfara state | Sediments | 423.3 ± 122.73 | 44.85 ± 13.49 | 175.92 ±2 5.78 | Akpanowo et al. 2020 |
| Iju, Ogun state | Sediments | 501 ± 11.1 | 24.1 ± 0.4 | 35.2 ± 1.1 | Maxwell et al. 2020 |
| Bitumen deposit area, Ondo state | Water | 33.03 ± 13.87 | 1.77 ± 0.58 | 1.41 ± 0.43 | Abey et al. 2017 |
| Ifelodun, Osun state | Sediments | 1356.07 ± 18.87 | 54.98 ± 6.61 | 48.22 ± 7.76 | Ogundele et al. 2018 |
| Ebonyi state | Water | 9.82 ± 1.69 | 1.22 ± 0.29 | 4.17 ± 0.65 | Ononugbo and Nwaka 2017 |
| Delta state | Water | 5.67 | 2.86 | 1.67 | Iwetan et al. 2019 |
| | Sediments | 302.15 | 8.66 | 11.66 | |
| Osogbo, Osun state | Water | 202.7 ± 10.54 | 8.38 ± 0.84 | 6.45 ± 0.38 | Adegunwa et al. 2019a |
| Kaduna state | Water | 32.18 ± 0.32 | 29.85 ± 0.32 | 15.57 ± 0.43 | Aliyu et al. 2018 |
| | Sediments | 52.61 ± 0.96 | 23.97 ± 1.6 | 68.53 ± 0.07 | |
| Enugu state | Sediments | 60.55 | 12.07 | 13.02 | Ugbede 2020 |
| Nkalagu, Ebonyi state | Water | 120.45 ± 6.51 | 5.49 ± 0.7 | 0.14 ± 0.01 | Ugbede et al. 2020 |
| Lagos state | Water | 1.96 ± 0.54 | 2.42 ± 0.28 | 0.4 ± 0.03 | Adedokun et al. 2020 |

Abey et al. (2017) carried out a study on the investigation of radioactivity levels of groundwaters around the Ondo state bitumen deposit area, Nigeria during the rainy and dry season. The mean activity concentrations of $^{40}K$, $^{226}Ra$, and $^{232}Th$ were 33.03 ± 13.87, 1.77 ± 0.58, and 1.41 ± 0.43 Bq/L respectively, during the rainy season while they were 3.50 ± 1.21, 1.84 ± 0.62, and 0.39 ± 0.14 Bq/L respectively during the dry season. The observed seasonal variation was attributed to enhanced mobility of radionuclides due to surface run-off during the rainy season, resulting in the deposition of the radionuclides in the groundwater. The elevated level of $^{40}K$ over $^{226}Ra$ and $^{232}Th$ was attributed to the minimal occurrence of the latter in aquifers. The calculated mean absorbed air dose rate (0.36) was lower than the recommended limit (1), indicating that groundwaters pose a less radiological risk.

Akpanowo et al. (2020) determined the radioactivity levels in sediments of Anka, Zamfara State, Nigeria using a Broad Energy Germanium (BEGe) detector. The mean activity concentrations of $^{40}K$, $^{226}Ra$, and $^{232}Th$ in the sediment samples were 423.30 ± 122.73, 44.85 ± 13.49, and 175.92 ± 25.78 Bq/Kg respectively. The activity concentrations of the sediment samples were generally higher than worldwide average values. In addition to the geological framework of the study area, the elevated levels of the radionuclides were attributed to the anthropogenic influences of the artisanal mining sites. The estimated mean absorbed air dose rate (145 ±27 $nGyh^{-1}$) was higher than the recommended value. The likelihood of cancer incidence could be increased upon chronic exposure by the mining workers and residents close to the mining sites.

Ugbede (2020) reported the activity concentrations of $^{40}K$, $^{226}Ra$, and $^{232}Th$ in river sediments in Enugu state, Nigeria. The distribution of the radionuclides was measured using a well-calibrated NaI (TI) detector. The mean activity concentrations of $^{40}K$, $^{226}Ra$, and $^{232}Th$ in the samples were 60.55, 12.07, and 13.02 respectively. Both the natural (river flow through geological formations

with underlying radioactive material deposit) and anthropogenic (anoxic nature of river bed due to human inputs) influences were held accountable for variations in the concentrations of the radionuclides. The calculated mean absorbed air dose rate (15.96) was lower than the maximum world average, suggesting the negligibility of radiological health hazards.

The sediments of river Iju, Ogun state, Nigeria were investigated by Maxwell et al. (2020) for their natural radioactivity levels using a NaI (TI) detector. The mean activity concentrations of $^{40}K$, $^{226}Ra$, and $^{232}Th$ were 501 ± 11.1, 24.1 ± 0.4, and 35.2 ± 1.1 Bq/kg respectively. The activity concentrations of $^{226}Ra$ and $^{232}Th$ were lower than worldwide average values by 27% and 22% respectively while $^{40}K$ was higher than the worldwide average value by 19%. The oxidative nature of uranium in aqueous components accounted for its relatively low concentration while the redeposition of feldspathic minerals accounted for the relatively high concentration of $^{40}K$. The estimated mean absorbed air dose rate (53.3 nGy/h), which is about 11% lower than the recommended value indicated that the river sediments posed little radiological hazards to the public. Similarity existed in the distribution patterns of the radionuclides reported by the various studies presented in this review. High concentrations of radionuclides in water samples as opposed to sediment samples of the same study area were attributed to a possible resuspension of the radionuclides, leading to an upsurge in their levels in the water bodies. The relative upsurge of $^{226}Ra$ over $^{232}Th$ in groundwater was attributed to the relative solubility and mobility of the former.

Chronic aquatic exposures to radioactive pollution cause biological hazards such as cell mutation, cancer, death of aquatic organisms, and distortion of trophic food chains. These negative impacts are biomagnified and consumption of polluted marine foods potentially puts humans at risk, especially residents of rural communities that depend directly on surface water for food and potable

water. Therefore, concerted efforts should be directed towards marine protection by ensuring that radioactive waste and landfills are removed away from coastal areas.

## 4. Remediation of radioactive pollution in environmental matrices

Radioactive pollution is defined as "the land in which the radioactivity levels are above the ubiquitous natural and artificial background that is typical of the area in which the land is located" (Gupta and Voronina 2019). In addition to the background levels of radioactive materials, the contamination of the environment by radionuclides emanating from energy initiatives is very fatal. It is becoming a subject of public concern due to the environmental mobility of these radionuclides (Lloyd and Renshaw 2005; Mahadevan and Zhao 2017, Nivesse et al. 2020). The mobility of radionuclides in soils is controlled by physicochemical exchanges with soil matrix, convective conveyance by flowing water, and diffusive crusade (Walther and Gupta 2015). The idea of remediation does not end with cleaning contaminated soils, water, and/or sediments; it further includes the protection of biological species from the harmful effects of ionizing radiation upon exposure (Gupta and Voronina 2019). To solve this global pollution problem caused by radionuclides, the need arises for the development and adoption of cost-effective and sustainable technological innovations.

The methods of mitigating radioactive pollution can be generally illustrated as physical remediation, bioremediation, and chemical remediation (Table 4). The physical remediation methods involve the removal of the soil's top layer from the contaminated soil (Dushenkov 2003). The chemical remediation methods involve the use of sodium peroxide, carbonates, and inorganic/organic chelating agents in the remediation of radionuclides (Ali et al. 2013). The bioremediation methods of remediation involve the combined uses of algae (otherwise referred to

as phycoremediation), plants (phytoremediation), fungi (mycoremediation), and microbes (microremediation) in the removal of radionuclides from environmental matrices (Choudhary and Sar 2011; Jagetiya et al. 2011; Galanda et al. 2014; Liu et al. 2014). Several recent studies have reported the extensive use of different methodical approaches in the remediation of radionuclides all over the world (Lingamdinne et al. 2017; Canner et al. 2018; McElroy et al. 2020; Prakash et al. 2020; Song et al. 2020; Faghihian et al. 2013; Crini et al., 2020). Many of these technologies include natural attenuation, adsorption, soil washing, bioremediation, etc. A summary of the methods used in the remediation of radioactive materials is presented in Table 5. Some of the principles and applications of these technological innovations are briefly discussed below.

**Table 4: Remediation methods of radionuclide contamination (Reddy et al. 2019).**

| Physical remediation | Chemical remediation | bioremediation |
|---|---|---|
| **Soil excavation:** contaminated soil moved in its present state or in a stabilized formed from the site of pollution to where it is contained and stored *(Kuppusamy et al. 2016).* | **Carbonate extraction:** The use of carbonates to form a stable complex with radioactive metals as a remediation approach *(Zhou and Gu 2005).* | **Microremediation:** use of microbes for degradation and detoxification of environmental contaminants *(Psaltou and Zouboulis 2020).* |
| **Soil flushing:** Insitu flushing of contaminated soil with water with/without additives *(Song et al. 2017).* | **Citric acid extraction:** citrate is used as a complexing agent to immobilize precipitated radioactive metal *(Mihalík et al. 2011).* | **Phycoremediation: u**se of micro- and macro-algae for removal or biotransformation of pollutants *(Galanda et al. 2014).* |
| **Solidification:** this process immobilizes radioactively contaminated soil in a solid matrix *(Kuppusamy et al. 2016).* | **Sodium peroxide:** oxidizing agent enhances uranium via oxidation *(Abdel-Sabour et al. 2007).* | **Mycoremediation:** use of fungi for degradation and detoxification of environmental contaminants *(Coelho et al. 2020a)* |
| **Permeable reactive barrier:** Underground wall created to clean-up contaminated groundwater with aid of different adsorbents *(Blowes et al. 2000).* | **Organic chelating agents:** the most efficient in extracting uranium from soils *(Fukuda 2005)* | **Phytoremediation:** use of plant-controlled interactions with groundwater or soils for site-specific remedial goals *(Mani and Kumar 2014)* |
| | **Inorganic chelating agents:** inorganic cultures such as polyphosphates have been used for remediation of radionuclide pollution *(Wuana et al. 2010).* | |

**Table 5: Recent strategies employed in the remediation of radioactive pollution**

| Technique employed | Radionuclide | Removal efficiency (%) | Reference |
|---|---|---|---|
| Electroremediation | Uranium | 94 | Agarwal and Sharma 2018 |
| Electroremediation | Uranium | 97.69 and 99.73 | Nariyan et al. 2018 |
| Electroremediation | Uranium | 98 | Liu et al. 2019 |
| Electroremediation | Uranium | 80.58 | Xiao et al. 2020a |
| Electroremediation | Uranium | 61.55 | 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 | 85.33, 79.19 | Zhang et al. 2021a |
| Adsorption | Uranium | > 90 | Zhang et al. 2021b |
| Adsorption | Uranium | 91.1, 86.5 | Wen et al. 2021 |
| Adsorption | Uranium | 100 | Liu et al. 2021 |
| Adsorption | Uranium | 87.45 | 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. 2020a |
| Bioremediation | Uranium | 118.61 | Chen et al. 2020b |
| Adsorption | Uranium | 30.71 | Wei et al. 2020 |
| Adsorption | Uranium | 99 | Hu et al. 2020 |
| Adsorption-photocatalysis | Uranium | 97.6 | He 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 |

### 4.1 Electroremediation

Electroremediation is also known as electrokinetics or electroreclamation (Reddy and Cameselle 2009). The principle of electroremediation is hinged upon the application of a low-intensity current between the cathode and anode through the soil. It particularly finds application in the decontamination of radionuclides present in soils and sediments. The application of direct current ensures the transport of water and ions towards the electrodes. In the process of movement, the contaminants are removed from the soil and they accumulate in the wells of the electrode. A circulation system ensures that the processing fluid is removed alongside the contaminants from the electrode wells. The removal operation continues until the levels of the contaminants (radionuclides) in the soils are below the desired level (Cameselle and Gouveia 2019). The principal mechanisms responsible for transport during electroremediation are electromigration and electro-osmosis. The former is characterized by the transportation of ions towards an electrode of opposite charge while the latter is defined as “the net flux of water induced by the electric field in the porous structure of the soil” (Cameselle and Reddy 2012).

The use of electroremediation in the removal of naturally occurring radionuclides from contaminated soils, water, and sediments are limited so far. However, its applicability has been reported in a few studies. The electrochemical separation of uranium in an aqueous medium was investigated by Agarwal and Sharma (2018) in 0.1 M KCl on poly(3,4-ethylenedioxythiophene) poly(styrenesulphonate) modified platinum (PEDOT: PSS/Pt) electrode. ICP-MS results showed

94% recovery and deposition of uranium on the electrode. Nariyan et al. (2018) investigated the removal of uranium from mine water by batch electrocoagulation. The effects of reaction time and electrode combinations were investigated. The maximum removal of uranium from the mine water was 97.69% and 99.73% using aluminum-stainless steel and iron-stainless steel electrode combinations respectively. Kinetics data revealed that the reaction followed the first-order kinetics, indicating a physical interaction between uranium and the coagulant. A novel direct electro-reductive method developed by Liu et al. (2019) was used to remove uranium from groundwater. Significant reduction of U(VI) to U(IV)$O_2$ was observed with the resulting reduced pollutant accumulating on the surface of the Ti electrode under high electric current efficiency of over 90%. The recovery of about 98% of the accumulated U(IV)$O_2$ is made possible by immersing the Ti electrode in dilute nitric acid. The feasibility of permeable reactive barrier-assisted electrokinetic remediation of uranium-contaminated soil was investigated using a mixture of citric acid and ferric chloride as the composite electrolyte. The maximum removal of uranium under optimized conditions was 80.58% (Xiao et al. 2020a). The electrokinetic remediation of uranium-contaminated red soil was investigated using different electrolytes. Results revealed that an optimum concentration mixture of 0.03 mol/L $FeCl_3$ and 0.1 mol/L citric acid gave a uranium removal efficiency of about 61.55%. In addition to the high removal efficiency, the advantages of less damage to the soil and low leaching toxicity after electroremediation were discovered (Xiao et al. 2020b).

The use of electroremediation technique in the remediation of naturally occurring radionuclides in soils and water is regarded as efficient, but relatively low removal efficiency of $^{232}Th$ and $^{238}U$ in soils has been reported in many studies (Kim et al. 2012; Mohamed Johar and Embong 2015; Kim et al. 2016). The observed low removal efficiency was credited to the low concentration of

radionuclides present and permeability in the soils, which essentially limit electromigration. The concentration of radionuclides present in soils determines the portion of mobile ions available for migration and a higher portion of the radionuclides may remain in residual fractions (Kim et al. 2003). Furthermore, the efficiency of electrokinetic remediation also depends on the applied voltage, ratio of AC-DC voltage, thus energy cost must be put into consideration especially for heavily polluted sites.

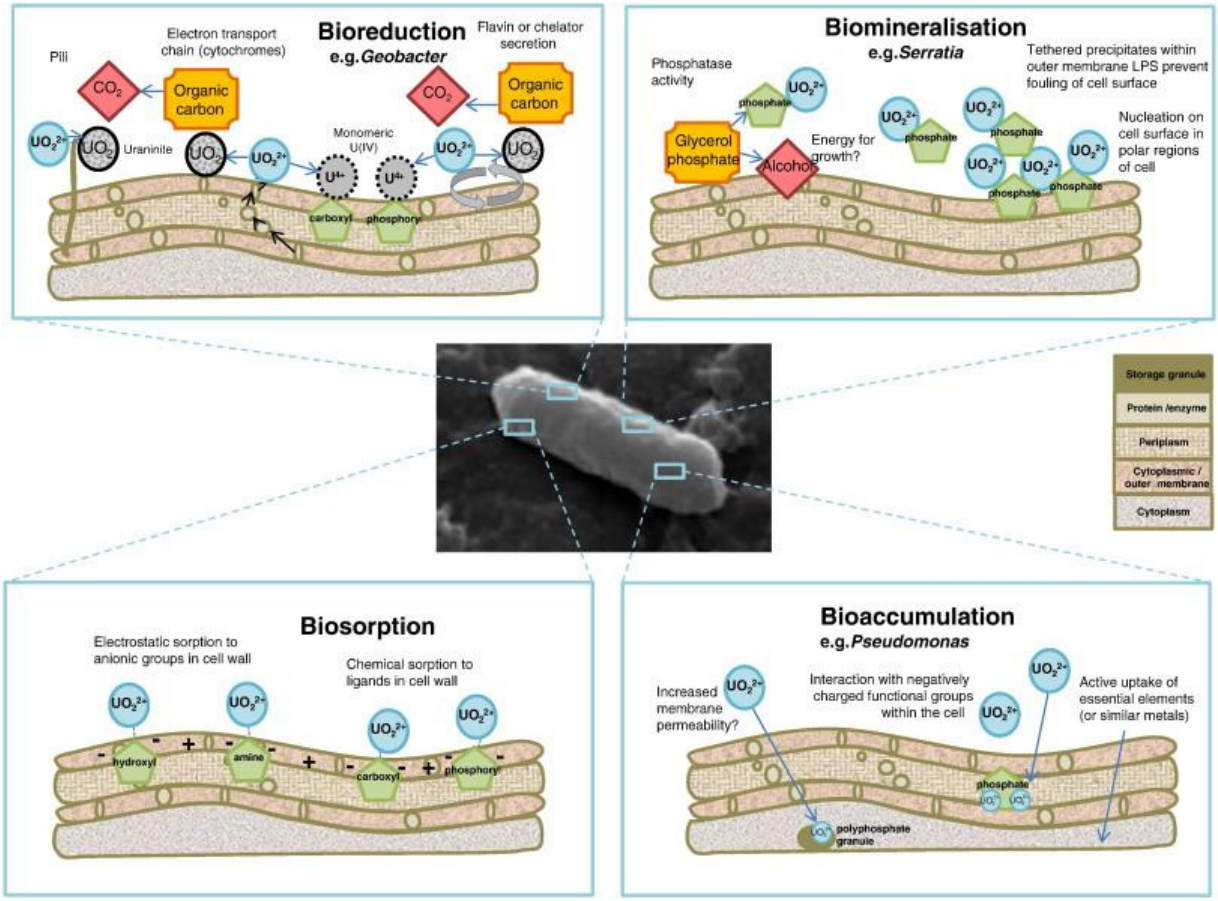


**Figure 4: M**echanisms of microbe-uranium interactions (*adapted from Chemical Geology, Newsome et al. 363, 164-184, copyright 2014 Elsevier*)

### 4.2 Bioremediation

Bioremediation is a technique that involves the use of plant enzymes, plants, microbial enzymes, and/or microorganisms in the detoxification of contaminants/pollutants in the environment (Gouma et al. 2014). Suitable organisms that are employed in bioremediation include fungi, plants, bacteria, etc. The choice of microorganisms is determined by their ability to detoxify, degrade or immobilize pollutants in a target matrix (Psaltou and Zouboulis 2020). More specifically, the plants used in bioremediation must have a dense shoot and root system, be disease-resistant, be fast-growing, among others (Couselo et al. 2012). Four major mechanisms comprising bioreduction, biomineralization, biosorption, and bioaccumulation exist in the interaction of microbes with radionuclides during bioremediation (Figure 4). Phytoremediation (the use of plants in remediation), broadly classified into direct phytoremediation and rhizoremediation, employs different modes in a bid to providing environmentally practicable and economically achievable routes for the clean-up of contaminants/pollutants. The different modes of remedial action include; phytostabilization (reduction of the mobility of pollutants), phytoaccumulation (absorption of contaminants and bioaccumulation in plant tissues), phytovolatilization (transformation of contaminants present in the soil to more volatile form, thus leading to their release into the air) and phytofiltration (removal of dissolved pollutants by via extra-and intra-cellular accumulation) (Sharma et al. 2015).

Despite the reported pathogenicity of *Staphylococcus aureus* biofilms, its bioremediation capacity for uranium was tested and reported by Shukla et al. (2020). Upon treatment with uranyl nitrate solution, the addition of phosphate enhanced the remediation of uranium. The removal efficiency of 47% U(VI) was observed, thus providing an alternative mechanism for uranium remediation (Shukla et al. 2020). Fifty-seven fungi were isolated and investigated for their uranium

bioremediation capacity. Eleven of the fungal isolates showed more than 60% removal of the uranium from an aqueous solution (Coelho et al. 2020a). The use of the fungus *Penicillium piscarium* was investigated in the remediation of radionuclide-contaminated sites. The influence of solution pH was monitored in the course of the reaction. The reaction was monitored at pH 3.5 and 5.5. The dead biomass of the fungus had a removal efficiency between 93.2 and 97.5% of uranium at pH 3.5 while it had a removal efficiency between 38 and 92% of uranium at pH 5.5 (Coelho et al. 2020b). The removal of uranium from simulated wastewater in a microbial fuel cell was investigated by Vijay et al. (2020) using a denitrifying bacteria consortium. The inorganic phosphate produced from glycerol 3 phosphate, effectively combined with the hexavalent form of uranium to produce insoluble uranyl phosphate. The process ensured that 90% of the initial uranium concentration was removed as uranyl phosphate. Ozdemir et al. (2020) developed a new magnetized thermophilic bacterium to preconcentrate thorium and uranium from environmental matrices. The bacteria *Bacillus cereus* SO-14, was used as a solid-phase biosorbent. Experimental conditions and limits of detection were optimized. The extraction recoveries of thorium and uranium yielded more than 95%.

Bioremediation is an efficient and cost-effective remediation approach for contaminated soil and water (Azubuike et al. 2016, Adeola and Forbes 2020). Some limitations of bioremediation include low efficiency in heavily polluted environments, lack of proper environmental conditions to suit the growth of microbes, the presence of metabolically active microbial populations, and negative impact on biodiversity (Megharaj et al. 2011; Gkorezis et al. 2016; Singh et al. 2020). Furthermore, it takes a very long time to achieve significant remediation, as enormous time is spent on microbial culture, process implementation, and optimization. Also, the use of plants in a biological treatment

approach requires special control systems, as herbivores like sheep, cattle, etc., can potentially feed on the plants, thus the risk of human exposure via food-chain.

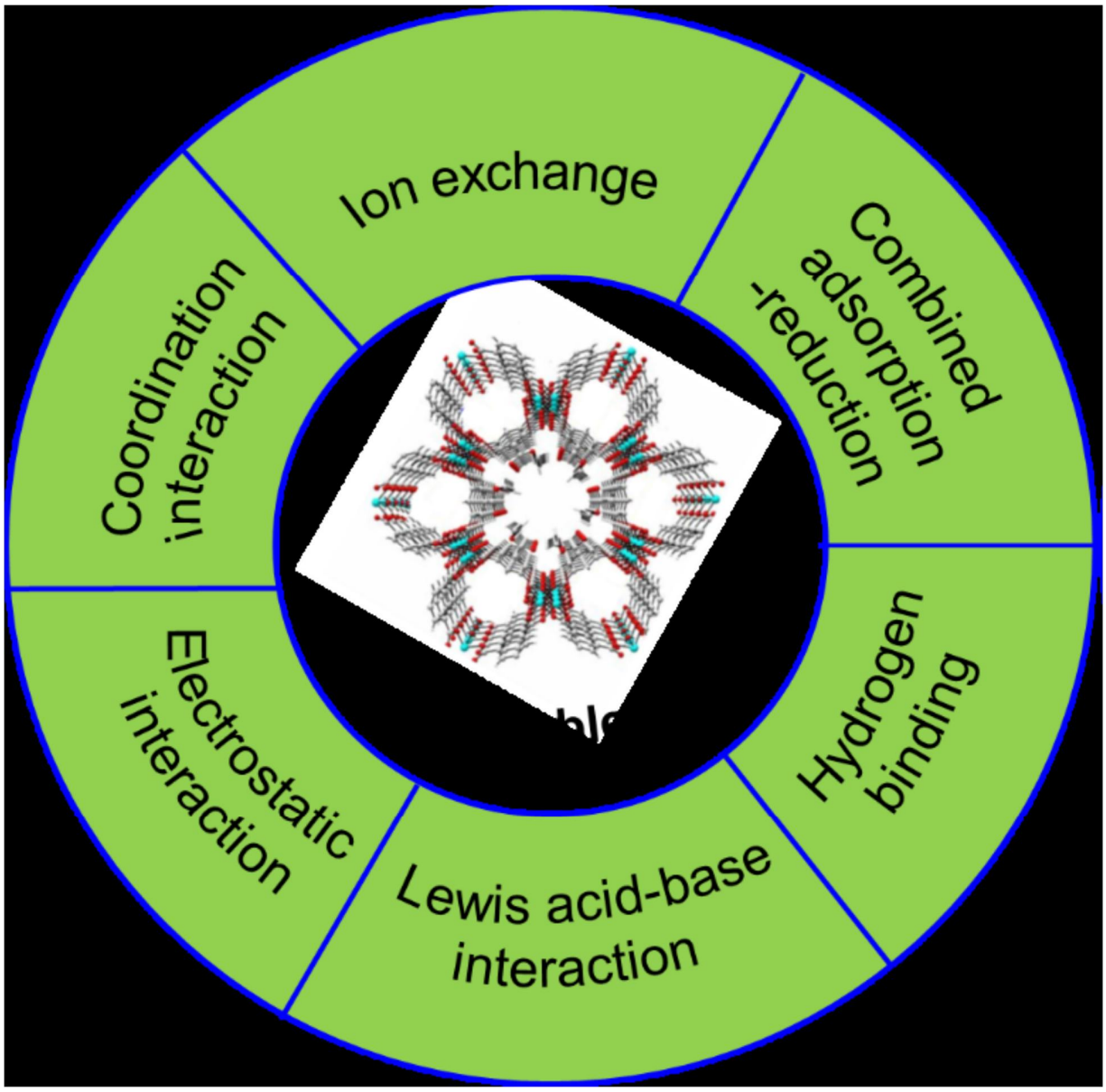


**Figure 5:** Adsorption mechanisms of water-stable metal-organic frameworks for radionuclides in water (*Reprinted from Chemosphere, 209, Feng et al., Water-stable metal-organic frameworks for aqueous removal of heavy metals and radionuclides: A review, 783-800, 2018, with permission from Elsevier).*

### 4.3 Adsorption

Adsorption is defined as a mass transfer process that involves the transfer of substances from a liquid phase to the surface of a solid phase (Faghihian et al. 2013; Hu and Xu 2020, Adeola and Forbes 2021). Many technologies have been developed and investigated for the removal and recovery of radionuclides from several waste sources. However, adsorption has certain advantages over other remediation strategies. These merits include ease of regeneration and reusability of spent adsorbent, ease of operation, and lesser tendency to generate sludge and/or secondary pollutants (Mohanty et al. 2006, Ore and Adeola 2021). The basic mechanisms governing the remediation of radionuclides in water by adsorption (Figure 5) include combined adsorption-reduction, Lewis acid-base interaction, electrostatic interaction, ion exchange, hydrogen bonding, and coordination interactions (Feng et al. 2018).

Zhang et al. (2021a) investigated the use of zero-valent-iron coated quartz sand (ZVI-S) in the removal of uranium from groundwater. Experiments conducted were designed to monitor the influence of concentration, contact time, and solution pH. The ZVI-S used was varied in terms of hydraulic loads and particle sizes. Batch experiments confirmed a removal efficiency of 85.33% while column experiments confirmed 79.19% removal efficiency of uranium. Wen et al. (2021) developed a new supramolecular poly(amidoxime) (PAO)-loaded macroporous resin (PLMR) adsorbent for the adsorption of uranium from seawater and wastewater. Upon immersion, the PAO was loaded on the microporous resin via a hydrophobic interaction mechanism. The recovery efficiencies of the PLMR adsorbent in wastewater and seawater were 91.1% and 86.5% respectively. The performance of photocatalysis-assisted adsorption of uranium was tested using a new carbon nitride, CN550, prepared by heating a mixture of zinc chloride and melamine under an argon atmosphere. Upon illumination for 390 minutes, approximately 100% of uranium was

removed from the solution (Liu et al. 2021). Zhang et al. (2021b) prepared an activated biochar-loaded nano zero-valent iron (A-BC-NZVI) and used it in the removal of uranium from sewage water. The A-BC-NZVI composite was synthesized by aqueous phase reduction under a nitrogen atmosphere at 800°C. The experiments were performed under the influence of variable solution pH, time, concentration, and temperature. After five cycles of sorption-desorption experiments, the adsorption efficiency of uranium was still over 90%. This showed the prospect of using A-BC-NZVI as an environmental-friendly adsorbent in the remediation of uranium-polluted water. In a study carried out by Sharma et al. (2020), Nitro-oxidized carboxycellulose nanofibers (NOCNF) were prepared using nitro-oxidation method. The obtained NOCNF had a good carboxylate content as well as a high surface charge. The removal mechanism of uranium by negatively charged NOCNF demonstrated maximum removal efficiency (80 - 87%) at neutral pH.

However, several factors must be put into consideration before choosing a suitable adsorbent for treatment of radiochemical-related pollution, factors such as the efficiency of the material, availability of material, non-toxicity, adaptability, robustness, reusability, etc. A routine post-remediation check is necessary after treatment of heavily polluted sites.

## 5. Conclusion

The knowledge of the distribution of radionuclides in the environment is important for environmental monitoring and protection. Anthropogenic activities such as mining, agriculture, and crude oil exploration could bring about an upsurge in the levels of naturally occurring radioactive materials, resulting in the redistribution of radionuclides in the environment and potentially causing health problems. The occurrence and levels of primordial radionuclides present in a geographical area can be used as a radioactive dating tool, as well as a suitable indicator of

the occurrence of potentially large deposits of radioactive elements in Nigeria. This review provides insights into the potential health risks associated with exposure to these radionuclides, as well as identifying hotspots of radioactive pollution emanating from sources that are neither natural nor geogenic. The choice of remediation method is greatly influenced by a proclivity for environmental sustainability as well as economic costs. Future research should focus on the optimization of remediation strategies for improved efficiency, particularly in residential areas with dense populations. There is a need to adopt an integrated approach such as adsorption-bioremediation, bioremediation-electroremediation, etc., for the sustainable and efficient remediation of heavily polluted sites. Asides from gamma-emitting radionuclides, other radionuclides such as alpha-emitting and beta-emitting naturally occurring radionuclides should be investigated in Nigerian soils, water, and sediments to identify potential hotspots and salvage the ecosystem. There is a need for synergistic effort between international and regional regulatory bodies, in conjunction with universities in order to carry out a comprehensive risk assessment and development of efficient radioactive waste management systems. Furthermore, discussions at the national level of government should be geared toward enforcing laws directed at mitigating the health risks associated with the indiscriminate disposal of radioactive wastes.

## Conflict of Interest

The authors declare that they have no conflict of interest.

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