Soil-to-Plant Transfer of Naturally Occurring Radionuclides in West Africa: Mechanisms, Transfer Factors, Food-Chain Contamination, And Human Health Implications

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ABSTRACT

Naturally occurring radionuclides (NORMs), including uranium-238 (^{238}U), thorium-232 (^{232}Th), radium-226 (^{226}Ra), and potassium-40 (^{40}K), are widely found in terrestrial ecosystems and are a significant source of environmental radiation exposure. Their movement from soil to plants is a crucial process through which radionuclides enter the food chain, leading to internal radiation doses in humans. This review summarizes the current understanding of the environmental distribution, mechanisms of soil-to-plant transfer, transfer factors, and the radiological consequences of naturally occurring radionuclides in West Africa Peer-reviewed papers from major scientific databases were used to undertake a structured literature review, with a focus on studies reporting radiological risk assessments, soil-to-plant transfer factors, and radioactive activity concentrations. The research that is now available suggests that a variety of factors, including soil physicochemical features, radionuclide speciation, plant traits, climate, and agricultural methods, influence the uptake of radionuclides by plants. Due to its vital biological role, potassium-40 often demonstrated the largest transfer to crops, while radionuclides from the uranium and thorium family showed relatively lesser mobility but were nonetheless significant contributors to long-term internal radiation exposure. The analysis also shows that while quantitative studies on soil-to-plant transfer are still scarce and spatially unequal, environmental radioactivity evaluations dominate research in West Africa. The majority of published studies are from Nigeria and Ghana, however there are still significant knowledge gaps in many other West African nations. Regional radiological risk assessment is made questionable by the absence of long-term environmental monitoring, locally determined transfer factor databases, and standardized procedures. Harmonized radioecological studies, the creation of region-specific transfer factors for important staple crops, integrated food-chain studies, and ongoing environmental monitoring should be the top priorities for future study. By filling in these gaps, West African decision-making on public health, food safety, and environmental radiation protection will be strengthened and exposure assessment accuracy will increase.

Keywords: Naturally occurring radionuclides; Soil-to-plant transfer; Transfer factor; Environmental radioactivity; Food chain; Radiological risk; West Africa.

INTRODUCTION

The Earth's crust is made up of naturally occurring radionuclides (NORMs), which can be found in rocks, soils, sediments, water, air, and biological systems. The main primordial radionuclides of environmental importance are potassium-40 (^{40}K), uranium-238 (^{238}U), thorium-232 (^{232}Th), and their radioactive decay products, especially radon-222 (^{222}Rn) and radium-226 (^{226}Ra). NORMs have existed since the formation of the Earth and are a constant source of background radiation exposure, in contrast to manmade radionuclides generated after

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nuclear accidents or weapons testing. Even though the concentrations of these radionuclides are typically low, geological processes and human activities like mining, phosphate fertilizer production, oil and gas operations, quarrying, and industrial mineral processing can greatly increase their environmental distribution (United Nations Scientific Committee on the Effects of Atomic Radiation [1,2]

Complex geochemical and biological mechanisms control the mobility, bioavailability, and transmission of naturally occurring radionuclides through terrestrial ecosystems. Before entering agricultural systems, radionuclides may travel through soils, groundwater, surface water, and air pathways after being released into the environment. These radionuclides are primarily stored in soil, which also acts as the main barrier preventing them from entering crops through root uptake. Numerous interrelated elements, such as soil physicochemical characteristics, radionuclide speciation, plant physiology, climate, and agricultural management techniques, affect how much radioactive accumulation occurs in plants. Thus, one of the most significant processes connecting environmental contamination with internal radiation exposure in humans is soil-to-plant transfer [2,3].

The soil-to-plant transfer factor (TF) is still the most commonly utilized measure of radionuclide bioavailability among the different radioecological metrics used to assess radionuclide migration. The TF is a key input parameter in radioecological models that predict radionuclide movement through food chains, estimate internal radiation doses, and evaluate radiological risks related to agricultural products. It quantitatively describes the efficiency with which radionuclides are transferred from soil into plant tissues. Because local environmental circumstances have a significant impact on radionuclide uptake, there is significant regional variability despite the availability of internationally recognized transfer factor databases. As a result, radionuclide behavior in tropical Africa may not be adequately represented by generalized transfer factors derived from temperate ecosystems [2,4].

Natural radioactivity varies geographically throughout West Africa due to its varied geological formations, which include phosphate deposits, granitic terrains, uranium-bearing rocks, and vast gold-mining belts. Concerns about the environmental redistribution of naturally occurring radionuclides and their transfer into food systems have also increased due to rapid population growth, agricultural intensification, artisanal and industrial mining, growing urbanization, and rising groundwater demand. Activity concentrations of naturally occurring radionuclides in soils, crops, groundwater, sediments, and mining settings have been documented in a number of studies from Nigeria, Ghana, Burkina Faso, Mali, Senegal, and Togo. However, relatively few research have measured soil-to-plant transfer factors or assessed radionuclide transport across agricultural food chains, while the majority of studies have focused on environmental radioactivity measurements and radiological hazard assessment. Additionally, there is still regional disparity in the published research, with many West African nations lacking the baseline radioecological data needed for accurate environmental and public health assessments [5].

In West Africa, radiological risk assessment is severely hampered by the scarcity of locally generated transfer factors. Many current exposure models still rely on default transfer coefficients that were created in environments that are very different from those seen throughout tropical Africa. Estimates of internal radiation dose may be unclear due to variations in soil mineralogy, weathering intensity, climate, cropping systems, and agricultural practices that can significantly affect radionuclide mobility and plant uptake. In order to address these uncertainties, a thorough synthesis of the available data is necessary to determine what is already known, assess regional trends, and identify areas that need more investigation [3,6].

The environmental distribution, soil-to-plant transfer, transfer factors, and radiological consequences of naturally occurring radionuclides in West Africa are therefore summarized in this paper. In particular, it looks at the variables influencing radionuclide mobility and plant uptake, compiles published data from nations in the region, assesses the consequences for human exposure through the food chain, pinpoints significant knowledge gaps, and suggests future research priorities to improve environmental monitoring, food safety evaluation, and radiation protection techniques. This analysis offers a thorough regional viewpoint that promotes better environmental management and evidence-based policies for long-term public health protection in West Africa by using the existing radioecological data.

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Sources and Environmental Distribution of Naturally Occurring Radionuclides

Radionuclides that occur naturally (NORM), especially ^{40}K, ^{238}U, and ^{232}Th are found in a variety of environmental compartments, such as rocks, soils, water, sediments, and vegetation, and are widely dispersed across the Earth's crust. Both manmade activities like mining, agriculture, industrial operations, and oil and gas extraction, as well as natural processes like weathering and geological formations, control their occurrence and distribution. These sources affect radionuclides' mobility, bioavailability, and subsequent transfer across terrestrial ecosystems, which ultimately determines how much of them accumulate in food crops and the radiological risks they pose to people. The main anthropogenic and natural sources of these radionuclides, as well as their environmental distribution, are covered in this part. This information serves as a foundation for comprehending soil-to-plant transfer and food chain contamination.

Table 1. Summary of the Major Sources and Environmental Distribution of Naturally Occurring Radionuclides (NORM)

Source Catego	**Primary Origin**	**Predo minan**	**Major Environmental Compartments**	**Distribution Mechanism**	**Implications for Soil-to-Plant Transfer**
Geologica l	Weathering of igneous, metamorphic, and sedimentary rocks	^{40}K, ^{238}U, ^{232}Th	Rocks, soils, sediments	Mineral weathering, erosion, and leaching	Determines the natural radionuclide inventory of soils and influences baseline plant uptake.
Agricultu ral	Phosphate and potash fertilizers, irrigation, and organic amendments	^{40}K, ^{238}U, ^{226}Ra.	Cultivated soils, crops	Fertilizer application, irrigation, and soil amendment	Enhances radionuclide bioavailability and accumulation in edible crops.
Mining and	Extraction and processing of mineral ores and rocks	^{238}U, ^{232}Th.	Mine soils, tailings, dust, nearby farmlands	Excavation, tailings disposal, and dust deposition	Increases radionuclide concentrations in soils and surrounding vegetation.
Oil and gas	Produced water, drilling wastes, scales, and sludge	^{226}Ra, ^{228}Ra.	Soils, sediments, surface water	Waste disposal, leakage, and accidental spills	May elevate radionuclide levels in agricultural soils and crops near production sites.
Industrial activities	Cement production, phosphate industries, coal combustion, and metal smelting	^{40}K, ^{238}U, ^{232}Th	Industrial soils, fly ash, sediments	Atmospheric deposition, industrial effluents, and waste disposal	Contributes to localized soil contamination and radionuclide uptake by plants.
Waste disposal	Municipal landfills, industrial waste dumps, and sewage sludge	^{238}U, ^{232}Th, ^{40}K	Soils, leachates, groundwater	Leaching, runoff, and waste decomposition	Alters radionuclide distribution and may increase crop contamination in nearby areas.
Natural redistribut	Weathering, flooding, erosion, and sediment transport	^{40}K, ^{238}U, ^{232}Th	Soils, rivers, wetlands, and floodplains	Water movement, wind erosion, and sediment deposition	Controls radionuclide mobility and spatial variability in agricultural ecosystems.

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Environmental	Combined natural and anthropogenic inputs	^{40}K, ^{238}U, ^{232}Th	Soil, water, sediment, air, and vegetation	Biogeochemical cycling	Acts as the immediate reservoir from which radionuclides become available for plant uptake and food-chain transfer.
Industrial activities	Cement production, phosphate industries, coal combustion, and metal smelting	^{40}K, ^{238}U, ^{232}Th	Industrial soils, fly ash, sediments	Atmospheric deposition, industrial effluents, and waste disposal	Contributes to localized soil contamination and radionuclide uptake by plants.

The main human and natural sources of naturally occurring radionuclides (^{238}U, ^{232}Th, ^{40}K), their environmental distribution, and their effects on soil-to-plant transmission are summarized in Table 1. The main natural source is generally found in geological formations, although activities related to agriculture, mining, industry, and oil and gas can increase the mobility and bioavailability of radionuclides, increasing the likelihood that they will enter the food chain.

Mechanisms of Soil-to-Plant Transfer of Naturally Occurring Radionuclides

The movement of naturally occurring radionuclides (NORM), especially ^{40}K, ^{238}U, and ^{232}Th is an important factor controlling the flow of radioactivity through terrestrial ecosystems and into the human food chain is the transfer from soil to plants. Plant roots are the main way that radionuclides are absorbed, and the intricate relationships between radionuclide properties, soil qualities, plant physiology, and environmental factors all affect this uptake. As a result, the quantity of radionuclides that accumulate in crops varies significantly depending on the type of soil, plant species, and climate [3,7].

The soil-to-plant transfer factor (TF), a crucial indicator for radioecological modeling, environmental monitoring, and radiological risk assessment, is frequently used to quantify the efficiency of radioactive uptake. Therefore, forecasting radionuclide bioavailability, evaluating food chain contamination, and creating efficient radiation protection techniques all depend on an understanding of the mechanisms governing radionuclide transfer. The main mechanisms and variables controlling the movement of ^{40}K, ^{238}U, and ^{232}Th from soil to plants are examined in the following sections.

3.1 Overview of Soil-to-Plant Transfer

The term "soil-to-plant transfer" describes the biological and physicochemical processes that transfer radionuclides from soil into plant tissues. It is a vital route in terrestrial ecosystems, allowing naturally occurring radionuclides (^{40}K, ^{238}U, and ^{232}Th) to enter the food chain and causing internal radiation exposure in humans and animals when contaminated agricultural products are consumed [2,3].

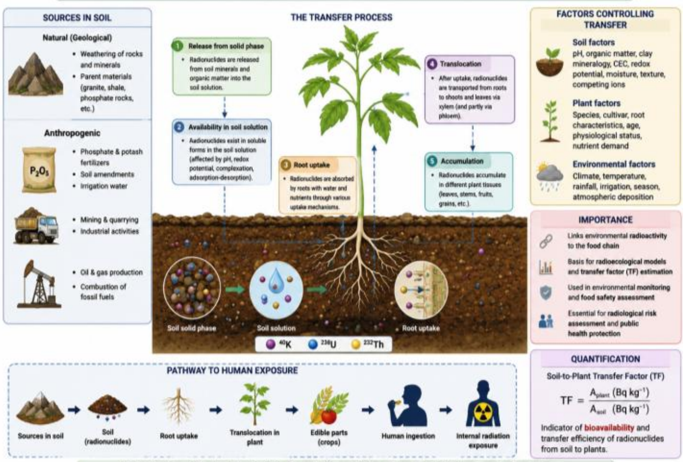

Figure 1. Overview of soil to plant-soil-human of naturally occurring radionuclides

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Due to the combined effects of radionuclide chemistry, soil features, plant traits, and meteorological circumstances, the degree of radioactive transfer varies significantly among various environmental situations. As a result, the soil-to-plant transfer process has emerged as a crucial element of radioecological research, environmental monitoring initiatives, and radiological risk assessments. It offers important data for forecasting radionuclide behavior, assessing food safety, and bolstering radiation protection tactics [7,4].

3.2 Root and Foliar Uptake Mechanisms

The main route that naturally occurring radionuclides reach plants is through root absorption. Through mechanisms such mass flow, diffusion, root interception, and membrane transport, radionuclides discharged into the soil solution are absorbed along with water and vital nutrients. Radionuclide speciation and bioavailability, which establish the percentage available for absorption by plant roots, govern the degree of uptake [2,3].

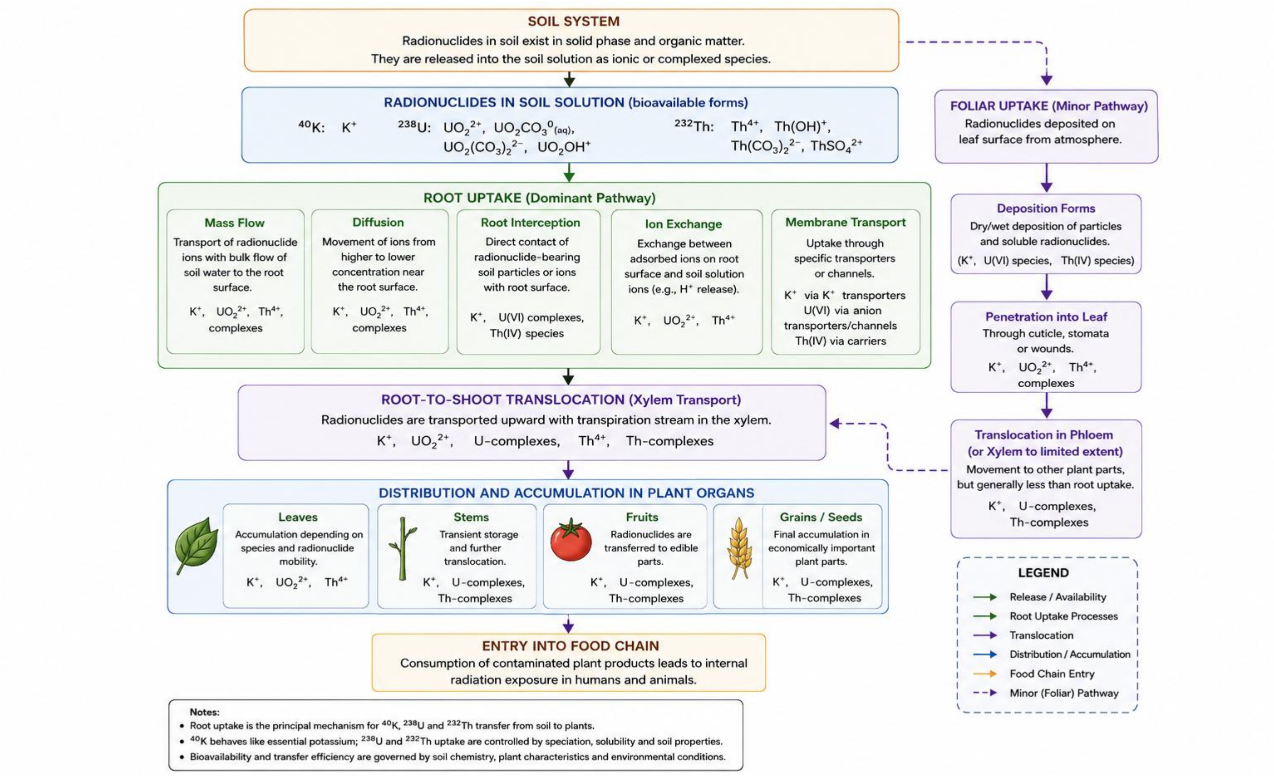

Figure 2. Mechanisms of Soil-to-Plant Transer of Naturally Occuring Radionuclides

During ingestion, each radionuclide behaves quite differently. Because it is chemically identical to stable potassium, a crucial macronutrient needed for plant growth, potassium-40 (K) is easily absorbed. On the other hand, because of their strong adsorption to soil minerals and restricted solubility, uranium (U) and thorium (Th) show relatively modest absorption. However, under oxidizing conditions, uranium may become more mobile by forming soluble uranyl complexes, which would increase its availability for root absorption [7].

Radionuclides are carried to aerial plant organs via the xylem after root absorption, where they accumulate at varying amounts based on the type of tissue, plant species, and radionuclide properties. Foliar uptake can also happen through the deposition of airborne particles and aerosols on leaf surfaces, even though root uptake is the primary transfer pathway in agricultural systems. This pathway may contribute to radioactive buildup in regions impacted by dust emissions from mining, quarrying, or industrial activity, but it is often less important for naturally occurring radionuclides [4].

Factors Influencing Soil-to-Plant Transfer

Radionuclide mobility, bioavailability, absorption, translocation, and accumulation within plant tissues are all determined by a number of interrelated processes that affect the transport of naturally occurring radionuclides (^{40}K, ^{238}U, and ^{232}Th) from soil to plants. The significance of comprehending the mechanisms governing

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radionuclide behavior in terrestrial ecosystems is highlighted by the significant differences in soil-to-plant transfer that are seen among various crops, soil types, and environmental conditions [3,7].

These regulating factors can be broadly divided into four groups: radionuclide properties, which affect chemical behavior and mobility; plant factors, which determine uptake efficiency and internal distribution; soil factors, which control radionuclide availability in the rhizosphere; and environmental factors, which alter soil-plant interactions under different climatic conditions. Together, these elements control how radionuclides move up the food chain and are essential for monitoring environmental radioactivity and evaluating radiological risk.

Soil Factors

The mobility, bioavailability, and subsequent uptake of naturally occurring radionuclides by plants are all significantly influenced by the characteristics of the soil. The physicochemical properties of soils affect the availability of radionuclides for root absorption by regulating their release from the solid phase into the soil solution. Much of the observed regional variability in soil-to-plant transfer factors documented across various agricultural and natural environments can be attributed to variations in soil parameters [2,3].

Soil pH, organic matter content, clay mineralogy, cation exchange capacity (CEC), redox potential, soil moisture, and texture are some of the interconnected characteristics that control the impact of soil on radionuclide transport. The amount of radionuclides available for plant absorption is ultimately determined by these parameters' effects on radionuclide speciation, adsorption-desorption processes, complexation, and movement within the rhizosphere. Therefore, forecasting radionuclide behavior and enhancing radiological risk assessments related to damaged agricultural systems require a thorough understanding of these soil features.

Soil pH

One of the most important variables influencing the mobility and bioavailability of naturally occurring radionuclides is soil pH. While neutral to alkaline conditions favor adsorption onto soil minerals and decrease mobility, acidic soils typically improve the solubility of uranium and other radionuclides, hence improving their availability for plant uptake. Because of its poor solubility and strong affinity for soil particles, thorium remains largely immobile over a wide pH range, whereas the availability of exchangeable potassium in the soil is the key factor influencing the uptake of ^{40}K [3,7].

Organic Matter

Radionuclide transmission is influenced by organic matter by complexation, adsorption, and the creation of stable organo-metallic complexes. In general, a high organic matter concentration decreases radionuclide mobility by increasing sorption sites; yet, in some environmental circumstances, soluble organic ligands may increase uranium mobility through complex formation. Thus, the impact of organic matter is contingent upon its composition, level of humification, and current soil chemistry [2,3].

Clay Mineralogy

Due to their large specific surface area and quantity of negatively charged adsorption sites, clay minerals have a strong control over radionuclide retention. Uranium and thorium are efficiently adsorbed by minerals such montmorillonite, illite, and kaolinite, which lowers their mobility and bioavailability. On the other hand, radionuclide mobility and transfer to plants are typically higher in sandy soils with low clay concentration [3].

Cation Exchange Capacity (CEC)

An essential measure of radionuclide availability, cation exchange capacity (CEC) represents the soil's capability to hold onto positively charged ions. High CEC soils have a higher capacity to retain ions, which lowers radioactive concentrations in the soil solution and restricts plant absorption. Conversely, soils with low CEC frequently show higher soil-to-plant transfer factors and increased radionuclide mobility [3,8].

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Redox Potential

Uranium's chemical speciation and mobility are greatly influenced by redox conditions, but thorium is less affected. Uranium is mostly found in soluble uranyl ($\square\square_2^{2+}$) complexes under oxidizing conditions, which are easily transported in the soil solution. Uranium's bioavailability and subsequent plant uptake are reduced when it is reduced to the less soluble tetravalent form (U^{+}) [2,7].

Soil Moisture

The disintegration, diffusion, and migration of radionuclides toward plant roots are all regulated by soil moisture. While excessive moisture can change soil redox conditions and radionuclide speciation, adequate moisture improves radionuclide transport through mass flow and facilitates root uptake. Radionuclide bioavailability and transfer efficiency can thus be affected by seasonal variations in soil water content [3]

Soil Texture

Through its impacts on water retention, permeability, and adsorption capacity, soil texture affects radionuclide mobility. Due to their greater surface area and higher adsorption capacity, fine-textured soils rich in clay and silt typically retain radionuclides better than coarse-textured sandy soils. As a result, under similar environmental conditions, sandy soils frequently show higher soil-to-plant transfer and radioactive mobility [3,7].

Plant Factors

The uptake, translocation, and accumulation of naturally occurring radionuclides (^{40}K, ^{238}U, and ^{232}Th) are significantly influenced by plant properties. Due to differences in root shape, nutrient uptake techniques, physiological processes, and growth characteristics, significant variability in radionuclide concentrations have been recorded among plant species, cultivars, and tissues even under similar soil circumstances. The heterogeneity of transfer factors described in the literature can be attributed to these biological differences, which have a direct impact on radionuclide bioavailability and the effectiveness of soil-to-plant transfer [4]. Plant species and genotype, root architecture, age and growth stage, physiological status, and nutrient need are the main plant-related factors affecting radionuclide transfer. Predicting radionuclide accumulation in edible crops and enhancing the precision of radiological risk assessments require an understanding of these factors' contributions.

Plant Species and Genotype

Due to variations in root membrane transporters, nutrient acquisition tactics, and physiological adaptations, different plant species and cultivars have different capacity for radionuclide uptake. As a result, even when produced under identical soil conditions, transfer factors vary significantly between cereals, vegetables, legumes, and forage crops. According to Dirican et al. [3] and Mahmoud & El-Zohry [7], these interspecific variations demonstrate the significance of plant genetics in affecting radionuclide accumulation and food-chain transfer.

Root Architecture and Morphology

The amount of soil explored and the effectiveness of water and nutrient acquisition are influenced by root architecture. In general, plants with more root hairs and deeper or more branched root systems have more interaction with the soil solution, which increases the chance of radionuclide absorption. Additionally, root morphology influences ion transport and rhizosphere chemistry, which in turn affects radionuclide uptake and translocation.

Plant Age and Growth Stage

Food demand and physiological activity vary with growth stage. This makes radionuclide uptake varies during plant development. Redistribution to reproductive organs may happen during grain or fruit development, but

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higher transpiration and nutrient uptake during active vegetative growth improve radioactive absorption. Thus, when assessing soil-to-plant transfer parameters, the sample stage should be taken into account [2,7].

Physiological Status

Radionuclide transport within plants is directly impacted by physiological activities such as transpiration, photosynthesis, and nutrition metabolism. High transpiration rates enhance xylem-mediated transfer of radionuclides from roots to shoots, while physiological stress can alter membrane permeability, transporter function, and ion homeostasis, consequently changing radionuclide accumulation in different plant tissues.

Nutrient Demand and Competition

Chemically identical ions compete for common transport channels; this makes nutrient availability to have a significant impact on radionuclide uptake. For instance, the availability of calcium, magnesium, phosphate, and iron can change the uptake of uranium and thorium by affecting their chemical speciation and competition at the root surface, while potassium deficiency increases the uptake of K through increased activity of potassium transporters. The bioavailability and transport of radionuclides in agricultural systems are significantly influenced by these ion interactions.

Radionuclide Properties

The behavior of radionuclides in the environment and their subsequent transfer from soil to plants are largely determined by their physicochemical characteristics. Radionuclide mobility, adsorption, desorption, and bioavailability are influenced by factors such chemical speciation, oxidation state, ionic charge, ionic radius, solubility, and affinity for soil constituents. As a result, even in equivalent soil and climate circumstances, radionuclides exhibit significant differences in their uptake, transport, and accumulation within plant tissues [2,3]. Chemical speciation, oxidation state, solubility, ionic radius and charge, and complexation behavior are the main radionuclide-related parameters affecting soil-to-plant transmission. The chemical forms of radionuclides in the soil solution, their interactions with organic matter and soil minerals, and their accessibility to plant roots are all determined by these characteristics. Therefore, forecasting radionuclide mobility, assessing transfer factors, and enhancing radiological risk assessments all depend on an understanding of these fundamental features.

Chemical Speciation

One of the most significant factors influencing radionuclide mobility and bioavailability is chemical speciation, which establishes the chemical forms that radionuclides take in the soil solution. In general, radionuclides that are soluble complexes or free ions are more readily absorbed by plants than those that are heavily adsorbed onto mineral surfaces or integrated into stable mineral lattices. According to Chen et al. [9] and Smedley et al. [10], thorium is mostly found as insoluble hydroxides and oxides, which results in relatively decreased mobility and plant uptake, while uranium is mostly found as soluble uranyl (UO_2^{2+}) complexes under oxidizing circumstances.

Oxidation State

While thorium is nearly always found in the tetravalent state, uranium's environmental behavior is substantially influenced by its oxidation state. Highly soluble uranyl-carbonate complexes are formed by hexavalent uranium, which easily move through soils and become available for plant absorption. Conversely, in reducing conditions, tetravalent uranium forms sparingly soluble minerals, which reduces its mobility and bioavailability. According to Chen et al. [9] and Smedley et al. [10], these redox changes are therefore essential for controlling uranium transport within the soil-plant system.

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Solubility

The concentration of radionuclides in the soil solution and, hence, their accessibility to plant roots is determined by their solubility. While poorly soluble radionuclide species stay attached to soil particles and have reduced transfer factors, soluble species are more easily carried through soil water by mass flow and diffusion, promoting root uptake. Radionuclide solubility and subsequent plant accumulation are greatly influenced by changes in soil chemistry, especially pH and carbonate concentration [3,9].

Ionic Radius and Charge

Radionuclides' interactions with plant membrane transporters and their adsorption behavior are influenced by their ionic charge and radius. Since potassium-40 is chemically the same as stable potassium (K^+), it is effectively absorbed through potassium transport systems and typically has higher transfer factors than uranium and thorium. On the other hand, the higher ionic charge of $\square\square_{2}^{2+}$ and $\square h_{4}^{+}$ increases their electrostatic attraction to negatively charged organic matter and clay minerals, decreasing their mobility and plant uptake [2,3].

Complexation and Sorption Behaviour

Depending on the stability of the complexes created, complexation with carbonate, phosphate, sulfate, and dissolved organic materials can either increase or decrease radionuclide mobility. Similarly, sorption onto soil organic matter, iron and manganese oxides, and clay minerals lowers radioactive concentrations in the soil solution, which restricts plant uptake. In terrestrial ecosystems, radionuclide transport, bioavailability, and soil-to-plant transfer are ultimately controlled by the dynamic balance between complexation and sorption [9,11].

Environmental and Climatic Factors

The mobility, bioavailability, and transfer of naturally occurring radionuclides from soil to plants are greatly impacted by environmental and climatic factors, which alter soil physicochemical characteristics, plant physiological processes, and radionuclide speciation. The transport and distribution of radionuclides within the soil–plant system are altered by variations in temperature, rainfall, irrigation techniques, seasonal shifts, and atmospheric deposition. This contributes to the temporal and spatial variability of soil-to-plant transfer factors reported across various ecosystems [3,4]. Radionuclide transmission is a dynamic process rather than a static event since the impact of environmental elements is frequently linked to soil and plant features. Therefore, assessing these characteristics is crucial for enhancing environmental monitoring and radiological risk assessment, forecasting radionuclide behavior under changing climatic conditions, and refining radioecological models.

Temperature

Temperature affects root growth, microbial activity, soil chemical reactions, and plant metabolism, all of which have an impact on radionuclide transmission. In general, higher temperatures improve transpiration and nutrient uptake, which may increase radionuclide absorption and translocation inside plants. By changing soil solution chemistry and reaction kinetics, temperature also affects radionuclide speciation and bioavailability [12].

Rainfall

Rainfall affects soil moisture, infiltration, leaching, and surface runoff, all of which control radionuclide mobility. While heavy rainfall may drain soluble radionuclides beyond the root zone or redistribute them through erosion and sediment movement, moderate rainfall encourages radionuclide transfer to the rhizosphere, improving plant absorption. Thus, seasonal and geographical differences in soil-to-plant transmission are mostly influenced by rainfall patterns [2,10].

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Irrigation Practices

Through changes in soil moisture, pH, and redox conditions, irrigation quality, quantity, and frequency affect radionuclide availability. While proper irrigation management can lower radionuclide accumulation through regulated water application and enhanced drainage, irrigation with groundwater or surface water containing naturally occurring radionuclides may gradually raise radionuclide concentrations in agricultural soils [2,7].

Seasonal Variation

Throughout the year, seasonal variations affect soil qualities, plant development, and climate, all of which have an impact on radionuclide transmission. Radionuclide mobility and plant physiological activity are impacted by temperature, rainfall, and soil moisture variations, which result in variations in uptake between growing seasons. Therefore, when comparing radionuclide concentrations between studies and assessing transfer factors, seasonal variations should be taken into account [4].

Atmospheric Deposition

Radionuclides can also enter vegetation by atmospheric deposition, which occurs when dust, aerosols, and airborne particles settle on leaf surfaces. In regions impacted by wind erosion, industrial pollution, mining, and quarrying, this route is especially crucial. Foliar deposition may contribute to radioactive accumulation in leafy vegetables and other crops exposed to contaminated airborne particles, even if root uptake continues to be the primary route for naturally occurring radionuclides [1,13].

Soil-to-Plant Transfer Factor (TF)

One of the most used radioecological metrics for assessing the movement of naturally occurring radionuclides from soil to plants is the soil-to-plant transfer factor (TF). By comparing the activity concentration in plant tissues to that in the same soil under similar conditions, it offers a quantitative estimate of radionuclide bioavailability. TF is an integrative metric that represents the combined impact of environmental factors, plant physiology, soil physicochemical features, and radionuclide properties on radioactive uptake [1]. The soil-to-plant transfer factor is mathematically expressed as:

$$\boldsymbol{TF_i} = \frac{C_i}{C_s} \qquad 1.$$

$\boldsymbol{TF_i}$ = Transfer factor for plant organ i

C_i = Activity concentration in the specific plant organ ($Bqkg^{-1}$ dry weight)

C_s = Activity concentration in the corresponding soil ($Bqkg^{-1}$ dry weight)

The radionuclide transfer efficiency is shown by the value of TF. While a lower TF denotes stronger retention within the soil matrix and decreased bioavailability, a larger TF suggests increased mobility and accumulation of radionuclides in plant tissues. TF values, however, are not constant and can differ significantly depending on radionuclides, crop species, soil types, climate, agricultural practices, and analytical techniques. As a result, it is important to evaluate TF value comparisons in light of the environmental circumstances that led to their determination [13]. In addition to measuring radionuclide uptake, the TF is a crucial input parameter in radioecological models that support environmental monitoring and radiological risk assessment, estimate internal radiation doses from dietary intake, assess contamination of agricultural products, and forecast food-chain transfer. The TF is still one of the major indices that international organizations, such as the International Atomic Energy Agency (IAEA), propose for evaluating radionuclide transport in terrestrial ecosystems because of its ease of use and wide range of applications.

Table 2. Major Studies on Soil-to-Plant Transfer of Naturally Occurring Radionuclides in Nigeria

Study Area	**Crop(s)**	**Radionuclide(s)**	**Major Findings**	**Author(s)**

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Southwestern Nigeria	*Amaranthus hybridus*	^{40}K, ^{226}Ra, ^{232}Th	Mean TFs of 26.58 (^{40}K), 0.62 (^{226}Ra), and 0.39 (^{232}Th) were reported. ^{40}K exhibited substantially higher transfer than the other radionuclides.	Mahmoud & El-Zohry, [7]
High background radiation area, Oyo State	Food crops	^{40}K, ^{226}Ra, ^{232}Th	Transfer factors varied significantly among crop species, reflecting differences in radionuclide uptake efficiency.	Ajayi [14]
Tropical ecosystem, abandoned tin-mining area	Maize	^{40}K, ^{238}U, ^{232}Th	Soil characteristics significantly influenced radionuclide transfer, with leaves showing higher accumulation than grains.	Adesiji & Ademola [15]
Minna and Kaduna States	Medicinal plants	^{238}U, ^{232}Th,^{40}K, ^{137}Cs	Medicinal plant species accumulated radionuclides differently, demonstrating species-dependent transfer characteristics.	Davis et al. [16]
Bassa LGA, Plateau State	Edible food crops	^{40}K, ^{226}Ra, ^{232}Th	Mean TF values followed the order ^{232}Th (0.666) > ^{226}Ra (0.557) > ^{40}K (0.473); all values were below unity.	Waida et al. [17]
Kwara State (gold and beryllium mining sites)	Guinea corn (*Sorghum bicolor*)	^{40}K, ^{238}U, ^{232}Th	Mining activities influenced radionuclide mobility and transfer, although estimated radiological risks remained within international safety limits.	Orosun et al. [13]
Southwestern Nigeria	Yam, cassava, maize, rice, vegetables, banana, pawpaw	^{40}K, ^{226}Ra, ^{232}Th	Significant interspecies variability in TFs was observed, with crop type and soil physicochemical properties identified as the principal determinants of radionuclide transfer	Oladele et al. [18]
Kano State	Rice (root, stem, leaf and grain)	^{40}K, ^{238}U, ^{232}Th	Leaves recorded the highest transfer of ^{40}K, whereas roots accumulated relatively higher uranium-series radionuclides, demonstrating organ-specific uptake.	Olabimtan et al. [19]
Southwestern Nigeria	Vegetation, meat and milk pathways	^{238}U, ^{232}Th	Estimated soil-to-vegetation TFs were 0.020 (^{238}U) and 0.090 (^{232}Th), indicating relatively low transfer into the food chain.	Moran-Hunter [20]

Table 3. Published Studies on Soil-to-Plant Transfer and Environmental Distribution of Naturally Occurring Radionuclides in Ghana

Study Area	**Crop(s) /Sample(s)**	**Radionuclide(s)**	**Transfer Factor (TF)**	**Major Findings**	**Sources**

Tano Basin, Western Region, Ghana	Cassava (*Manihot esculenta*)	^{40}K, ^{238}U, ^{232}Th	^{40}K: 0.04–0.28; ^{238}U: 0.06–0.12; ^{232}Th: 0.01–0.10	Uranium showed greater soil-to-cassava transfer than thorium, while ^{40}K showed the widest variation among samples.	Doyi et al. [21]
Greater Accra Region, Ghana	Vegetables	^{226}Ra, ^{228}Ra, ^{40}K	Reported	Transfer factors from fertilized soils to vegetables were evaluated. Lettuce showed higher ^{226}Ra transfer, while cauliflower showed the highest ^{40}K and ^{228}Ra transfer.	Adjirackor et al. [22]
Mining and non-mining districts, Ghana	Cassava (*Manihot esculenta*)	^{238}U, ^{232}Th	Reported	Transfer factors differed between mining and non-mining areas, showing the influence of geology and mining activities on radionuclide uptake.	Ankapong et al. [23]
Mining, oil and gas communities in Ghana	Soil, water, farmland water, sludge and scale	Soil: ^{238}U, ^{232}Th, ^{40}K; Water: ^{226}Ra, ^{228}Th, ^{40}K	Not reported	Mean soil activities were 59 ± 16 Bq kg^{-1} for ^{238}U, 48 ± 15 Bq kg^{-1} for ^{232}Th, and 286 ± 57 Bq kg^{-1} for ^{40}K. Total annual effective dose was below the ICRP public dose limit.	Faanu et al. [24]
New Eastern Concession Area, Perseus Gold Mine, Central	Soil, rock, ore and water	^{238}U, ^{232}Th, ^{40}K	Not reported	Mean activities were 65.1 ± 2.2 Bq kg^{-1} for ^{238}U, 71.8 ± 2.2 Bq kg^{-1} for ^{232}Th, and 1168.3 Bq kg^{-1} for ^{40}K. Total annual effective dose was 0.918 mSv, below the 1 mSv public exposure limit.	Faanu et al. [24]
Atiwa West, Eastern Region, Ghana	Soil, water and vegetation	^{226}Ra, ^{232}Th, ^{40}K	Estimated for ^{226}Ra in vegetation	Artisanal gold mining influenced environmental radioactivity. Water posed greater radiological concern than soil, with some samples exceeding WHO screening levels.	Akuo-ko et al. [25]
Lower Basin of River Pra, Central and Western Regions, Ghana	Soil, sediment and water	^{238}U, ^{232}Th, ^{40}K	Not reported	Mean soil activities were 25.51 Bq kg^{-1} for ^{238}U, 28.04 Bq kg^{-1} for ^{232}Th, and 238.98 Bq kg^{-1} for ^{40}K. Annual effective dose from water remained within recommended limits.	Adukpo et al. [26]

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Communities bordering the Tano Basin, Ghana	Soil	^{238}U, ^{232}Th, ^{40}K	Not reported	Mean activities were 8.65 Bq kg^{-1} for ^{238}U, 12.5 Bq kg^{-1} for ^{232}Th, and 214 Bq kg^{-1} for ^{40}K. Hazard indices and ELCR were within recommended limits.	Doyi et al. [21]
Ghana	Maize	^{40}K, ^{226}Ra, ^{232}Th	Not reported	Radionuclide concentrations in maize were measured and radiological implications assessed, but soil-to-plant transfer factors were not calculated.	Acquah & Pooko-Aikins [27]

Note: TF = transfer factor. Studies marked "Not reported" are relevant to environmental distribution and radiological assessment but did not calculate soil-to-plant transfer factors.

Table 4. Published Studies on Environmental Distribution, Naturally Occurring Radionuclides (NORMs), and Radiological Assessment in Burkina Faso

Study Area	**Crop(s)/ Sample(s)**	**Radionuclide(s)**	**Transfer Factor (TF)**	**Major Findings**	**Sources**
Northeastern Burkina Faso	Soil	^{238}U, ^{232}Th, ^{40}K	Not reported	Activity concentrations of ^{238}U, ^{232}Th and ^{40}K were measured using HPGe gamma-ray spectrometry. Three high-background radiation zones associated with uranium, thorium and potassium were identified. Most radiological hazard indices (Raeq, H_{ex}, H_{in}, AEDE and ELCR) were below internationally recommended limits, although Niapsi recorded slightly elevated dose indices.	Beogo et al. [28]
Pilot Site of Uranium Anomaly, Sahel Region, Burkina Faso	Soil	^{238}U, ^{232}Th, ^{40}K	Not reported	Uranium activity concentrations (181.89–191.37 Bq kg^{-1}) were approximately five times the global average, while thorium concentrations were nearly twice the global average. Absorbed dose rate, internal hazard index, annual effective dose and excess lifetime cancer risk exceeded recommended limits, indicating elevated radiological hazards.	Beogo et al. [28]
Solhan, Sahel Region, Burkina Faso	Soil	^{40}K, ^{238}U, ^{232}Th	Not reported	High concentrations of uranium and thorium were observed relative to world averages. Radiological assessment indicated elevated absorbed dose rate, annual effective dose and excess lifetime cancer risk, whereas radium equivalent activity and external hazard index remained within acceptable limits.	Beogo et al. [28]

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Ouagadougou, Burkina Faso	Soil	^{2340}K, ^{238}U, ^{232}Th ^{137}Cs	Not reported	Activity concentrations of naturally occurring radionuclides were below UNSCEAR global averages. Calculated absorbed dose rates and annual effective doses indicated low terrestrial radiation exposure and minimal radiological risk.	Yaméogo et al. [29]
Kalsaka Gold Mining Area, North Region, Burkina Faso	Soil	^{226}Ra, ^{232}Th, ^{40}K	Not reported	Mean activity concentrations and all calculated radiological hazard indices were below internationally accepted limits, indicating negligible radiological risk around the gold mining area.	Kaboré et al. [30]
Mana Gold Mine, near Mana Village, Burkina Faso	Waste rock, ore-processing sludge and	Uranium- and thorium-series radionuclides (NORMs)	Not reported	Naturally occurring radionuclides were detected in waste rock and ore-processing sludge at relatively low concentrations. Radiation exposure to mine workers did not exceed natural background levels, and waste rock was considered suitable for reuse in road construction.	Nabayaogo et al. [31]

Factors Influencing Soil-to-Plant Transfer of Naturally Occurring Radionuclides

A complex interplay of soil properties, radionuclide chemistry, plant physiology, and environmental factors controls the movement of naturally occurring radionuclides from soil to plants. Thus, even for the same crop species and radionuclide, soil-to-plant transfer factors (TFs) show significant temporal and geographical heterogeneity. Predicting radionuclide mobility, evaluating food-chain contamination, and enhancing radiological risk assessment all depend on an understanding of these regulating mechanisms. Since radionuclide uptake is dependent on site-specific environmental circumstances and agricultural methods, international guideline acknowledges that no single transfer factor is universally applicable [1,3].

Soil Physicochemical Properties

Radionuclide mobility and bioavailability are largely influenced by the physicochemical characteristics of the soil. Radionuclide adsorption, desorption, dissolution, and complexation are controlled by factors including soil pH, organic matter concentration, clay mineralogy, cation exchange capacity, soil texture, moisture content, and redox potential. While clay-rich and organic matter-rich soils immobilize radionuclides through adsorption and ion-exchange reactions, decreasing plant uptake, acidic soils typically increase the mobility of uranium and radium. Recent studies also show that the spatial distribution and bioavailability of naturally occurring radionuclides are strongly influenced by soil mineralogy and geological composition [3].

Radionuclide Characteristics

The oxidation state, ionic radius, chemical speciation, valence, and half-life of radionuclides all have a significant impact on how they behave in the environment. Since potassium is a necessary plant macronutrient and frequently produces higher transfer factors than uranium-238 and thorium-232, potassium-40 is easily absorbed. Because of its great affinity for organic matter and soil minerals, thorium typically has the lowest mobility, while uranium exhibits intermediate mobility based on its oxidation state and the development of soluble carbonate complexes [3,13].

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Plant Species and Physiological Characteristics

The ability of different plant species to absorb, translocate, and accumulate radionuclides varies greatly due to differences in development stage, metabolic activity, transpiration rate, root shape, and nutrient uptake processes. While shallow-rooted species mostly reflect radioactive concentrations in surface soils, deep-rooted crops may have access to radionuclides from deeper soil layers. Because of limited translocation through the vascular system, roots often show higher activity concentrations than edible tissues when it comes to radionuclide accumulation [3,13].

Agricultural and Environmental Conditions

Radionuclide bioavailability is significantly influenced by agricultural practices. Radionuclide mobility is impacted by soil chemistry changes brought about by the use of phosphate fertilizers, irrigation, liming, organic additions, and tillage. By affecting weathering processes, microbial activity, and root formation, climate factors like temperature, rainfall, and seasonal moisture dynamics further control radionuclide transfer. Radionuclide concentrations in agricultural soils may rise as a result of mining and mineral processing operations, raising the possibility of food chain transmission [13].

Competitive Uptake and Elemental Interactions

Competitive interactions between radionuclides and chemically similar nutritional elements in the soil solution also affect radionuclide uptake. Phosphate affects uranium mobility by adsorption and complexation processes, potassium competes with caesium, and calcium competes with radium. As a result, in addition to radioactive concentration, radionuclide transfer also depends on nutritional availability and the larger geochemical environment, which adds to the variation in transfer factors found in different ecosystems [3].

Analytical and Methodological Factors

Variability in reported transfer factors is also significantly influenced by variations in sampling strategy, experimental design, and analytical methods. Calculated TF values can be greatly impacted by variables such sampling depth, plant growth stage, sample preparation, moisture adjustment, analytical equipment, and the use of fresh- versus dry-weight measurements. Therefore, for a meaningful comparison of transfer factors across studies and geographical regions, standardized analytical methodologies and quality assurance procedures are necessary [1].

Synthesis of Published Studies and Research Gaps in West Africa

The distribution, transmission, and radiological evaluation of naturally occurring radionuclides in West Africa vary significantly, according to published research. Despite significant contributions from Burkina Faso, Ghana, and Nigeria to the regional body of evidence, research is nonetheless methodologically inconsistent and geographically dispersed. Relatively few studies have measured radionuclide transmission through terrestrial food chains, while the majority have concentrated on assessing radiological hazard indices and activity concentrations of naturally occurring radionuclides in environmental media.

Uneven Geographical Distribution of Research

Nigeria and Ghana account for the majority of published studies on naturally occurring radionuclides in West Africa, according to the country-specific study. Groundwater, food crops, mining environments, agricultural soils, and environmental dose assessment are all included in these investigations. Peer-reviewed studies from Benin, Côte d'Ivoire, Guinea, Guinea-Bissau, Liberia, Sierra Leone, The Gambia, and Cabo Verde are either nonexistent or extremely rare, whereas Burkina Faso and Mali have comparatively few published studies. This unequal geographic distribution makes it difficult to compare radionuclide behavior across various geological and climatic zones and restricts the creation of an extensive regional radioecological database [7,8,9].

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Predominance of Environmental Radioactivity Studies

According to the reviewed literature, the majority of studies have focused on determining the activity concentrations of ^{222}Ra, ^{232}Th, and ^{40}K in mining environments, soils, sediments, and water. This has been followed by the estimation of radiological hazard indices like excess lifetime cancer risk (ELCR), radium equivalent activity (Ra_{eq}), absorbed dose rate (ADR), annual effective dose equivalent (AEDE), external hazard index (H_{ex}), internal hazard index (H_{in}), and external hazard index. These evaluations offer useful data on radiation exposure in the environment, but they don't provide much information about radionuclide transport through agricultural food chains and subsequent internal human exposure [11].

Limited Soil-to-Plant Transfer Investigationsy

The scarcity of studies documenting soil-to-plant transfer factors (TFs) is one of the biggest knowledge gaps found. The majority of research from Burkina Faso and Mali concentrated solely on environmental radioactivity and radiological hazard assessment, while Ghana and a few studies from Nigeria indicated transfer factors for specific crops. In most of West Africa, there is still a lack of quantitative data on radionuclide uptake by major crops such maize, rice, cassava, sorghum, millet, yam, and vegetables. This restriction adds a great deal of uncertainty to internal dosage assessment and food-chain modeling.

Insufficient Crop Diversity

Current studies are often limited to a small number of agricultural goods and assess only one or two crop species within specific research regions. Despite their significance in regional diets, major staple crops consumed throughout West Africa such as millet, sorghum, cowpea, groundnut, yam, cocoyam, plantain, and leafy vegetables have gotten very little attention. As a result, it is still difficult to determine radionuclide transfer coefficients that are typical of West African food systems.

Lack of Standardized Methodologies

Studies varied significantly in terms of reporting units, sample preparation, analytical methods, sampling procedures, and transfer factor computations. Although the most common analytical method is high-purity germanium (HPGe) gamma spectrometry, direct comparison between studies is complicated by differences in sampling depth, soil characterization, plant sampling protocols, moisture correction, and quality assurance procedures. The creation of trustworthy regional transfer databases is hampered by the lack of standardized procedures.

Limited Integration of Soil Properties with Radionuclide Transfer

Relatively few studies concurrently characterize soil parameters like pH, cation exchange capacity, organic carbon, clay mineralogy, redox potential, and particle-size distribution with radionuclide transfer measurements, despite the fact that soil physicochemical properties have a significant impact on radionuclide bioavailability. As a result, our mechanistic knowledge of radionuclide mobility in tropical West African soil is still lacking.

Scarcity of Long-Term Monitoring Programmes

The majority of the studies that are currently accessible are cross-sectional and reflect individual sampling campaigns. Long-term monitoring of radioactive concentrations in soils, crops, irrigation water, and groundwater is virtually lacking. Detecting temporal variations related to mining operations, fertilizer application, temperature fluctuation, land-use change, and environmental deterioration requires this kind of monitoring.

Limited Human Dose and Health Risk Assessments

Few studies combined radionuclide transfer data with dietary consumption patterns to estimate committed effective dose, lifetime cancer risk, or age-specific internal exposure, despite the fact that several studies measured exterior radiation exposure. Despite their increased susceptibility to ionizing radiation, there are still

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very few studies that specifically address newborns, young children, pregnant women, and other susceptible populations.

Need for Region-Specific Transfer Factors

In West Africa, a lot of radioecological risk estimates are still based on default transfer factors from the IAEA or other international databases. Although these values offer helpful benchmarks, they might not fully capture radionuclide behavior in West Africa's distinct climatic, geological, pedological, and agricultural contexts. Therefore, creating transfer factors for important staple crops that are derived locally has to be prioritized in regional research.

Human Exposure Pathways

Humans can be exposed to naturally occurring radionuclides by eating, breathing, or being exposed to them. Geological circumstances, environmental contaminants, dietary practices, occupational activities, and lifestyle all affect each pathway's relative contribution. The risk of long-term exposure to naturally occurring radionuclides is increased in West Africa due to artisanal mining, agriculture, groundwater usage, and reliance on locally produced foods. As a result, measuring internal and exterior radiation doses and assessing related public health hazards require an understanding of these routes [5].

Ingestion

The main way that naturally occurring radionuclides reach the human body under typical environmental circumstances is by ingestion. Regular use of potable water, seafood, livestock products, and crops can expose humans to radionuclides. While radionuclides of the uranium and thorium series typically exist at lower concentrations but may contribute more significantly to internal radiation exposure due to their radiotoxicity, potassium-40 typically contributes the highest activity concentrations since it is an essential food. Therefore, radionuclide content, food consumption habits, and regional agricultural techniques all affect dietary exposure [5].

Inhalation

Radon gas and dust containing radionuclides can be inhaled. Airborne particles enriched with naturally occurring radionuclides can be produced by mining, quarrying, agriculture, and wind erosion. Because its decay products accumulate in the respiratory system and raise the risk of lung cancer after extended exposure, radon (^{222}Rn), which is created from the decay of ^{226}Ra, is especially significant. Mining communities and inadequately ventilated interior spaces are especially vulnerable to this pathway [31,32].

External Irradiation

Gamma radiation from naturally occurring radionuclides found in soils, rocks, sediments, and building materials causes external irradiation. The main sources of gamma radiation on land are uranium-238, thorium-232, and potassium-40. The majority of studies conducted in West Africa report radiation levels within internationally recommended limits; however, some mining environments and geological formations rich in phosphate and uranium have been found to have elevated exposures, which calls for ongoing environmental monitoring [1,33].

Occupational Exposure

Workers engaged in mining, mineral processing, phosphate industries, and oil and gas operations where naturally occurring radioactive materials (NORMs) are concentrated are primarily affected by occupational exposure. Inhalation, ingestion, and external radiation exposure can all happen at the same time. Continuous monitoring, engineering controls, and suitable radiation protection measures are crucial for reducing long-term health concerns, even when occupational doses often stay below legal limits [2].

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Cumulative Exposure

Instead of a single channel, human exposure typically arises from the combined effects of eating, inhalation, and external irradiation. In order to evaluate the overall effective dosage, a thorough radiological risk assessment incorporates environmental radionuclide concentrations with transfer factors, food intake rates, occupancy factors, and age-specific dose coefficients. In areas impacted by naturally occurring radionuclides, such integrated evaluations offer a more practical foundation for environmental management and public health protection [5].

Health Effects of Naturally Occurring Radionuclides

Human health may be negatively impacted by exposure to naturally occurring radionuclides, depending on the kind of radionuclide, activity concentration, exposure route, length of exposure, and individual susceptibility. Long-term exposure to high amounts of naturally occurring radioactive materials (NORMs) may raise the risk of stochastic consequences, especially cancer, even though natural background radiation is an inevitable aspect of the environment. Because radionuclides can build up in particular organs and constantly irradiate nearby tissues, internal exposure through ingestion and inhalation is typically more concerning than exterior irradiation [1,2,33].

Cancer Risk

Long-term exposure to uranium, radium, radon, and their decay products has been linked to higher risks of kidney, lung, and bone malignancies. According to WHO [32], ingestion of contaminated food and drinking water may increase internal radiation exposure and long-term cancer risk, while radon inhalation is acknowledged as the second most common cause of lung cancer after tobacco use.

Organ Toxicity

Radionuclides that occur naturally tend to build up in particular organs. Because of its chemical resemblance to calcium, radium is mostly deposited in bones, while uranium mostly builds up in the kidneys, where extended exposure may induce both chemical and radiological damage. The biological effects of long-term radionuclide exposure are influenced by several organ-specific behaviors [33].

Sensitive Populations

Due to rapid tissue growth, physiological variations, or chronic exposure, radiation-induced health problems are more likely to affect infants, children, pregnant women, and occupational exposed workers. Therefore, accurate radiological risk assessment and efficient public health protection depend on age-specific dose assessment [33].

Public Health Implications

The majority of West African research reports environmental radionuclide quantities that fall within globally advised bounds. However, there may be increased exposure concerns in specific locations connected to mining, phosphate resources, and uranium-rich geological formations. Thus, evidence-based radiation protection and food safety policies require ongoing environmental monitoring, food surveillance, groundwater evaluation, and the creation of locally derived transfer factors [5].

Future Research Directions

Development of Local Transfer Factors

The creation of locally developed soil-to-plant transfer factors (TFs) for important staple crops grown in various agroecological environments in West Africa should be the main focus of future research. The application of generalized transfer coefficients from temperate environments would be less uncertain and radioecological models would be more reliable using region-specific TF measurements [1,2,33].

Integrated Environmental Monitoring

To better understand radionuclide transport across terrestrial food chains, extensive research incorporating soils, irrigation water, crops, groundwater, and food items are needed. These interdisciplinary methods would increase estimates of internal radiation exposure and bolster environmental monitoring [5].

Long-Term Monitoring

Single sample efforts provide the basis for the majority of existing research. Therefore, long-term environmental surveillance is necessary to assess temporal variations in radionuclide distribution and related radiological risks, especially in mining regions, phosphate-bearing formations, and naturally high-background radiation areas [34].

Methodological Harmonization

Standardized sampling techniques, analytical techniques, quality assurance procedures, and reporting frameworks should be used in future research to assist the creation of regional radioecological databases and enable study comparison. Transfer factor datasets and environmental risk assessments will be more reliable with harmonized approaches [3]

Public Health Research

With a focus on infants, children, pregnant women, and populations living in mining and high-background radiation areas, future research should incorporate dietary exposure assessment, age-dependent dose modeling, and epidemiological studies. These investigations are crucial for bolstering evidence-based radiation protection and food safety regulations [5,35].

Regional Collaboration

Strengthening collaboration among research institutions, regulatory agencies, and international organizations will facilitate data sharing, harmonized monitoring programmes, and coordinated radioecological research. Regional cooperation is essential for developing comprehensive environmental radionuclide databases and improving radiation protection strategies across West Africa [5].

CONCLUSION

In West Africa, naturally occurring radionuclides continue to be a significant source of environmental radiation exposure, and their transfer from soil to plants is a crucial route for human consumption through the food chain. This research shows that soil qualities, radionuclide chemistry, plant traits, and environmental factors all influence the mobility and bioavailability of radionuclides, leading to significant diversity in soil-to-plant transfer factors. The reviewed papers show that while quantitative studies of soil-to-plant transmission are still scarce and spatially unequal, research in West Africa has mostly concentrated on environmental radioactivity and radiological hazard assessment. The majority of published research comes from Nigeria and Ghana, although there are still large information gaps in many other West African nations. Regional exposure and risk evaluations are also made questionable by the absence of long-term monitoring programs, locally generated transfer factors, and standardized procedures. Standardized radioecological studies, the creation of region-specific transfer factor databases for important staple crops, integrated food-chain evaluations, and ongoing environmental monitoring should be the main focus of future research. By filling in these gaps, radiological risk assessment will be strengthened, evidence-based food safety and environmental management will be supported, and radiation protection policies throughout West Africa will be improved.

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