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Groundwater in arid environments: A review of uranium occurrence and impacts

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ABSTRACT

Study region: This review focuses on major uranium-producing arid regions, including Australia, Chile, Kazakhstan, the USA, Niger, South Africa, and Namibia. These regions are globally significant not only for their uranium deposits but also because communities rely heavily on groundwater as a primary drinking water source.
Study focus: The paper synthesises existing knowledge on the occurrence of uranium in groundwater across these arid environments, examining its impacts on water quality and associated health risks. It further evaluates available remediation technologies and considers their applicability under diverse hydrogeological and socio-economic settings. Unlike previous studies limited to individual sites or countries, this review provides a cross-regional comparison that integrates hydrochemical, radiological, and remediation perspectives.
New hydrological insights for the region: The analysis reveals recurring hydrogeochemical challenges in arid uranium provinces, particularly the limited application of isotopic tracers, radionuclide monitoring, and advanced groundwater modelling. By comparing case studies across continents, the review identifies consistent knowledge gaps and emphasises that remediation strategies must be tailored to local hydrogeology and cost constraints. This synthesis presents a novel global perspective on understanding uranium-related groundwater risks in arid regions and outlines a roadmap for future research and adaptive water management.

1. Introduction

Groundwater contamination is a pressing global issue that threatens human health and ecosystems, arising from both natural processes and anthropogenic activities such as industrial waste, mining, urbanisation, and agriculture (Akhtar et al., 2021; Li et al., 2021; Karunanidhi et al., 2022; Jibitha and Sabu, 2023). In arid regions, groundwater is particularly scarce due to limited recharge, yet it remains the primary source of drinking water worldwide, relied upon by nearly three billion people (Famiglietti and Ferguson, 2021; Benaissa et al., 2023; Zhang et al., 2024; Elsaidy et al., 2025). Its natural protection, favourable bacteriological quality, and accessibility make safeguarding groundwater resources a global priority.

Uranium is a naturally occurring, toxic, and radioactive heavy metal with an average crustal abundance of 3 ppm, though

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concentrations in uranium-rich provinces can reach up to 500 ppm (Stumpf et al., 2020; Smedley and Kinniburgh, 2022; Ighalo et al., 2024). When mobilised through erosion, dissolution, or acid mine drainage, uranium contaminates groundwater and poses severe health risks. Globally, guidelines and standards for uranium in drinking water vary considerably and remain relatively recent in

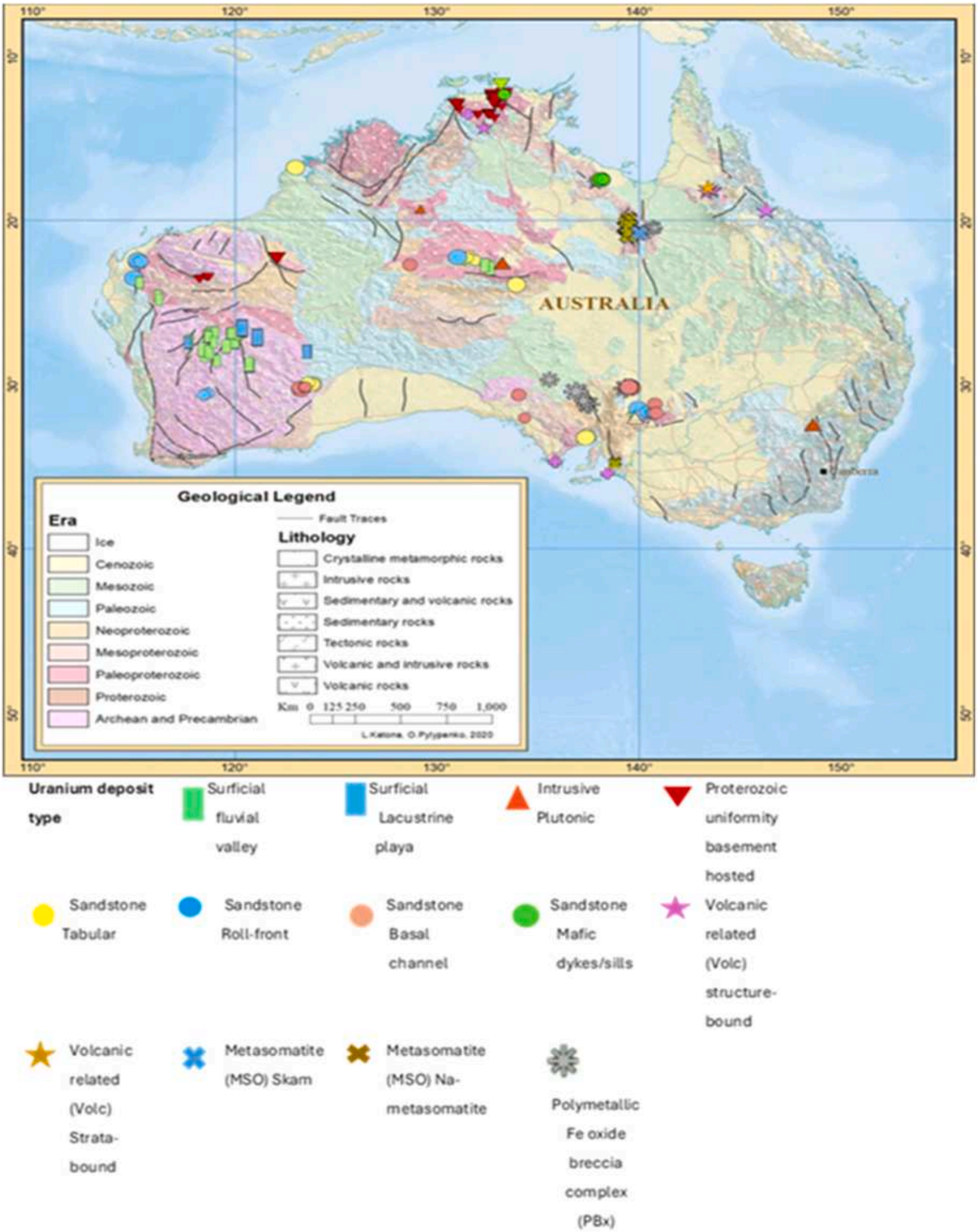

Fig. 1. Geographic distribution of uranium deposit types in Australia.

development. The World Health Organisation recommends a guideline of 30 μg/L in drinking water, yet elevated levels remain widespread, with exposure linked to kidney damage, neurological effects, and increased cancer risks (Lapworth et al., 2021; Smedley and Kinniburgh, 2022; Vengosh et al., 2022).

Around the world, a number of arid regions host uranium deposits, notably in Australia, Chile, Kazakhstan, the USA, Niger, Namibia, and South Africa, where mining activities heighten contamination risks (Ma et al., 2020; Mathuthu et al., 2021; Smedley and Kinniburgh, 2022; Ibrayeva et al., 2025). In these environments, groundwater contamination is aggravated by solute concentration through evaporation and poorly managed waste disposal, which mobilise uranium and associated radionuclides into aquifers (Smedley and Kinniburgh, 2022; Vengosh et al., 2022; Ibrayeva et al., 2025). Research conducted in the mid-20th century in the United States, Canada, and Europe established a link between radon exposure and lung cancer (Nilsson and Tong, 2020; Ngoc et al., 2022; Richardson et al., 2022; Ruano-Ravina et al., 2023). In Namibia, Mathuthu et al. (2021) observed that isotopic ratios of uranium (234U/238U) in groundwater samples were below unity (<1), suggesting that the uranium originated from mining activities rather than natural sources. The rising global demand for uranium has led to increased mining activities, intensifying the need to assess groundwater pollution in arid regions. The OECD (2025) report serves as a cornerstone reference in uranium research, offering the most comprehensive and authoritative account of global resources, production, and demand. Its detailed synthesis of market dynamics, policy developments, and environmental and social considerations makes it an essential source for evaluating both the status and the broader impacts of uranium mining worldwide

This review provides a comprehensive synthesis of uranium contamination in groundwater, particularly in arid regions, where recharge limitations and geochemical conditions exacerbate the vulnerability. Unlike previous studies that focus on isolated sites or individual aspects, this work integrates uranium occurrence and remediation approaches across multiple uranium provinces. By highlighting underrepresented regions such as Africa, the study addresses critical knowledge gaps and advances understanding of groundwater risks in mining-affected arid environments.

2. A review of uranium occurrence and impacts

2.1. Australia

Australia is one of the largest global uranium producers, alongside Kazakhstan (Herrmann, 2023; Britt and Czarnota, 2024; OECD, 2025). Approximately 90 % of Australia's uranium reserves are found in hematite breccia complexes and unconformity-related deposits(International Atomic Energy Agency, 2020; Hiatt et al., 2021). Fig. 1 highlights the spatial clustering of deposits across Australia, particularly in the Northern Territory, South Australia, and Western Australia. It illustrates the major deposit categories as defined by the International Atomic Energy Agency (2020), with symbols and colours representing different deposit types (e.g., surficial fluvial valley intrusive plutonic and others). The legend is adapted from the IAEA's "World Uranium Geology, Exploration, Resources, and Production" (2020).

Significant uranium deposits in Australia include the Olympic Dam Iron Oxide Copper Gold-Uranium (IOCG-U) deposit in South Australia and the unconformity-related deposits of Ranger, Jabiluka, Nabarlek, and Koongarra in the Northern Territory. Other notable deposits include Kintyre in Western Australia and Yeelirrie (Gigon et al., 2019; Reid, 2019; Courtney-Davies et al., 2020; OECD, 2025). Most of the countries' uranium mines are found in Western Australia (4 mines) and Southern Australia (4 mines) (OECD, 2025).

The International Atomic Energy Agency (2020) and Herrmann (2023) note that uranium mining in Australia is governed by a complex regulatory framework that operates at both the federal and state/territory levels. Proponents of uranium mines are required to undertake rigorous and comprehensive environmental impact assessment processes that incorporate public comments on the proposal, as per the requirements of Australia's Commonwealth and relevant state or territory legislative frameworks (OECD, 2025). Aboriginal Land Rights and Native Title laws ensure that Aboriginal peoples' cultural and land concerns are respected in approval processes (OECD, 2025). Mining is a key driver of Western Australia's economy, with the Yilgarn Craton hosting significant uranium concentrations primarily associated with carnotite in calcrete formations (Drummond et al., 2021; Ralph et al., 2020, 2024). Mining operations in Western Australia face notable radiological challenges, with 19 sites identified where workers were exposed to naturally occurring radioactive materials (Ralph and Cattani, 2021). Average worker radiation doses increased by 32.4 %, reaching 0.94 mSv in 2019–20, a level close to regulatory intervention thresholds (Ralph and Cattani, 2021). While natural uranium concentrations in groundwater are generally below 5 μg/L, elevated levels above the WHO (World Health Organisation) guideline of 30μg/L were observed in granitic terrains and uranium-rich zones in Australia (Smedley and Kinniburgh, 2022). Groundwater near uranium deposits in Koongarra, exhibits uranium concentrations as high as 440 μg/L (Smedley and Kinniburgh, 2022). The consumption of water contaminated with uranium has been associated with adverse health effects, including kidney damage (Guéguen and Frerejacques, 2022; Horvit and Molony, 2022; Anderson et al., 2025), particularly in Western Australia (Rajapakse et al., 2019). However, it is essential to note that the Australian government supports the development of a sustainable uranium mining industry that adheres to the highest global environmental and safety standards (OECD, 2025).

2.2. Chile

Uranium exploration in Chile began in the early 1950s, with the first deposits discovered at Estación Romero in northern Chile (International Atomic Energy Agency, 2020; OECD, 2025). In 1965, Chile established the Chilean Nuclear Energy Commission (CCHEN) to address issues related to atomic energy and radioactive materials (OECD, 2025). The commission was tasked with advising the government on matters related to nuclear energy and overseeing radioactive materials (Gutiérrez, 2014; International Atomic

Energy Agency, 2020; OECD, 2025). The distribution of uranium deposits in Chile is shown in Fig. 2. The symbols and colours represent different uranium deposit categories (e.g., volcanic-hosted, surficial, intrusive, and others), with the legend adapted from the IAEA's "World Uranium Geology, Exploration, Resources and Production"(2020).

Chile's uranium resources were estimated at 1448 tonnes of uranium (tU) as of January 2017, comprising 561 tU of reasonably assured resources and 886 tU of inferred resources (International Atomic Energy Agency, 2020). Significant uranium-bearing deposits are hosted within Chile's Paleozoic Coastal Batholith (Collao et al., 2019; OECD, 2025). These deposits include surface uranium resources of 68.8 tU, metasomatic deposits of 1762.8 tU, Cenozoic volcanic deposits of 100 tU, and unconventional deposits totalling 1798 tU (Collao et al., 2019; OECD, 2025).

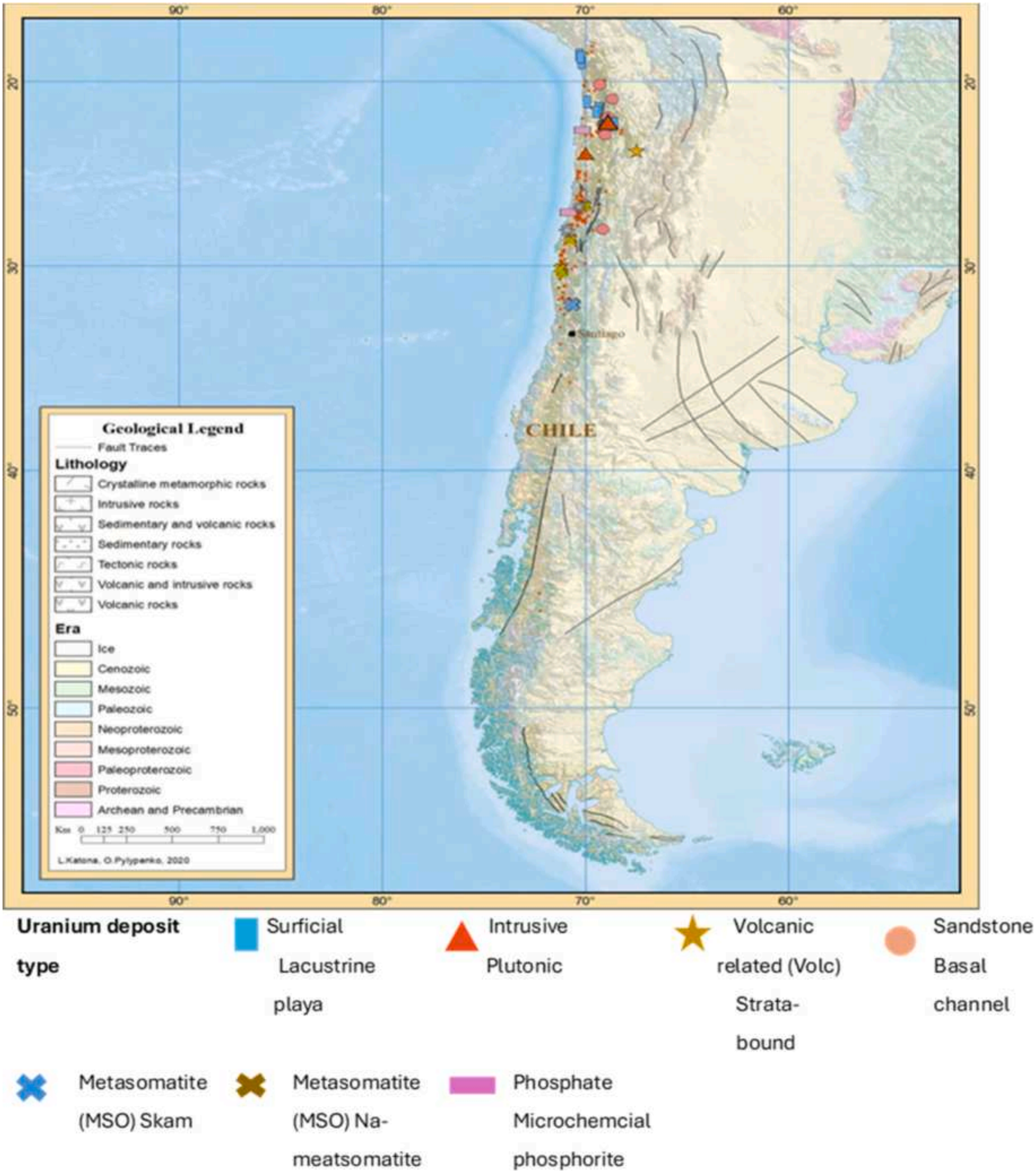

Fig. 2. Uranium deposits of Chile showing the distribution of major deposit types as defined by the International Atomic Energy Agency (2020).

Although limited literature exists on the effects of uranium on groundwater quality, the Chilean government has made significant strides in enhancing environmental and mining regulatory standards (Ghorbani and Kuan, 2017; OECD, 2025). These efforts include enacting the Environmental Basics Law in 1994 and establishing the Ministry of Environment in 2010 to oversee and enforce environmental policies (Ghorbani and Kuan, 2017). These policies covered the protection of the public, animal health, national protected areas, landfills and residue disposal. Chile has not reported any exploration and development expenditures for uranium since 2016 (OECD, 2025).

2.3. Kazakhstan

Kazakhstan accounts for 40 % of global uranium production, solidifying its position as a key player in the international uranium

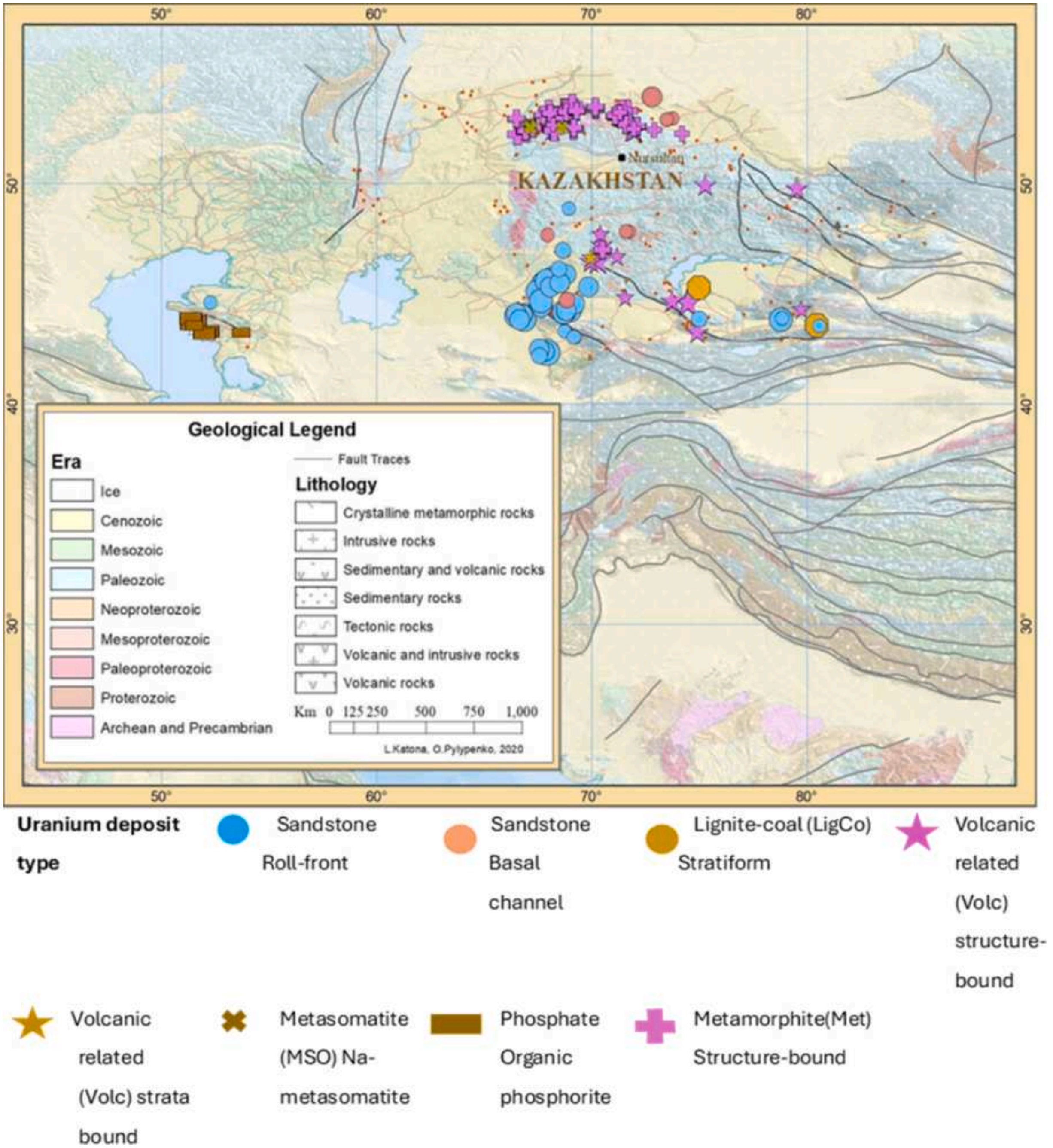

Fig. 3. Uranium reserve distribution across the uranium provinces of Kazakhstan.

market (Kenzhetaev et al., 2021; Britt and Czarnota, 2024). Kazakhstan has abundant natural resources, including metal ores, natural gas, minerals, and oil reserves (International Atomic Energy Agency, 2020; Kayukov et al., 2020). Despite its resource wealth, the country's vast territory and diverse economic activities result in an uneven and insufficient water supply, posing challenges to sustainable economic development (Alimbaev et al., 2021; Adenova et al., 2023). Mining and metallurgical industries form the backbone of Kazakhstan's economy (Alimbaev et al., 2020). Uranium mining in the country began in the 1940s, with significant deposits

Fig. 4. Distribution of different uranium deposit types in the United States.

identified in nine regions (Kayukov et al., 2020; OECD, 2025). These deposits are primarily found in branching vein networks and in layers of sandstone formations. Fig. 3 highlights Kazakhstan's significant reserves, which host some of the world's largest in-situ recovery operations. It illustrates the spatial extent and types of uranium deposits as defined by the International Atomic Energy Agency (2020). Symbols and colours indicate different deposit categories, with the legend adapted from the IAEA's "World Uranium Geology, Exploration, Resources and Production" (2020

Kazakhstan employs in-situ leaching (ISL) mining techniques at 26 sites operated by 13 uranium mining companies (Kenzhetaev et al., 2021; OECD, 2025). Although ISL is considered cost-effective and environmentally favourable, it releases uranium, thorium, radium, radon, and their decay products into the environment. This process alters groundwater chemistry, resulting in pollution (Zhanbekov et al., 2019; OECD, 2025).

Uranium mining and milling activities in Kazakhstan's northern and southern regions have led to significant environmental pollution, including elevated radioactivity levels in water sources (Kayukov et al., 2020; Subbotin et al., 2024; Aumalikova, 2025; Ibrayeva et al., 2025). The southern region, in particular, faces high pollution levels, with radionuclide concentrations in natural environments and groundwater undergoing considerable changes (Mukhamedzhanov et al., 2019; Beisenova, 2020; Bakhtin et al., 2025; Ibrayeva et al., 2025). Key contributors to groundwater pollution include open-air storage of radioactive waste, uranium ore processing, open-pit mining, and transportation (Kayukov et al., 2020; Aumalikova, 2025; Ibrayeva et al., 2025). Tleuova et al. (2023) recommend intensive monitoring of water supply wells in industrial and uranium mining areas in southern Kazakhstan to mitigate these impacts.

Kazakhstan faces severe environmental challenges, with over 21 billion tons of accumulated waste and an annual increase of 1 billion tons, underscoring the urgent need for long-term waste management programs to support sustainable social and economic development (Alimbaev et al., 2021; Aumalikova, 2025; Ibrayeva et al., 2025). The impacts of uranium mining are particularly concerning, as studies report elevated disease prevalence in villages near active deposits, such as those in Syrdarya province, and radioactivity levels at production sites, surrounding soil, and wastewater that exceed national standards (Zhanbekov et al., 2019; Kayukov et al., 2020). Intensive mining and agricultural practices have further contributed to widespread groundwater pollution, with areas like Mailuu-Suu experiencing exacerbated contamination from naturally occurring radionuclides and trace elements (Liu et al., 2021; Adenova et al., 2023; Egemberdieva and Kamchybekova, 2024; Egemberdieva, 2025; Ibrayeva et al., 2025). Anthropogenic activities have altered natural conditions, resulting in temperature-driven changes in groundwater quality, depletion of available water resources, and a decline in overall water availability (Osipov et al., 2020; Adenova et al., 2023, 2025). In-situ leaching and other mining practices underscore the urgent need for improved groundwater monitoring and sustainable resource management to mitigate environmental and public health risks.

2.4. United States of America (USA)

Uranium is found in various deposits across the USA, as shown in Fig. 4. The figure presents the major deposit categories as defined by the International Atomic Energy Agency (2020), with symbols and colours representing types such as sandstone-hosted, volcanic, intrusive, and other classifications. The legend is adapted from the IAEA's "World Uranium Geology, Exploration, Resources and Production" (2020). It highlights the concentration of deposits in the western United States, particularly in states such as Wyoming, New Mexico, and Texas, which host significant sandstone-hosted resources.

Significant sources of uranium pollution stem from mining, milling, tailings disposal, coal combustion, and phosphate fertilisers derived from uranium-rich rocks (Burow et al., 2017; Gardner et al., 2023; Padhi et al., 2023; Fegadel and Lynch, 2024). Major uranium mining areas include the Colorado Plateau, which encompasses regions of New Mexico, Arizona, Colorado, and Utah (Winde et al., 2017). Arizona's Grand Canyon contains some of the highest-grade uranium deposits (0.6 % uranium oxide) in the USA (Bern et al., 2022; Tillman et al., 2021).

Despite over three decades of uranium mining, federal regulations addressing worker health and environmental protection were implemented only recently, leading to illnesses and fatalities among workers and contamination near communities and water sources (Gilles, 2020; Redvers et al., 2021; Winde et al., 2017). In 2012, the federal government imposed a 20-year moratorium on uranium mining near the Grand Canyon, suspending operations until 2032 due to insufficient information on environmental impacts, except where valid mining rights already existed (Tillman et al., 2021; Halbleib, 2023).

The legacy of uranium mining in the USA is significant, with many abandoned uranium mines concentrated in the western states (Hoover et al., 2017; De Pree, 2020; Ingram et al., 2020). Remediation efforts for contaminated sites are estimated to have cost approximately USD 5 billion (Winde et al., 2017; Dinis and Fiúza, 2021). Since 2015, former miners and millers have received compensation amounting to USD 774 million, a financial burden that could have been avoided with earlier regulatory measures (Winde et al., 2017). Groundwater quality has been systematically monitored across the USA since 1991 by the U.S. Geological Survey (USGS) National Water Quality Assessment (NAWQA) program (Burow et al., 2017; Tillman et al., 2021; Belitz et al., 2022; Lindsey et al., 2023). Due to geogenic and anthropogenic activities, uranium concentrations in groundwater exceed 30 μg/L in arid western states, raising human health concerns in these areas (Balaram et al., 2022; Smedley and Kinniburgh, 2022). However, it is noteworthy that even in states without anthropogenic activities, aquifers such as the High Plains and Central Valley, uranium concentrations in groundwater can surpass drinking water standards due to natural geological factors (Ingram et al., 2020; Lopez et al., 2021; Balaram et al., 2022; Mine and Ziegler, 2022). Due to anthropogenic activities, uranium concentrations in groundwater in the San Joaquin Valley, California, have increased over time, posing significant health risks to local populations (Burow et al., 2017; Tisherman et al., 2023). The health impacts of uranium contamination in the USA include kidney disease and a potential link to congenital disabilities associated with uranium exposure (Vengosh et al., 2022). These findings emphasise the critical need for enhanced monitoring and stricter regulatory frameworks to safeguard public health.

Rural and tribal populations in the USA face disproportionately higher exposure to uranium contamination from abandoned hard-rock mines than other groups (Lin et al., 2020; Redvers et al., 2021; Martinez-Morata et al., 2022; Madrigal et al., 2024). This is primarily due to inadequate infrastructure for water access, which often necessitates the consumption of unregulated water sources. This vulnerability highlights the need for targeted interventions to enhance water access and quality in these underserved communities.

Existing studies' recommendations emphasise the need for increased water quality monitoring nationwide, particularly in areas with elevated uranium levels. Moreover, ensuring access to safe drinking water in rural regions with high uranium concentrations is paramount. Public education campaigns targeting these communities should raise awareness about the health risks associated with consuming unregulated water. Such community engagement initiatives are crucial for mitigating health risks and fostering proactive measures to address uranium contamination.

2.5. Africa

Africa contributes significantly to the global uranium market, accounting for approximately 16 % of global production (OECD, 2025). Uranium mining on the continent dates back to the 1920s, reflecting its long-standing role in the industry (Kinnaird and Nex, 2016). The continent hosts a diverse array of uranium deposits, distributed across several countries, including Namibia, Niger, Mali, Malawi, and South Africa (Kinnaird and Nex, 2016; Bezuidenhout, 2021; Sanusi et al., 2022; Wilde, 2023; Mwalongo et al., 2024; OECD, 2025). Notable deposit types include Archaean quartz-conglomerate-hosted gold-uranium deposits in South Africa, Neoproterozoic end-orogeny sheeted leucogranites and small intrusive granitic stocks in Namibia, Mesozoic sandstone-hosted roll-front and calcrete deposits in Niger and Mali, as well as alluvial deposits in Mali (Kinnaird and Nex, 2016; Bezuidenhout, 2021; Frimmel, 2023; Wilde, 2023). Fig. 5, adapted from Kinnaird and Nex (2016), illustrates the distinction between primary deposits (formed directly from magmatic or hydrothermal processes) and secondary deposits (derived from weathering, sedimentary processes, or reworking).

Namibia, Niger, and South Africa are the leading producers of uranium in Africa (International Atomic Energy Agency, 2020;

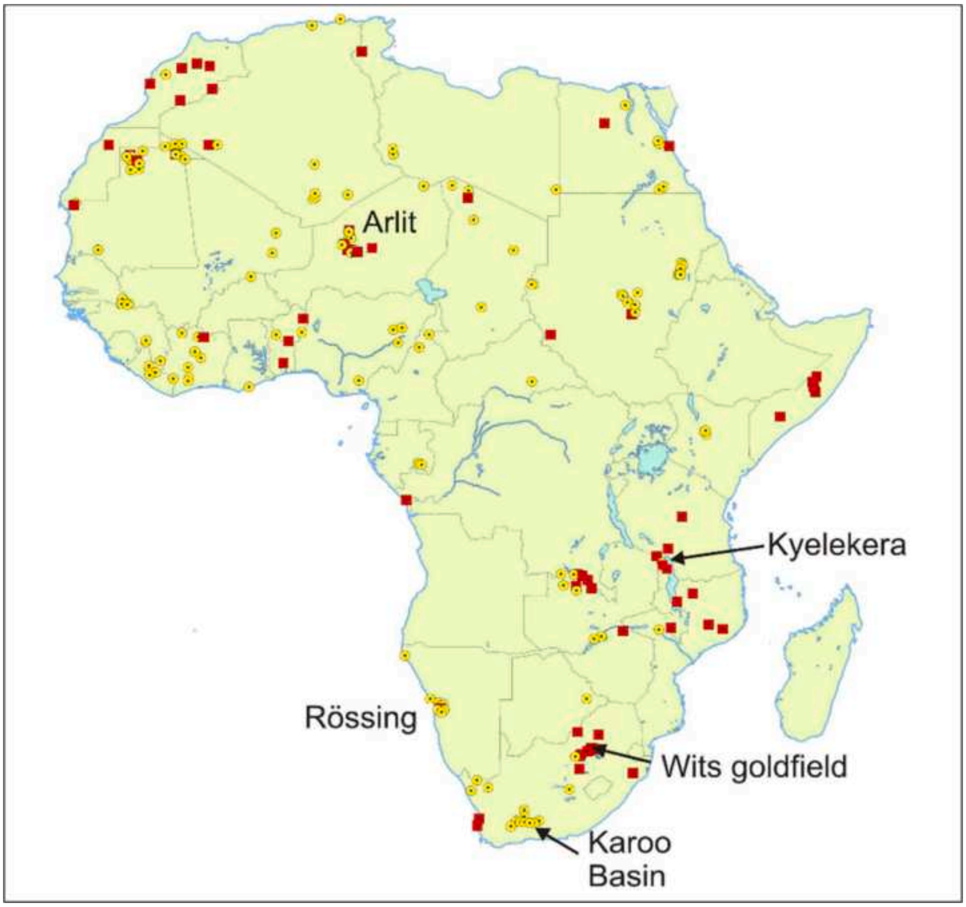

Fig. 5. Distribution of primary and secondary uranium deposits in Africa.

Wilde, 2023; Mwalongo et al., 2024; OECD, 2025). Despite their substantial contributions to the global uranium supply, the continent faces challenges related to water resource management. Over the past three decades, efforts to improve water and sanitation infrastructure have advanced; however, inadequate management of domestic and industrial waste continues to pose significant threats to groundwater quality and availability (Lapworth et al., 2018; Foster et al., 2020; Bruce and Limin, 2021; Omohwovo, 2024).

2.5.1. Niger

Niger is a landlocked country situated between the savannah and desert biomes, characterised by a scorching and arid climate (Sacré Regis M. et al., 2020; Adamou et al., 2021; Almouctar et al., 2024). Uranium was first discovered in Niger in the late 1950s by French surveyors (Volberding and Warner, 2018; Adamson, 2021; LeBlanc, 2022; OECD, 2025). Today, Niger ranks as one of the top global producers of uranium, contributing approximately 5 % of the world's uranium supply (Mamadou et al., 2022; Soumaila, 2023). The country's uranium deposits are primarily found in mid-grade ore within sandstone formations (Winde et al., 2017; International Atomic Energy Agency, 2020; Bohari et al., 2022; Mamadou et al., 2022; OECD, 2025). Fig. 6 highlights the concentration of deposits in Niger, particularly in the Tim Mersoi Basin. The Tim Mersoï uranium province holds one of the world's largest reserves of U, the Djado and Emi Lulu basins, located in the Palaeozoic formation, exhibit significant uranium potential (Mamadou et al., 2022; OECD, 2025).

Since 2011, several foreign companies have halted exploration activities in Niger due to geopolitical tensions (International Atomic Energy Agency, 2020). As reported by the OECD (2025), Orano's mining operations prioritise environmental protection, maintaining ISO 14001 certification and reducing water use by 35 % through the AMAN project despite increased production. The company supports local communities with free healthcare facilities, housing, education, and agricultural initiatives. Sustainability efforts include building an 8 MW solar power plant and advancing remediation plans for Cominak's closure to ensure safety, social support, and sustainable land use (OECD, 2025). At Dasa, environmental assessments indicate limited impact on nearby populations and livelihoods. However, despite being one of the largest producers of uranium globally, the country has a notable lack of studies on the impact of uranium mining on groundwater quality.

2.5.2. South Africa

As shown in Fig. 7, South Africa hosts significant uranium deposits, primarily in the Karoo Uranium Province, the Witwatersrand Basin, the Springbok Flats Basin, Intrusives, and Namaqualand surficial uranium deposits (Makubalo et al., 2020; Pretorius et al., 2020; Raji et al., 2021; Moshupya et al., 2022). The figure shows the distribution of uranium deposit types as defined by the International Atomic Energy Agency (2020), with symbols and colours representing different categories. The legend is adapted from the IAEA's "World Uranium Geology, Exploration, Resources and Production" (2020).

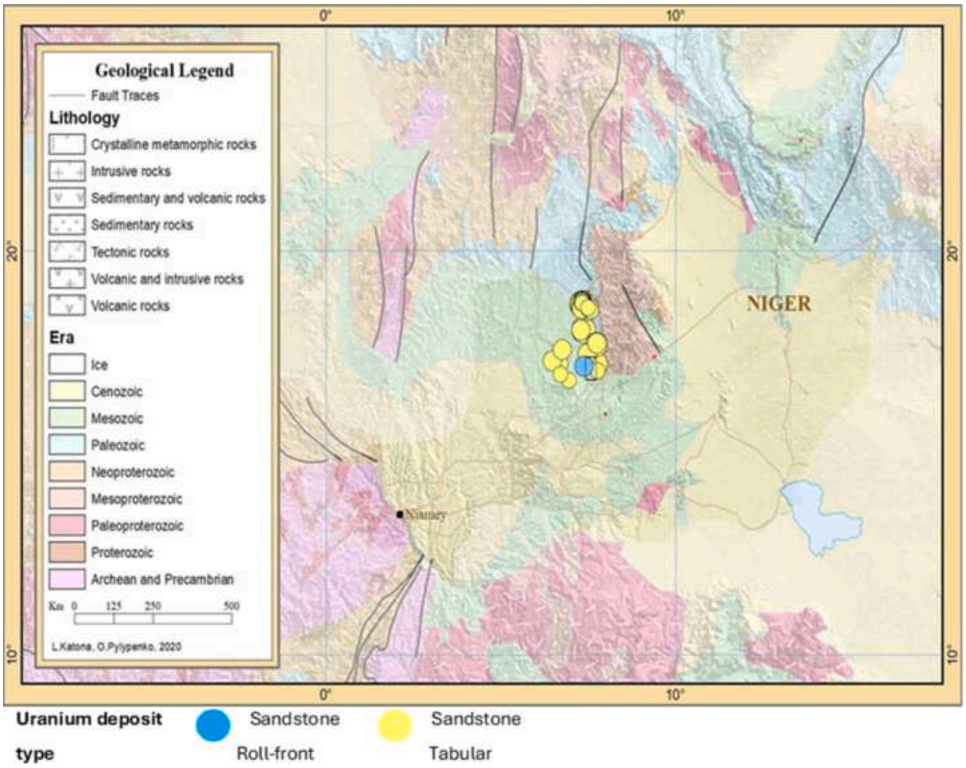

Fig. 6. Uranium deposits in Niger showing the distribution of major deposit types as defined by the International Atomic Energy Agency (2020).

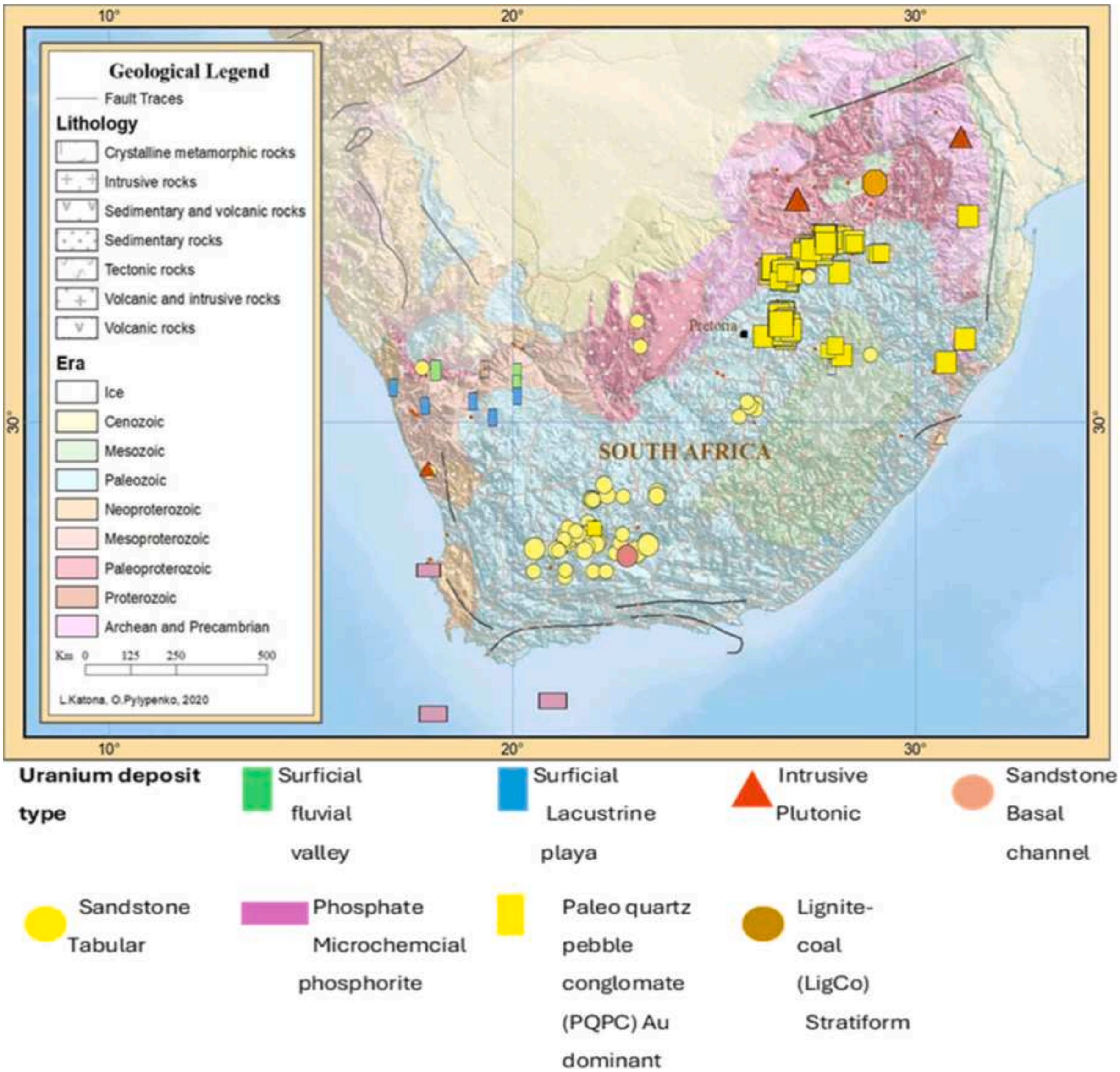

Fig. 7. Major uranium deposits in South Africa.

The Northern Cape Province in South Africa is an arid region where groundwater is the sole drinking water source, like most arid regions in the world (Lalumbe and Kanyerere, 2022; Abdessamed et al., 2023). Uranium mining in the province has caused elevated levels of uranium in the groundwater, averaging 0.155mg/L, which is 5 times higher than the drinking water quality guideline (Makubalo and Diamond, 2020). Uranium bioaccumulates in plants, particularly grasses, thereby posing a risk to livestock and potentially leading to significant human exposure through the consumption of mutton and sheep organs, which serve as dietary staples (Lalumbe and Kanyerere, 2022; Cui et al., 2023; Duhan et al., 2023).

Groundwater in Namaqualand, located within the Northern Cape Province, undergoes complex geochemical processes such as parent rock weathering, which result in unique groundwater chemistry (Adadzi, 2020; Makubalo and Diamond, 2020; van Gend et al., 2021). When compared to South Africa's drinking water quality standards, data from Namaqualand showed that 41 % of samples exceeded the gross alpha standard derived from uranium isotopes (Abiye and Shaduka, 2017)(Gross Alpha Activity (pCi/L)=Uranium Concentration (μg/L)$\times$ 0.67) (Scott et al., 2023). In their study, Smedley and Kinniburgh (2022) reported uranium concentrations in Namaqualand groundwater ranging from 1.3 to 5100 μg/L due to evaporation and secondary uranium mineralisation. Hence, they recommended that groundwater be treated before consumption, as uranium levels exceeded the acceptable water quality standards. Mining companies in South Africa are required to use resources responsibly, rehabilitate exploration sites, and comply with environmental management plans through regular inspections (OECD, 2025). Companies must also engage with affected communities during the application process for mining rights and implement Social and Labour Plans.

2.5.3. Namibia

Uranium was first discovered in Namibia in 1928 near the Rossing deposit (World Nuclear Association, 2023; Namibia Uranium Association, 2024; OECD, 2025). The Rossing mine, the country's first operational uranium mine, began production in 1976 under Rio Tinto. Namibia is now the third-largest global supplier of uranium (Namibia Uranium Association, 2024; OECD, 2025). Fig. 8 shows the different types of uranium deposits in the country. Currently, only Rossing, Langer Heinrich, and Husab are operational, while the Trekkopje mine remains under care and maintenance, alongside six ongoing exploration projects (Namibia Uranium Association, 2024).

In 2023, Namibia produced 8283 tonnes of uranium, marking a 24.5 % increase from the previous year (Namibia Chamber of Mines, 2024). However, the region's location in the Namib Desert presents challenges due to limited groundwater resources and vulnerable aquifers (Hamutoko et al., 2014; Lohe et al., 2021; Atlas of Namibia Team, 2022). Namibia has low-grade uranium ore, ranging from 80 to 540 ppm U3O8, and the country hosts both primary and secondary deposits (Wilde, 2023; Namibia Uranium Association, 2024; OECD, 2025).

The uranium mines in Namibia have made significant efforts to monitor groundwater quality in their surrounding areas, as reported

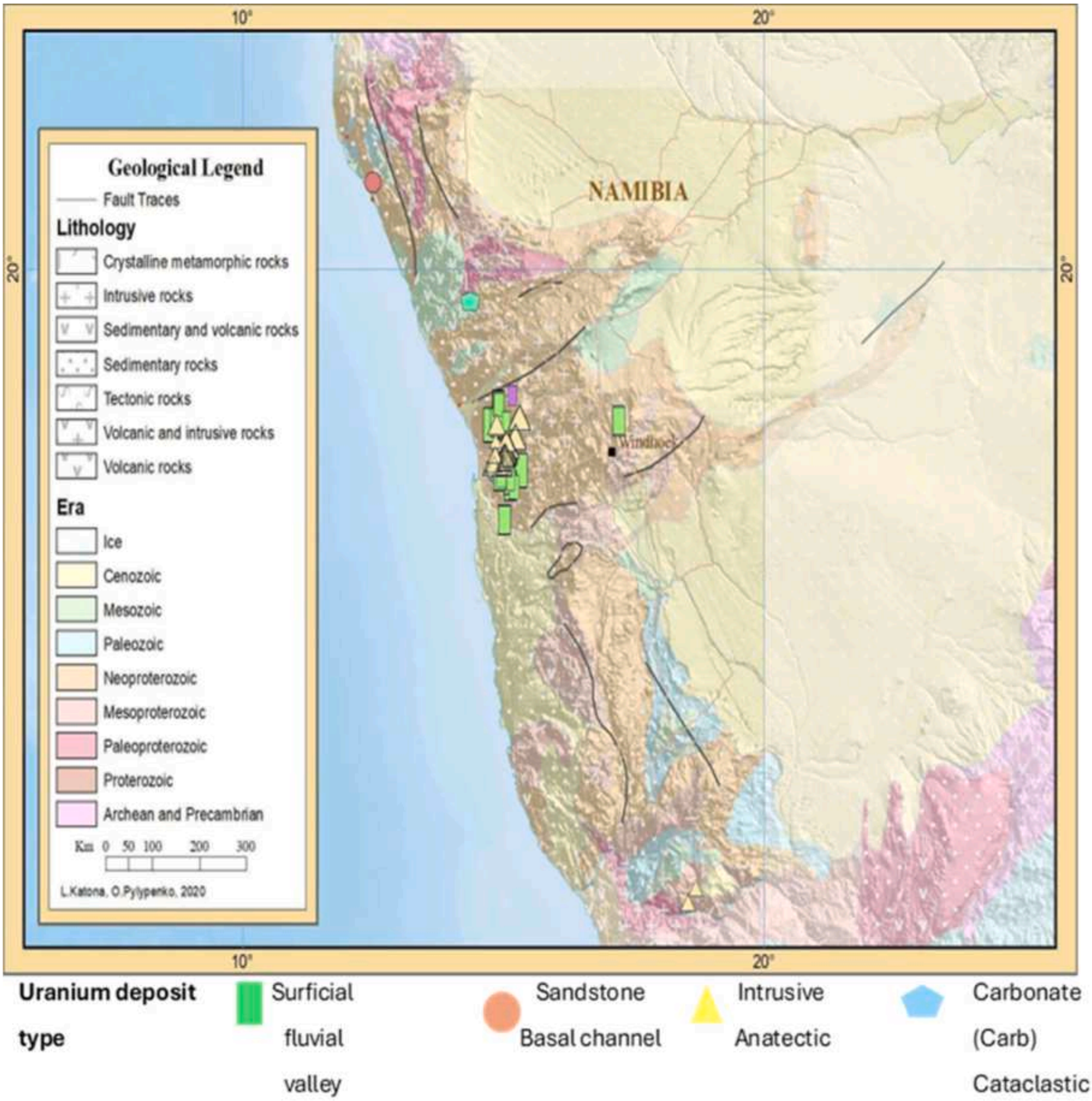

Fig. 8. Uranium deposits in Namibia,illustrating the distribution of major deposit types as defined by the International Atomic Energy Agency (2020).

in their annual reports and supported by the Air and Water Quality working group of the Uranium Association of Namibia (Namibia Uranium Association, 2024). Uranium mining operations, in collaboration with the line Ministries, maintain active monitoring of key environmental concerns (Musiyarira et al., 2017; Namibia Uranium Association, 2024; OECD, 2025). Emphasis is placed on adopting best practices and exchanging experiences through participatory approaches to environmental planning and management, alongside the promotion of effective waste management strategies (OECD, 2025). However, in the uranium province, Kringel et al. (2010) observed elevated uranium levels in the groundwater near the Rossing uranium mine, Langer Heinrich mine, and the Swakop River valley. Unable to confirm whether the elevated levels were due to pollution, they recommended further studies to determine whether the high uranium concentrations stemmed from contamination or natural sources. Similarly, Hamutoko et al. (2014) concluded that the groundwater in the Khan and Swakop rivers (located in the uranium province) was unfit for human consumption based on its hydrochemistry, uranium levels, and radionuclide content due to natural dispersion rather than anthropogenic activities. They recommended further analysis of other aquifers in the uranium province to assess their suitability for water supply. Mathuthu et al. (2021) indicate that the average values of absorbed dose rate (D= 118.11nGyh^{-1}) and annual effective dose equivalent for ingestion (H_{in}= 1.26 mSvy^{-1}) in groundwater samples exceeded the thresholds recommended by UNSCEAR, pointing to a potential radiological hazard. Their isotopic ratio analysis further suggests that the uranium present in the groundwater is primarily associated with mine seepage contamination rather than natural geological sources. These results emphasise that seepage water constitutes a significant radiological risk to both human health and the environment due to the elevated hazard parameters identified.

In Namibia, most rivers are ephemeral or seasonal, characterised by infrequent yet often intense flow. These seasonal floods can influence uranium concentrations in alluvial aquifers through the mobilisation of contaminants and dilution (Balaram et al., 2022; Geris et al., 2022; Smedley and Kinniburgh, 2022). This can dilute the concentration of uranium in groundwater, but it can also transport contaminants into groundwater. These rivers' alluvial aquifers and sand beds represent vital water sources for local communities, particularly subsistence farmers, highlighting the importance of understanding surface–groundwater interactions in assessing water quality and contamination risks. In a study by Abiye and Shaduka (2017), the main findings reported indicate that uranium contamination in the Gawib shallow aquifer system is a direct result of seepage from unlined uranium tailings. The high permeability of the alluvial aquifer facilitates the movement of groundwater in this arid region, thereby enhancing the spread of contamination. Their study further highlights the risk of uranium migration into the deeper aquifer system and downstream into the Swakop River, with the potential to extend as far as the Atlantic Ocean through seasonal flash flood events.

3. Remediation

Numerous polluted sites worldwide have been identified as requiring uranium remediation (Dinis and Fiúza, 2021; Akash et al., 2022; Arfasa et al., 2022; Balaram et al., 2022). Examples include Kazakhstan, due to in-situ mining in the northern and southern regions (Zhanbekov et al., 2019; Kayukov et al., 2020; Subbotin et al., 2024; OECD, 2025); the United States, particularly in California's San Joaquin Valley (Gardner et al., 2023; Padhi et al., 2023); South Africa, notably in the Northern Cape (Makubalo and Diamond, 2020; Smedley and Kinniburgh, 2022); and Namibia, around the unlined tailings dams of uranium mines (Abiye and Shaduka, 2017; Mathuthu et al., 2021). Without proper closure plans or rehabilitation projects, mining sites continue to be significant sources of environmental pollution, with groundwater contamination being a primary concern.

Regulators utilise various technologies to control contamination, with remediation enhancing uranium recovery from groundwater while supporting environmental protection and resource efficiency (Dinis and Fiúza, 2021; Balaram et al., 2022; Gandhi et al., 2022). Groundwater remediation requires dynamic, adaptive approaches due to continuously changing subsurface conditions and

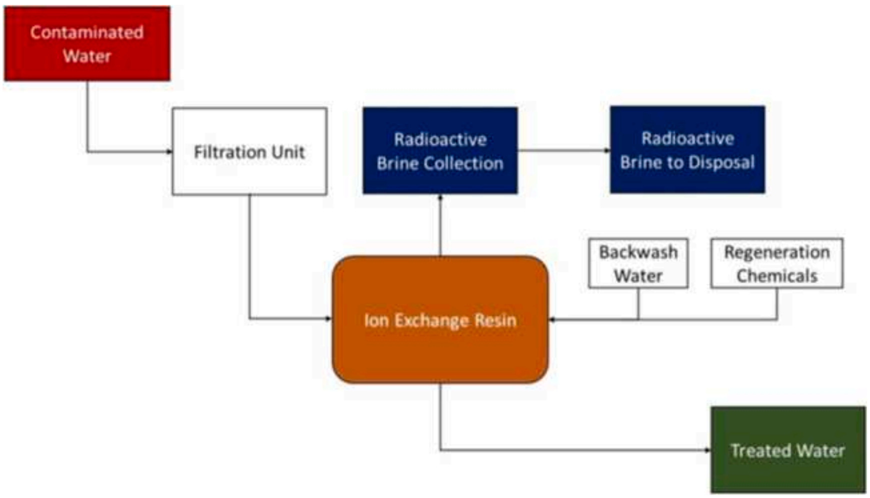

Fig. 9. Schematic representation of the ion exchange process in uranium recovery.
adapted from Dinis and Fiúza (2021).

site-specific complexities (Naseri-Rad et al., 2022; Warner et al., 2023). These methods can be broadly classified into three categories: chemical, physical, and biological remediation (Motlagh et al., 2020; Dinis and Fiúza, 2021).

3.1. Chemical remediation

Ion exchange technology has effectively reduced radionuclide levels in water (Dinis and Fiúza, 2021; Ighalo et al., 2024). This method is relatively simple to develop and operate, is cost-effective and has a long lifespan (Alexandratos, 2021; Gandhi et al., 2022; Zhang et al., 2023; Zimmermann et al., 2025). As illustrated in Fig. 9, contaminated water is filtered and passed through an ion exchange resin, where ion exchange processes remove the contaminants (Barman et al., 2023; Gandhi et al., 2022b; Ighalo et al., 2024).

Ion exchange resins with high exchange capacity are widely used for removing contaminants like uranium, particularly in countries such as South Africa and Australia (Ighalo et al., 2024). However, the concentrated wastewater produced by this process must be treated, stored, or disposed of properly to prevent further pollution (Liu et al., 2021; Banayan Esfahani et al., 2023; Hamza et al., 2024). A significant limitation of ion exchange is its high sensitivity to pH levels, which affects uranium concentration polarisation and speciation (Quinn et al., 2020; Gopalakrishnan et al., 2024; Ighalo et al., 2024). Additionally, the presence of certain cations, due to their hydration radius and high mobility, can reduce uranium removal efficiency (Chen et al., 2022; Gandhi et al., 2022; Hao et al., 2025).

3.1.1. Permeable reactive barrier (PRB)

Permeable reactive barriers (PRB) are an in-situ remediation technique that can be used independently or in combination with other remediation methods (Torres and Gómez, 2020; Akhtar et al., 2021; Singh et al., 2023). This process is passive, sustainable, and remarkably effective for remediating migrating groundwater plumes, as illustrated in Fig. 10 (Torres and Gómez, 2020; Budania and Dangayach, 2023; Sakr et al., 2023; Singh et al., 2023). A barrier containing reactive materials facilitates geochemical reactions that remove pollutants from groundwater (Torres and Gómez, 2020; Li and Liu, 2022; Sakr et al., 2023; Meky et al., 2025). The reactive materials employed in this process include activated carbon (AC), zeolites and zero-valent iron (ZVI), which are the most widely used (Bilardi et al., 2023; Singh et al., 2023; Wu et al., 2024).

However, the successful implementation of PRBs requires careful site selection, with numerical models typically employed to determine groundwater flow patterns and volumes before a barrier is installed (Guo et al., 2024; Wang et al., 2024; Jiang et al., 2025). Under ideal conditions, PRBs can remain effective for decades, providing a reliable means of removing radionuclide isotopes from groundwater over an extended period (Kwak et al., 2024; Meky et al., 2025; Sakr et al., 2023; Sánchez Hidalgo et al., 2025). Less expensive reactive media can be utilised to reduce costs, and the technology is continuously evolving, with ongoing research into new reactive materials and alternative construction methods (Dayanthi et al., 2024; Ren et al., 2024; Sánchez Hidalgo et al., 2025)

3.2. Physical remediation

3.2.1. Membrane filtration

Membrane filtration technologies, such as nanofiltration, ultrafiltration, and reverse osmosis, are capable of separating uranium from water (Dinis and Fiúza, 2021; Gandhi et al., 2022; Ighalo et al., 2024). Ultrafiltration employs low-pressure membranes that are energy-efficient; it is less effective at separating low molecular weight species or dissolved salts (Urošević and Trivunac, 2020; Joshi et al., 2022; Giacobbo et al., 2023). Reverse osmosis, although chemical-free and environmentally friendly, requires high energy input and is constrained by slow water production rates and the need for pre-filtration (Shalaby et al., 2022; Abushawish

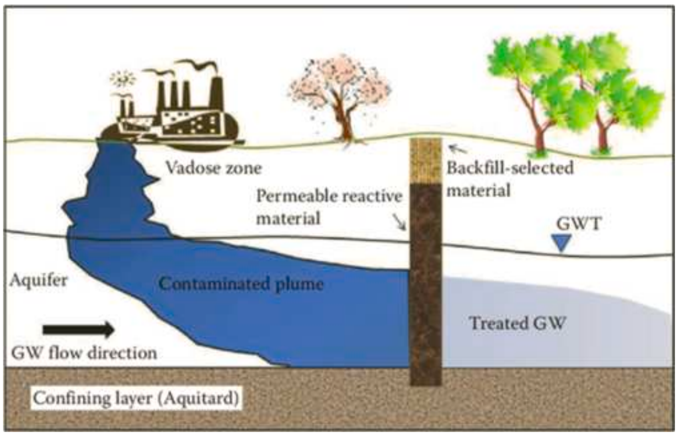

Fig. 10. Schematic representation of the permeable reactive barrier (PRB) process for groundwater remediation, adapted from Naidu and Birke (2015).

et al., 2023; Harby et al., 2024; Ighalo et al., 2024). Nanofiltration, though effective in removing heavy metals and salts, requires high-energy membranes and has a relatively short lifespan (Covaliu-Mierlă et al., 2023; Nompumelelo et al., 2023; Mahmoud and Mostafa, 2023; Ighalo et al., 2024).

However, challenges such as membrane fouling, scaling, high energy demand, and material degradation continue to drive research focused on sustainable materials and optimisation strategies for membrane filtration (Chen et al., 2022; Akinyemi et al., 2023; Ilyas and Vankelecom, 2023; Osman et al., 2024). Despite these limitations, membrane filtration is gaining attention as a uranium remediation process due to its high efficiency, low cost, and compact space requirements (Chen et al., 2022; Gandhi et al., 2022; Ilyas and Vankelecom, 2023; Ighalo et al., 2024).

3.2.2. Adsorption

Adsorption is recognised as one of the most effective approaches for removing uranium from water because of its high efficiency, simplicity, and cost-effectiveness (Jun et al., 2021; Gandhi et al., 2022; Verma and Kim, 2022; Ighalo et al., 2024; Liu et al., 2025). In an adsorption process, extraction rates of 70–90 % for uranium were achieved using TiO2 microsphere-infused alginate beads (Bhoria et al., 2021; Ighalo et al., 2024). A wide range of adsorbents has been explored, including clay minerals, metal oxides, layered double hydroxides (LDHs), graphene oxides (GOs), and metal–organic frameworks (MOFs) (Mohapi et al., 2020; Bhoria et al., 2021; Akhtar et al., 2024). Nonetheless, significant challenges persist in scaling these technologies for large-scale applications, necessitating ongoing research aimed at enhancing adsorbent performance and advancing sustainable, cost-effective solutions (Raji et al., 2023; Satyam and Patra, 2024).

3.3. Biological remediation

3.3.1. Bioremediation

Bioremediation methods, such as bioleaching, bioreduction, and biosorption, are employed to remove uranium from polluted environments (You et al., 2021; Akash et al., 2022; Ighalo et al., 2024). This technology utilizes microorganisms to degrade pollutants into harmless components, making it one of the most environmentally friendly remediation techniques (Motlagh et al., 2020; Mukherjee et al., 2021; Gandhi et al., 2022; Muttaleb and Ali, 2022; Kuppan et al., 2024). It is typically used in situ to treat groundwater contamination, with natural bioremediation relying on both aerobic and anaerobic bacteria (Rossi et al., 2021; Madison et al., 2023; Skinner et al., 2024). Bioremediation faces significant limitations, including biological specificity, environmental variability, site heterogeneity, scalability challenges, and regulatory hurdles (Patel et al., 2022; Kuppan et al., 2024b; Mahanayak, 2024). When enzymes are employed, additional constraints arise from their low stability under variable pH and temperature conditions, challenges in separating them from the reaction medium, and limited reusability (Somu et al., 2022; Ekeoma et al., 2023).

3.3.2. Phytoremediation

Phytoremediation is another effective method, particularly suited for treating low concentrations of pollutants. In this process, plants and microbes remove environmental pollutants by accumulating them in the plant's root systems, as depicted in Fig. 11 (Dinis and Fiúza, 2021; Mitra et al., 2021; Raklami et al., 2022; Khatoon et al., 2024). This method is ideal for the remediation of tailings material (Acosta-Núñez et al., 2025). However, selecting the appropriate plant species for phytoremediation can be challenging due to

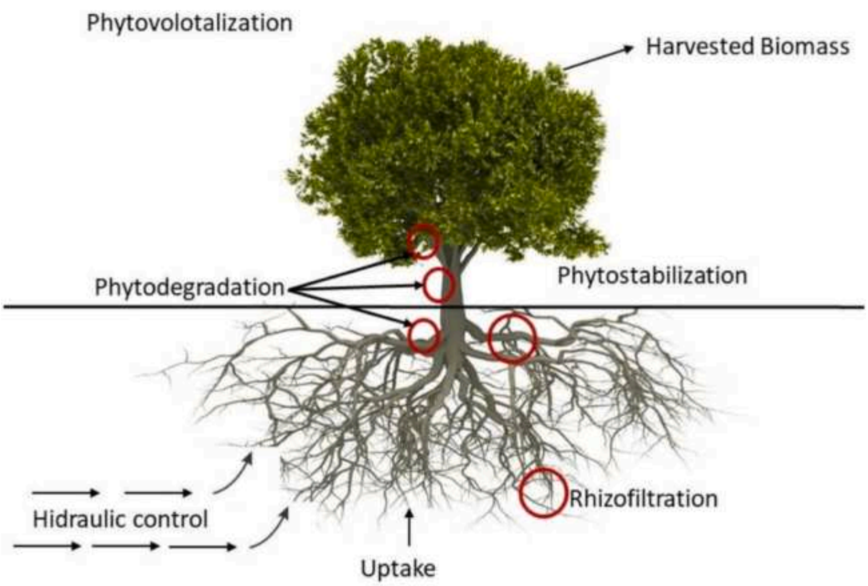

Fig. 11. Schematic representation of the phytoremediation process for uranium-contaminated soils and water adapted from Dinis and Fiúza (2021).

various factors involved in uranium remediation (Gandhi et al., 2022; Huang et al., 2022; Kafle et al., 2022; Amabogha et al., 2023). Additionally, this process has limitations, as the contaminant must be located near the surface and within the reach of the plant roots (Kafle et al., 2022; Khan et al., 2023; J. Wang and Aghajani Delavar, 2023).

Significant experience has been gained in remediation technologies; however, these technologies are costly when applied to large-scale contaminated sites. While well-developed technologies for groundwater contaminated with radionuclides exist, many challenges remain to be addressed. Uranium pollution remediation is receiving increasing global attention, and the development of processes and procedures within the nuclear industry could serve as a model for broader applications. A key challenge across all technologies is the safe disposal of the liquid and solid waste produced after treatment. Membrane filtration and ion exchange are among the most efficient techniques for uranium removal compared to other remediation methods. Various modelling tools are available to simulate the behaviour of uranium and other contaminants in groundwater systems. Commonly used groundwater simulation programs, including MODFLOW, MT3DMS, RT3D, FEFLOW, and MODPATH, allow for accurate contaminant transport modelling when model objectives are clearly defined and flow processes are thoroughly characterised (Chowdhury and Rahnuma, 2023; Kumar and Gour, 2021). For radiological risk assessment at uranium-impacted sites, tools such as AMBER, GoldSim, NORM, Legacy Site Assessment, PRG-dose calculator, and RESRAD-OFFSITE have been employed (Bello et al., 2022, 2022; Branko et al., 2022; Pepin et al., 2022). Comparative studies between these models emphasise the need to select context-specific tools and, where appropriate, integrate multiple modelling approaches to support effective remediation planning (Kumar and Gour, 2021).

4. Discussion

Groundwater contamination from uranium mining in arid regions is a challenge of both local and global relevance, and the present findings contribute to bridging this knowledge gap. The United States, for example, possesses extensive records, while many other regions remain underrepresented. This imbalance highlights the need for broader global assessments of uranium contamination in arid regions.

Country experiences reflect this uneven knowledge base. In Australia, integrated and interdisciplinary approaches are needed to evaluate the spatial and socio-environmental impacts of uranium mining. Chile has strengthened regulatory frameworks, but groundwater quality near mines remains underexplored. Kazakhstan, facing acute water scarcity, must adopt stronger policies to balance resource use with aquifer protection. In the United States, despite extensive datasets, continued baseline monitoring is crucial for tracking changes during and after mining operations. In Africa, limited monitoring of uranium exposure has allowed long-term environmental and health risks to persist, resulting in significant financial burdens for remediation. Evidence from Niger shows mining consumes significant groundwater reserves, while studies in South Africa call for robust epidemiological assessments and institutional mechanisms for risk reduction. Namibia has advanced groundwater monitoring through industry-led initiatives, but the absence of peer-reviewed publications restricts scientific validation and broader application.

Sustainable uranium mining depends on effective tailings and water management supported by collaborative research and technological innovation. Overreliance on single remediation methods should be avoided in favour of integrated, cost-effective strategies. Comprehensive water quality monitoring, geological and hydrochemical investigations, and the development of modelling-based tools are critical for understanding uranium transport processes and improving groundwater resource management.

5. Conclusion

The findings of this study highlight the persistent environmental and health risks associated with uranium mining and reveal critical gaps in global groundwater monitoring, particularly in underrepresented regions such as Africa, South America, and Central Asia. By synthesising previous studies, this work provides new insights into the uneven distribution of uranium contamination knowledge and highlights regions where scientific evidence is urgently needed.

The study demonstrates that sustainable uranium mining requires an integrated, multidisciplinary approach that combines hydrochemical, geological, and epidemiological assessments to evaluate contamination risks and guide effective mitigation strategies accurately. Practical implications include the need for cost-effective and complementary remediation technologies, advanced modelling tools to predict contaminant transport, and strengthened regulatory frameworks to safeguard both water resources and public health. Importantly, this research emphasises the value of international collaboration among scientists, policymakers, and industry stakeholders to establish robust monitoring networks and implement adaptive management strategies. By addressing data gaps and promoting evidence-based interventions, the findings provide a roadmap for mitigating the long-term impacts of uranium mining on groundwater resources, supporting both local community safety and broader environmental sustainability.

Future studies should expand peer-reviewed datasets in underrepresented regions, refine monitoring frameworks, develop innovative remediation technologies, and evaluate long-term water management effectiveness. By addressing data gaps and promoting evidence-based interventions, these efforts provide a roadmap for mitigating uranium mining impacts on groundwater, safeguarding both local communities and environmental sustainability.

Author statement

Ms Laurica Afrikaner contributed to the drafting of the original review paper. Prof Benjamin Mapani and Prof Hilma Amwele assisted with editing and approving the review for publication. All authors have reviewed and approved the final manuscript for submission. The authors declare no conflicts of interest and confirm that this work is original and not under consideration elsewhere

CRediT authorship contribution statement

Hilma Amwele: Writing – review & editing, Supervision. **Afrikaner Laurica:** Writing – original draft, Project administration, Funding acquisition, Conceptualization. **Benjamin Mapani:** Writing – review & editing, Supervision.

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Statement

During the preparation of this work, the corresponding author used Grammarly and ChatGPT to improve language and grammar. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the review paper.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

No data was used for the research described in the article.

References

Abdessamed, D., Jodar-Abellan, A., Ghoneim, S.S.M., Almaliki, A., Hussein, E.E., Pardo, M.Á., 2023. Groundwater quality assessment for sustainable human consumption in arid areas based on GIS and water quality index in the watershed of ain sefra (SW of Algeria). Environ. Earth Sci. 82 (21), 510. https://doi.org/10.1007/s12665-023-11183-9.

Abiye, T., Shaduka, I., 2017. Radioactive seepage through groundwater flow from the uranium mines, Namibia. Hydrology 4 (1). https://doi.org/10.3390/hydrology4010011.

Abushawish, A., Bouaziz, I., Almanassra, I.W., AL-Rajabi, M.M., Jaber, L., Khalil, A.K.A., Takriff, M.S., Laoui, T., Shanableh, A., Atieh, M.A., Chatla, A., 2023. Desalination pretreatment technologies: current status and future developments. Water 15 (8), 1572. https://doi.org/10.3390/w15081572.

Acosta-Núñez, L.F., Mussali-Galante, P., Castrejón-Godínez, M.L., Rodríguez-Solís, A., Castañeda-Espinoza, J.D., Tovar-Sánchez, E., 2025. In situ phytoremediation of mine tailings with high concentrations of cadmium and lead using dodonaea viscosa (Sapindaceae). Plants 14 (1). https://doi.org/10.3390/plants14010069.

Adadzi, P., 2020. Geostatistics and spatial analysis of groundwater hydrochemistry near leliefontein in the Northern cape, South Africa. J. Ecol. Eng. 21 (8), 243–260. https://doi.org/10.12911/22998993/126877.

Adamou, R., Ibrahim, B., Latif Bonkaney, A., Seyni, A.A., Idrissa, M., Bonn, N.B., 2021. Working Paper 200 Niger-Land, climate, energy, agriculture and development A study in the Sudano-Sahel Initiative for Regional Development, Jobs, and Food Security. https://doi.org/10.22004/AG.ECON.308806.

Adamson, M., 2021. Nuclear reach: uranium prospection and the global ambitions of the French nuclear programme, 1945–65. Cold War. Hist. 21 (3), 319–336. https://doi.org/10.1080/14682745.2020.1806238.

Adenova, D., Tazhiyev, S., Sagin, J., Absametov, M., Murtazin, Y., Trushel, L., Miroshnichenko, O., Zaryab, A., 2023. Groundwater quality and potential health risk in zhambyl region, Kazakhstan. Water (Switz.) 15 (3). https://doi.org/10.3390/w15030482.

Adenova, D., Sapargaliyev, D., Sagin, J., Absametov, M., Murtazin, Y., Smolyar, V., 2025. Assessing groundwater and soil quality in west Kazakhstan amid climate impacts and oil industry contamination risks. Sci. Rep. 15 (1), 6663. https://doi.org/10.1038/s41598-025-90033-z.

Akash, S., Sivaprakash, B., Raja, V.C.V., Rajamohan, N., Muthusamy, G., 2022. Remediation techniques for uranium removal from polluted environment – review on methods, mechanism and toxicology. Environ. Pollut. 302, 119068. https://doi.org/10.1016/j.envpol.2022.119068.

Akhtar, M.S., Ali, S., Zaman, W., 2024. Innovative adsorbents for pollutant removal: exploring the latest research and applications. Molecules 29 (18), 4317. https://doi.org/10.3390/molecules29184317.

Akhtar, N., Syakir Ishak, M.I., Bhawani, S.A., Umar, K., 2021. Various natural and anthropogenic factors responsible for water quality degradation: a review. Water 13 (19), 2660. https://doi.org/10.3390/w13192660.

Akinyemi, B.T., Ogundele, O.D., Afolabi, A.B., 2023. Advancements in sustainable membrane technologies for enhanced remediation and wastewater treatment: a comprehensive review. Acadlore Trans. Geosci. 2 (4), 196–207. https://doi.org/10.56578/atg020402.

Alexandratos, S.D., 2021. Trends in ion exchange: analysis of the literature. React. Funct. Polym. 169, 105066. https://doi.org/10.1016/j.reactfunctpolym.2021.105066.

Alimbaev, D.U., Omarova, B., Tuleubayeva, S., Kamzayev, B., Aipov, N., Mazhitova, Z., 2021. Ecological problems of water resources in Kazakhstan. E3S Web Conf. 244. https://doi.org/10.1051/e3sconf/202124401004.

Alimbaev, T., Mazhitova, Z., Beksultanova, C., Tentigulkyzy, N., 2020. Activities of mining and metallurgical industry enterprises of the republic of Kazakhstan: environmental problems and possible solutions. E3S Web Conf. 175. https://doi.org/10.1051/e3sconf/202017514019.
Almouctar, M.A.S., Wu, Y., Zhao, F., Qin, C., 2024. Drought analysis using normalized difference vegetation index and land surface temperature over Niamey region, the southwestern of the Niger between 2013 and 2019. J. Hydrol. Reg. Stud. 52, 101689. https://doi.org/10.1016/j.ejrh.2024.101689.
Amabogha, O.N., Garelick, H., Jones, H., Purchase, D., 2023. Combining phytoremediation with bioenergy production: developing a multi-criteria decision matrix for plant species selection. Environ. Sci. Pollut. Res. 30 (14), 40698–40711. https://doi.org/10.1007/s11356-022-24944-z.
Anderson, W.A., Domingo-Relloso, A., Galvez-Fernandez, M., Schilling, K., Glabonjat, R.A., Basu, A., Nigra, A.E., Gutierrez, O.M., Scherzer, R., Goldsmith, J., Sarnak, M.J., Bonventre, J.V., Kimmel, P.L., Vasan, R.S., Ix, J.H., Shlipak, M.G., Navas-Acien, A., 2025. Uranium exposure and kidney tubule biomarkers in the Multi-Ethnic study of atherosclerosis (MESA). Environ. Res. 271, 121060. https://doi.org/10.1016/j.envres.2025.121060.
Arfasa, G.F., Cobbina, S.J., Ampofo, J.A., 2022. Remediation technologies for polluted sites: review. J. Environ. Earth Sci. https://doi.org/10.7176/JEES/12-12-02.
Atlas of Namibia Team, 2022. Atlas OF Namibia,its land, water and wildlife. Namibia Nature Foundation.
Aumalikova, M., 2025. Impact of uranium mining on radiation levels in Kazakhstan: a case study of two major provinces. Bull. L. N. Gumilyov Eurasian Natl. Univ. Phys. Astron. Ser. 151 (2), 45–59. https://doi.org/10.32523/2616-6836-2025-151-2-45-59.
Bakhtin, M., Ibrayeva, D., Kashkinbayev, Y., Aumalikova, M., Altaeva, N., Tazhedinova, A., Shokabayeva, A., Kazymbet, P., 2025. Environmental monitoring in uranium deposit and indoor radon survey in settlements located near uranium mining area, south Kazakhstan. Atmosphere 16 (5), 536. https://doi.org/10.3390/atmos16050536.
Balaram, V., Rani, A., Rathore, D.P.S., 2022. Uranium in groundwater in parts of India and world: a comprehensive review of sources, impact to the environment and human health, analytical techniques, and mitigation technologies. Geosyst. Geoenviron. 1 (2), 100043. https://doi.org/10.1016/J.GEOGEO.2022.100043.
Banayan Esfahani, E., Dixit, F., Asadi Zeidabadi, F., Johnson, M.R., Mayilswamy, N., Kandasubramanian, B., Mohseni, M., 2023. Ion exchange and advanced oxidation/reduction processes for per- and polyfluoroalkyl substances treatment: a mini-review. Curr. Opin. Chem. Eng. 42, 100953. https://doi.org/10.1016/j.coche.2023.100953.
Barman, M.K., Bhattarai, A., Saha, B., 2023. Applications of ion exchange resins in environmental remediation. Vietnam J. Chem. 61 (5), 533–550. https://doi.org/10.1002/vjch.202300027.
Beisenova, A.S., 2020. Environmental problems in Kazakhstan. In Sustainable Development in Central Asia. Routledge, pp. 159–166. https://doi.org/10.4324/9781315026534-13.
Belitz, K., Fram, M.S., Lindsey, B.D., Stackelberg, P.E., Bexfield, L.M., Johnson, T.D., Jurgens, B.C., Kingsbury, J.A., McMahon, P.B., Dubrovsky, N.M., 2022. Quality of groundwater used for public supply in the continental United States: a comprehensive assessment. ACS EST Water 2 (12), 2645–2656. https://doi.org/10.1021/acsestwater.2c00390.
Bello, S., Garba, N.N., Muhammad, B.G., Simon, J., 2022. Application of RESRAD and ERICA tools to estimate dose and cancer risk for artisanal gold mining in Nigeria, 106932 J. Environ. Radioact. *251–252*. https://doi.org/10.1016/j.jenvrad.2022.106932.
Benaissa, C., Bouhmadi, B., Rossi, A., 2023. An assessment of the physicochemical, bacteriological quality of groundwater and the water quality index (WQI) used GIS in ghis nekor, Northern Morocco. Sci. Afr. 20, e01623. https://doi.org/10.1016/j.sciaf.2023.e01623.
Bern, C.R., Campbell, K.M., Walton-Day, K., Van Gosen, B.S., 2022. Laboratory simulation of groundwater along Uranium-Mining-Affected flow paths near the Grand Canyon, arizona, USA. Mine Water Environ. 41 (2), 370–386. https://doi.org/10.1007/s10230-022-00872-9.
Bezuidenhout, J., 2021. Estimating indoor radon concentrations based on the uranium content of geological units in South Africa. J. Environ. Radioact. 234, 106647. https://doi.org/10.1016/j.jenvrad.2021.106647.
Bhoria, N., Pokhrel, J., Anastasiou, S., Suresh Kumar Reddy, K., Romanos, G., Karanikolos, G.N., 2021. Composite porous nanostructures as multi-action adsorbents and membrane fillers for carbon dioxide separation: comparative performance of metal organic framework – graphene oxide hybrids. Mater. Today. Proc. 37, 4044–4048. https://doi.org/10.1016/j.matpr.2020.07.466.
Bilardi, S., Calabrò, P.S., Moraci, N., 2023. A review of the hydraulic performance of permeable reactive barriers based on granular zero valent iron. Water 15 (1), 200. https://doi.org/10.3390/w15010200.
Bohari, A.D., Harouna, M., Mosaad, A., Qian, W., Laouali, I.S., 2022. Petrographic and geochemical implications for ore genesis and mineralogical composition studies of the tarat formation hosted sandstone uranium deposit in the tamari prospect from arlit, Niger. J. Afr. Earth Sci. 185, 104395. https://doi.org/10.1016/j.jafrearsci.2021.104395.
Branko, K., Paul, B., Simon, F., Alan, P., Ming, Z., Tamara, Y., Michael, W., Stephane, P., Tine, B., Marko, B., 2022. Demonstrating the use of a framework for risk-informed decisions with stakeholder engagement through case studies for NORM and nuclear legacy sites. J. Radiol. Prot. 42 (2), 020504. https://doi.org/10.1088/1361-6498/ac5816.
Britt, A.F., Czarnota, K., 2024. A review of critical mineral resources in Australia. Aust. J. Earth Sci. 71 (8), 1016–1049. https://doi.org/10.1080/08120099.2024.2430279.
Bruce, M., Limin, M., 2021. Recent advances on water pollution research in Africa: a critical review. Int. J. Sci. Adv. 2 (3). https://doi.org/10.51542/ijscia.v2i3.23.
Budania, R., Dangayach, S., 2023. A comprehensive review on permeable reactive barrier for the remediation of groundwater contamination. J. Environ. Manag. 332, 117343. https://doi.org/10.1016/j.jenvman.2023.117343.
Burow, K.R., Belitz, K., Dubrovsky, N.M., Jurgens, B.C., 2017. Large decadal-scale changes in uranium and bicarbonate in groundwater of the irrigated Western U.S. Sci. Total Environ. 586, 87–95. https://doi.org/10.1016/j.scitotenv.2017.01.220.
Chen, T., Wei, X., Chen, Z., Morin, D., Alvarez, S.V., Yoon, Y., Huang, Y., 2022. Designing energy-efficient separation membranes: knowledge from nature for a sustainable future. Adv. Membr. 2, 100031. https://doi.org/10.1016/j.advmem.2022.100031.
Chowdhury, A., Rahnuma, M., 2023. Groundwater contaminant transport modeling using MODFLOW and MT3DMS: a case study in rajshahi city. Water Pract. Technol. 18 (5), 1255–1272. https://doi.org/10.2166/wpt.2023.076.
Collao, S., Stange, F., Hernández, L., Uribe, M., 2019. Mineralogy of a Radioactive-Rare earth elements occurrence in the paleozoic batholith, South-Central Chile. Int. J. Geosci. 10 (06), 632–651. https://doi.org/10.4236/ijg.2019.106036.
Courtney-Davies, L., Ciobanu, C.L., Tapster, S.R., Cook, N.J., Ehrig, K., Crowley, J.L., Verdugo-Ihl, M.R., Wade, B.P., Condon, D.J., 2020. Opening the magmatic-hydrothermal window: high-precision U-Pb geochronology of the mesoproterozoic olympic dam Cu-U-Au-Ag deposit, South Australia. Econ. Geol. 115 (8), 1855–1870. https://doi.org/10.5382/econgeo.4772.
Covaliu-Mierlă, C.I., Păunescu, O., Iovu, H., 2023. Recent advances in membranes used for nanofiltration to remove heavy metals from wastewater: a review. Membranes 13 (7), 643. https://doi.org/10.3390/membranes13070643.
Cui, Q., Zhang, Z., Beiyuan, J., Cui, Y., Chen, L., Chen, H., Fang, L., 2023. A critical review of uranium in the soil-plant system: distribution, bioavailability, toxicity, and bioremediation strategies. Crit. Rev. Environ. Sci. Technol. 53 (3), 340–365. https://doi.org/10.1080/10643389.2022.2054246.
Dayanthi, W.K.C.N., Jagoda, S.W., Hasini, K.A.A., 2024. Laboratory experiments on remediation of landfill leachate contamination with permeable reactive barriers (PRBs) of reactive media derived from waste. Eng. J. Inst. Eng. Sri Lanka 57 (1), 95–106. https://doi.org/10.4038/engineer.v57i1.7640.
De Pree, T.A., 2020. The politics of baselining in the grants uranium mining district of northwestern new Mexico. J. Environ. Manag. 268, 110601. https://doi.org/10.1016/j.jenvman.2020.110601.
Dinis, M. de L., Fiúza, A., 2021. Mitigation of uranium mining Impacts—A review on groundwater remediation technologies. Geosciences 11 (6), 250. https://doi.org/10.3390/geosciences11060250.
Drummond, J.B.R., Kyser, T.K., Bowell, R.R., James, N.P., Layton-Matthews, D., 2021. Diagenesis of paleodrainages in lake way and lake maitland, Western Australia, and the role of authigenic Mg-clays and dolomite in the genesis of channel and playa uranium deposits. Can. Mineral. 59 (5), 947–984. https://doi.org/10.3749/canmin.2000053.
Duhan, S.S., Khyalia, P., Solanki, P., Laura, J.S., 2023. Uranium sources, uptake, translocation in the soil-plant system and its toxicity in plants and humans: a critical review. Orient. J. Chem. 39 (2), 303–319. https://doi.org/10.13005/ojc/390210.

Egemberdieva, A., Kamchybekova, K., 2024. Assessment of technogenic pollution of environmental objects in the conditions of Mailuu-Suu (Kyrgyzstan). E3S Web Conf. 537, 03005. https://doi.org/10.1051/e3sconf/202453703005.
Egemberdieva, A.D., 2025. Environmental and health impacts of technogenic and microbiological pollution in the Mailuu-Suu river basin, Kyrgyzstan: a comprehensive assessment for sustainable water management. Eurasia J. Sci. Multidiscip. Res. 1 (I), 131–135. https://doi.org/10.63666/ejsmr.1694-9013.1.I.2025.17.
Ekeoma, B.C., Ekeoma, L.N., Yusuf, M., Haruna, A., Ikeogu, C.K., Merican, Z.M.A., Kamyab, H., Pham, C.Q., Vo, D.-V.N., Chelliapan, S., 2023. Recent advances in the biocatalytic mitigation of emerging pollutants: a comprehensive review. J. Biotechnol. 369, 14–34. https://doi.org/10.1016/j.jbiotec.2023.05.003.
Elsaidy, A., Yimer, E.A., Mogheir, Y., Huysmans, M., Villani, L., van Griensven, A., 2025. Groundwater drought and anthropogenic amplifiers: a review of assessment and response strategies in arid and semi-arid areas. Sci. Total Environ. 978, 179406. https://doi.org/10.1016/j.scitotenv.2025.179406.
Famiglietti, J.S., Ferguson, G., 2021. The hidden crisis beneath our feet. Science 372 (6540), 344–345. https://doi.org/10.1126/science.abh2867.
Fegadel, A.R., Lynch, M.J., 2024. Native American victimization and resistance: an examination of uranium mining in the northwest and Northern plains. Safer Commun. 23 (2), 142–151. https://doi.org/10.1108/SC-08-2023-0034.
Foster, S., Eichholz, M., Nlend, B., Gathu, J., 2020. Securing the critical role of groundwater for the resilient water-supply of urban Africa. Water Policy 22 (1), 121–132. https://doi.org/10.2166/wp.2020.177.
Frimmel, H.E., 2023. Linking archaean climate change with gold metallogeny. Can. J. Earth Sci. 60 (7), 802–817. https://doi.org/10.1139/cjes-2022-0058.
Gandhi, T.P., Sampath, P.V., Maliyekkal, S.M., 2022. A critical review of uranium contamination in groundwater: treatment and sludge disposal. Sci. Total Environ. 825, 153947. https://doi.org/10.1016/j.scitotenv.2022.153947.
Gardner, C.B., Wichterich, C., Calero, A.E., Welch, S.A., Widom, E., Smith, D.F., Carey, A.E., Lyons, W.B., 2023. Carbonate weathering, phosphate fertilizer, and hydrologic controls on dissolved uranium in rivers in the US corn belt: disentangling seasonal geogenic- and fertilizer-derived sources. Sci. Total Environ. 861, 160455. https://doi.org/10.1016/j.scitotenv.2022.160455.
van Gend, J., Francis, M.L., Watson, A.P., Palcsu, L., Horváth, A., Macey, P.H., le Roux, P., Clarke, C.E., Miller, J.A., 2021. Saline groundwater in the buffels river catchment, namaqualand, South Africa: a new look at an old problem. Sci. Total Environ. 762, 143140. https://doi.org/10.1016/j.scitotenv.2020.143140.
Geris, J., Comte, J.-C., Franchi, F., Petros, A.K., Tirivarombo, S., Selepeng, A.T., Villholth, K.G., 2022. Surface water-groundwater interactions and local land use control water quality impacts of extreme rainfall and flooding in a vulnerable semi-arid region of Sub-Saharan Africa. J. Hydrol. 609, 127834. https://doi.org/10.1016/j.jhydrol.2022.127834.
Ghorbani, Y., Kuan, S.H., 2017. A review of sustainable development in the Chilean mining sector: past, present and future. In: In International Journal of Mining, Reclamation and Environment, 31. Taylor and Francis Ltd, pp. 137–165. https://doi.org/10.1080/17480930.2015.1128799.
Giacobbo, A., Pasqualotto, I.F., Machado Filho, R.C., de, C., Minhalma, M., Bernardes, A.M., Pinho, M.N. de, 2023. Ultrafiltration and nanofiltration for the removal of pharmaceutically active compounds from water: the effect of operating pressure on electrostatic Solute—Membrane interactions. Membranes 13 (8), 743. https://doi.org/10.3390/membranes13080743.
Gigon, J., Skirrow, R.G., Harlaux, M., Richard, A., Mercadier, J., Annesley, I.R., Villeneuve, J., 2019. Insights into B-Mg-Metasomatism at the ranger u deposit (NT, Australia) and comparison with Canadian Unconformity-Related u deposits. Minerals 9 (7), 432. https://doi.org/10.3390/min9070432.
Gilles, C., 2020. No one ever told us: native Americans and the great uranium experiment. In Governing the Atom. Routledge, pp. 103–125. https://doi.org/10.4324/9780429334016-7.
Gopalakrishnan, A., Asare, S., Adu-Boahene, F., Schäfer, A.I., 2024. Uranium adsorption by iron modified zeolite and zeolite composite membranes. Chemosphere 368, 143711. https://doi.org/10.1016/j.chemosphere.2024.143711.
Guéguen, Y., Frerejacques, M., 2022. Review of knowledge of Uranium-Induced kidney toxicity for the development of an adverse outcome pathway to renal impairment. Int. J. Mol. Sci. 23 (8), 4397. https://doi.org/10.3390/ijms23084397.
Guo, F., Ren, Y., Zhou, Y., Sun, S., Cui, M., Khim, J., 2024. Machine learning vs. Statistical model for prediction modeling and experimental validation: application in groundwater permeable reactive barrier width design. J. Hazard. Mater. 469, 133825. https://doi.org/10.1016/j.jhazmat.2024.133825.
Gutiérrez, G., 2014. Antecedents and perspectives on the development of nuclear energy in Chile. J. Phys. Conf. Ser. 511, 012089. https://doi.org/10.1088/1742-6596/511/1/012089.
Halbleib, K., 2023. Examining uranium mining in the canyon mine. Pace Environ. Law Rev. 40 (2), 357. https://doi.org/10.58948/0738-6206.1872.
Hamutoko, J.T., Mapani, B.S., Ellmies, R., Bittner, A., Kuells, C., 2014. A fingerprinting method for the identification of uranium sources in alluvial aquifers: an example from the khan and swakop rivers, Namibia. Phys. Chem. Earth 72, 34–42. https://doi.org/10.1016/j.pce.2014.09.006.
Hamza, Z., Al-Sulaiman, A., Abdel-Shafy, H., 2024. A scientometric analysis and bibliometric review of IOEX as a treatment to remove pollutants. AlQadisiyah J. Eng. Sci. 17 (2), 121–127. https://doi.org/10.30772/qjes.2024.145618.1095.
Hao, Y., Hou, C., Chen, C., Zhou, H., Liu, Y., Lin, Y., Li, H., Hu, K., 2025. Advances in the efficient removal of the key radioactive nuclide 90 sr using crystalline Ion-Exchange materials: a review. Chem. Asian J. https://doi.org/10.1002/asia.202401320.
Harby, K., Emad, M., Benghanem, M., Abolibda, T.Z., Almohammadi, K., Aljabri, A., Alsaiari, A., Elgendi, M., 2024. Reverse osmosis hybridization with other desalination techniques: an overview and opportunities. Desalination 581, 117600. https://doi.org/10.1016/j.desal.2024.117600.
Herrmann, T., 2023. Australia, Western: uranium mining. In Encyclopedia of Mineral and Energy Policy. Springer Berlin Heidelberg, pp. 32–35. https://doi.org/10.1007/978-3-662-47493-8_130.
Hiatt, E.E., Kyser, T.K., Polito, P.A., Marlatt, J., Pufahl, P., 2021. The paleoproterozoic kombolgie subgroup (1.8 Ga), McArthur basin, Australia: sequence stratigraphy, basin evolution, and unconformity-related uranium deposits following the great oxidation event. Can. Mineral. 59 (5), 1049–1083. https://doi.org/10.3749/canmin.2000102.
Hoover, J., Gonzales, M., Shuey, C., Barney, Y., Lewis, J., 2017. Elevated arsenic and uranium concentrations in unregulated water sources on the navajo nation, USA. Expo. Health 9 (2), 113–124. https://doi.org/10.1007/s12403-016-0226-6.
Horvit, A., Molony, D., 2022. A Systematic Review and Meta-Analysis of Mortality and Kidney Function in Uranium – Exposed Individuals. https://doi.org/10.37766/inplasy2022.4.0122.
Huang, M., Liu, Z., Li, X., 2022. Phytoremediation of rare Tailings-Contaminated soil. J. Renew. Mater. 10 (12), 3351–3372. https://doi.org/10.32604/jrm.2022.022393.
Ibrayeva, D., Bakhtin, M., Aumalikova, M., Kashkinbayev, Y., Kazymbet, P., Masaharu, H., Sakaguchi, A., 2025. Preliminary studies of the water contamination in settlements located near the uranium mining territory in Northern Kazakhstan. Environ. Sci. Pollut. Res. 32 (17), 11242–11250. https://doi.org/10.1007/s11356-025-36398-0.
Ighalo, J.O., Chen, Z., Ohoro, C.R., Oniye, M., Igwegbe, C.A., Elimhingbovo, I., Khongthaw, B., Dulta, K., Yap, P.S., Anastopoulos, I., 2024. A review of remediation technologies for uranium-contaminated water. In: In Chemosphere, 352. Elsevier Ltd. https://doi.org/10.1016/j.chemosphere.2024.141322.
Ilyas, A., Vankelecom, I.F.J., 2023. Designing sustainable membrane-based water treatment via fouling control through membrane interface engineering and process developments. Adv. Colloid Interface Sci. 312, 102834. https://doi.org/10.1016/j.cis.2023.102834.
Ingram, J.C., Jones, L., Credo, J., Rock, T., 2020. Uranium and arsenic unregulated water issues on navajo lands. J. Vac. Sci. Technol. A 38 (3). https://doi.org/10.1116/1.5142283.
International Atomic Energy Agency. (2020). World Uranium Geology, Exploration, Resources and Production INTERNATIONAL ATOMIC ENERGY AGENCY VIENNA. www.iaea.org/publications.
Jiang, J., Chen, J., Ou, X., Luo, H., Wang, S., 2025. Prediction of heavy metal contamination in soil-groundwater systems at contaminated sites. Environ. Technol. 46 (16), 3011–3023. https://doi.org/10.1080/09593330.2025.2451257.
Jibitha, J.B., Sabu, J., 2023. Sources of groundwater contamination: a review. Int. J. Res. Rev. 10 (10), 121–126. https://doi.org/10.52403/ijrr.20231016.
Joshi, U.S., Bhalani, D.V., Chaudhary, A., Jewrajka, S.K., 2022. Multipurpose tight ultrafiltration membrane through controlled layer-by-layer assembly for low pressure molecular separation. J. Membr. Sci. 641, 119908. https://doi.org/10.1016/j.memsci.2021.119908.

Jun, B.-M., Lee, H.-K., Park, S., Kim, T.-J., 2021. Purification of uranium-contaminated radioactive water by adsorption: a review on adsorbent materials. Sep. Purif. Technol. 278, 119675. https://doi.org/10.1016/j.seppur.2021.119675.

Kafle, A., Timilsina, A., Gautam, A., Adhikari, K., Bhattarai, A., Aryal, N., 2022. Phytoremediation: mechanisms, plant selection and enhancement by natural and synthetic agents. Environ. Adv. 8, 100203. https://doi.org/10.1016/j.envadv.2022.100203.

Karunanidhi, D., Subramani, T., Srinivasamoorthy, K., Yang, Q., 2022. Environmental chemistry, toxicity and health risk assessment of groundwater: environmental persistence and management strategies. Environ. Res. 214, 113884. https://doi.org/10.1016/j.envres.2022.113884.

Kayukov, P.G., Feodorov, G.V., Yakovleva, N.A., Sadvakasov, Y.K., Ayupov, K.A., 2020. Radiation situation on the territory of Shuchinsk-Borovskaya resort area and measures on the radiation risks reduction. NEWS Natl. Acad. Sci. Repub. Kazakhstan 4 (442), 70–76. https://doi.org/10.32014/2020.2518-170X.86.

Kenzhetaev, Z., Nurbekova, M., Togizov, K., Abdraimova, M., Toktaruly, B., 2021. Methods for intensification of borehole uranium mining at the fields with low filtration characteristics of ores. Min. Miner. Depos. 15 (3), 95–101. https://doi.org/10.33271/MINING15.03.095.

Khan, S., Masoodi, T.H., Pala, N.A., Murtaza, S., Mugloo, J.A., Sofi, P.A., Zaman, M.U., Kumar, R., Kumar, A., 2023. Phytoremediation prospects for restoration of contamination in the natural ecosystems. Water 15 (8), 1498. https://doi.org/10.3390/w15081498.

Khatoon, Z., Orozco-Mosqueda, Ma. del C., Santoyo, G., 2024. Microbial contributions to heavy metal phytoremediation in agricultural soils: a review. Microorganisms 12 (10), 1945. https://doi.org/10.3390/microorganisms12101945.

Kinnaird, J.A., Nex, P.A.M., 2016. Uranium in Africa. Episodes 39 (2), 335–359. https://doi.org/10.18814/epiiugs/2016/v39i2/95782.

Kringel, R., Wagner, F., Klinge, H., 2010. Groundwater quality assessment in the Khan-and Swakop-River catchment with respect to geogenic background concentrations of dissolved uranium.

Kumar, M., Gour, A., 2021. Novel approach to groundwater contaminant transport modelling. J. Univ. Shanghai Sci. Technol. 23 (07), 281–292. https://doi.org/10.51201/JUSST/21/07132.

Kuppan, N., Padman, M., Mahadeva, M., Srinivasan, S., Devarajan, R., 2024. A comprehensive review of sustainable bioremediation techniques: eco friendly solutions for waste and pollution management. Waste Manag. Bull. 2 (3), 154–171. https://doi.org/10.1016/j.wmb.2024.07.005.

Kwak, E., Kim, J.-H., Choi, N.-C., Seo, E., Lee, S., 2024. Longevity prediction of reactive media in permeable reactive barriers considering the contamination level and groundwater velocity at the planning site, with a focus on cadmium removal by zeolite. Chemosphere 353, 141532. https://doi.org/10.1016/j.chemosphere.2024.141532.

Lalumbe, L., Kanyerere, T., 2022. Characterisation of Hydro-Geochemical processes influencing groundwater quality in rural areas: a case study of soutpansberg region, Limpopo province, South Africa. Water 14 (12), 1972. https://doi.org/10.3390/w14121972.

Lapworth, D.J., Stuart, M.E., Pedley, S., Nkhuwa, D.C.W., Tijani, M.N., 2018. A review of urban groundwater use and water quality challenges in Sub-Saharan Africa.

Lapworth, D.J., Brauns, B., Chattopadhyay, S., Gooddy, D.C., Loveless, S.E., MacDonald, A.M., McKenzie, A.A., Muddu, S., Nara, S.N.V., 2021. Elevated uranium in drinking water sources in basement aquifers of Southern India. Appl. Geochem. 133, 105092. https://doi.org/10.1016/j.apgeochem.2021.105092.

LeBlanc, J., 2022. Stratigraphic lexicon: the sedimentary formations of the republic of Niger, Africa. Pro-Metrics. https://doi.org/10.47909/978-9916-9760-6-7.

Li, H., Liu, Q., 2022. Reaction medium for permeable reactive barrier remediation of groundwater polluted by heavy metals. Front. Environ. Sci. 10. https://doi.org/10.3389/fenvs.2022.968546.

Li, P., Karunanidhi, D., Subramani, T., Srinivasamoorthy, K., 2021. Sources and consequences of groundwater contamination. Arch. Environ. Contam. Toxicol. 80 (1), 1–10. https://doi.org/10.1007/s00244-020-00805-z.

Lin, Y., Hoover, J., Beene, D., Erdei, E., Liu, Z., 2020. Environmental risk mapping of potential abandoned uranium mine contamination on the navajo nation, USA, using a GIS-based multi-criteria decision analysis approach. Environ. Sci. Pollut. Res. 27 (24), 30542–30557. https://doi.org/10.1007/s11356-020-09257-3.

Lindsey, B.D., Fleming, B.J., Goodling, P.J., Dondero, A.M., 2023. Thirty years of regional groundwater-quality trend studies in the United States: major findings and lessons learned. J. Hydrol. 627, 130427. https://doi.org/10.1016/j.jhydrol.2023.130427.

Liu, D., Wang, Y., Zuo, L., Guo, M., Liu, S., 2025. Advanced materials for uranium adsorption: a mini review of recent developments. Front. Mater. 12. https://doi.org/10.3389/fmats.2025.1541204.

Liu, Z., Haddad, M., Sauvé, S., Barbeau, B., 2021. Alleviating the burden of ion exchange brine in water treatment: from operational strategies to brine management. Water Res. 205, 117728. https://doi.org/10.1016/j.watres.2021.117728.

Lohe, C., Amster, R., Swartz, B., 2021. Groundw. Namib. Explan. Hydrogeol. Map.

Lopez, A.M., Wells, A., Fendorf, S., 2021. Soil and aquifer properties combine as predictors of groundwater uranium concentrations within the central valley, california. Environ. Sci. Technol. 55 (1), 352–361. https://doi.org/10.1021/acs.est.0c05591.

Ma, M., Wang, R., Xu, L., Xu, M., Liu, S., 2020. Emerging health risks and underlying toxicological mechanisms of uranium contamination: lessons from the past two decades. Environ. Int. 145, 106107. https://doi.org/10.1016/j.envint.2020.106107.

Madison, A.S., Sorsby, S.J., Wang, Y., Key, T.A., 2023. Increasing in situ bioremediation effectiveness through field-scale application of molecular biological tools. Front. Microbiol. 13. https://doi.org/10.3389/fmicb.2022.1005871.

Madrigal, J.M., Flory, A., Fisher, J.A., Sharp, E., Graubard, B.I., Ward, M.H., Jones, R.R., 2024. Sociodemographic inequities in the burden of carcinogenic industrial air emissions in the United States. JNCI Journal National Cancer Institute 116 (5), 737–744. https://doi.org/10.1093/jnci/djae001.

Mahanayak, B., 2024. Environmental restoration through bioremediation: methods, advantages, and challenges. Int. J. Res. Publ. Rev. 5 (6), 6661–6664. https://doi.org/10.55248/gengpi.5.0624.1637.

Mahmoud, A.E.D., Mostafa, E., 2023. Nanofiltration membranes for the removal of heavy metals from aqueous solutions: preparations and applications. Membranes 13 (9), 789. https://doi.org/10.3390/membranes13090789.

Makubalo, S.S., Diamond, R.E., 2020. Hydrochemical evolution of high uranium, fluoride and nitrate groundwaters of namakwaland, South Africa. J. Afr. Earth Sci. 172. https://doi.org/10.1016/j.jafrearsci.2020.104002.

Makubalo, S.S., Supervisor, P., Dr, Diamond, R.E., Kenan, M.A.O., 2020. Hydrogeochemistry of the groundwater in the Namaqualand region, South Africa: implications for surficial uranium mineralization.

Mamadou, M.M., Cathelineau, M., Deloule, E., Reisberg, L., Cardon, O., Vallance, J., Brouand, M., 2022. The tim Mersoï basin uranium deposits (Northern Niger): geochronology and genetic model. Ore Geol. Rev. 145. https://doi.org/10.1016/j.oregeorev.2022.104905.

Martinez-Morata, I., Bostick, B.C., Conroy-Ben, O., Duncan, D.T., Jones, M.R., Spaur, M., Patterson, K.P., Prins, S.J., Navas-Acien, A., Nigra, A.E., 2022. Nationwide geospatial analysis of county racial and ethnic composition and public drinking water arsenic and uranium. Nat. Commun. 13 (1), 7461. https://doi.org/10.1038/s41467-022-35185-6.

Mathuthu, M., Uushona, V., Indongo, V., 2021. Radiological safety of groundwater around a uranium mine in Namibia. Phys. Chem. Earth 122. https://doi.org/10.1016/j.pce.2020.102915.

Meky, M.M., Hassan, N.A., Soussa, H., Gabr, M.E., 2025. Permeable reactive barriers for groundwater contaminant removal: mechanisms, materials, and challenges. J. Degraded Min. Lands Manag. 12 (4), 8005–8014. https://doi.org/10.15243/jdmlm.2025.124.8005.

Mine, A., Ziegler, B., 2022, June 20. Biogeochemical controls on natural and anthropogenic groundwater contaminants in California's central valley. 34th Keck Proc. Vol. https://doi.org/10.18277/AKRSG.2022.34.02.

Mitra, A., Chatterjee, S., Gupta, D.K., 2021. Plant-microbe interaction: relevance for phytoremediation of heavy metals. In Handbook of Bioremediation. Elsevier, pp. 263–275. https://doi.org/10.1016/B978-0-12-819382-2.00016-8.

Mohapi, M., Sefadi, J.S., Mochane, M.J., Magagula, S.I., Lebelo, K., 2020. Effect of LDHs and other clays on polymer composite in adsorptive removal of contaminants: a review. Crystals 10 (11), 957. https://doi.org/10.3390/cryst10110957.

Moshupya, P.M., Mohuba, S.C., Abiye, T.A., Korir, I., Nhleko, S., Mkhosi, M., 2022. In situ determination of radioactivity levels and radiological doses in and around the gold mine tailing dams, gauteng province, South Africa. Minerals 12 (10), 1295. https://doi.org/10.3390/min12101295.

Motlagh, A.M., Yang, Z., Saba, H., 2020. Groundwater quality. Water Environ. Res. 92 (10), 1649–1658. https://doi.org/10.1002/wer.1412.

Mukhamedzhanov, M.A., Kazanbayeva, L.M., Nurgaziyeva, A.A., Rakhmetov, I.K., 2019. ENVIRONMENTAL PROBLEMS OF SOUTH KAZAKHSTAN AND POLLUTION OF DRINKING GROUNDWATER. https://doi.org/10.5593/sgem2019/1.2/S02.027.

Mukherjee, S., Narula, R., Bhattacharjee, S., Dutta, D., Bose, I., Mahakud, J., Paul, S., Bhattacharjee, S., Paul, S., 2021. Bioremediation: the eco-friendly solution to the hazardous problem of environmental pollution. J. Environ. Eng. Landsc. Manag. 29 (4), 477–483. https://doi.org/10.3846/jeelm.2021.14439.

Musiyarira, H.K., Tesh, D., Dzinomwa, G., 2017. Sustainable water management: implications for mining in environmentally sensitive areas. GeoResour. Environ. Eng. 2. https://doi.org/10.15273/gree.2017.02.024.

MUTTALEB, W.H., ALI, Z.H., 2022. Bioremediation an eco-friendly method for administration of environmental contaminants. MINAR Int. J. Appl. Sci. Technol. 04 (02). https://doi.org/10.47832/2717-8234.11.3.

Mwalongo, D.A., Haneklaus, N.H., Lisuma, J.B., Mpumi, N., Amasi, A.I., Mwimanzi, J.M., Chuma, F.M., Kivevele, T.T., Mtei, K.M., 2024. Uranium dissemination with phosphate fertilizers globally: a systematic review with focus on east Africa. Sustainability 16 (4), 1496. https://doi.org/10.3390/su16041496.

Namibia Uranium Association. (2024). Uranium mining in Namibia. namibianuranium/uranium-mining-in-namibia/.

Naidu, R., Birke, V., 2015. Permeable Reactive Barrier Sustainable Groundwater Remediation. CRC Pres Taylor & Francis Group.

Namibia Chamber of Mines. *ANNUAL REVIEW of the Chamber of Mines of Namibia*.

Naseri-Rad, M., Berndtsson, R., Aminifar, A., McKnight, U.S., O'Connor, D., Persson, K.M., 2022. DynSus: dynamic sustainability assessment in groundwater remediation practice. Sci. Total Environ. 832, 154992. https://doi.org/10.1016/j.scitotenv.2022.154992.

Ngoc, L.T.N., Park, D., Lee, Y.-C., 2022. Human health impacts of residential radon exposure: updated systematic review and Meta-Analysis of Case–Control studies. Int. J. Environ. Res. Public Health 20 (1), 97. https://doi.org/10.3390/ijerph20010097.

Nilsson, R., Tong, J., 2020. Opinion on reconsideration of lung cancer risk from domestic radon exposure. Radiat. Med. Prot. 1 (1), 48–54. https://doi.org/10.1016/j.radmp.2020.01.001.

Nompumelelo, K.S.M., Edward, N.N., Muthumuni, M., Moloko, M., Makwena, M.J., 2023. Fabrication, modification, and mechanism of nanofiltration membranes for the removal of heavy metal ions from wastewater. ChemistrySelect 8 (33). https://doi.org/10.1002/slct.202300741.

OECD (2025) Nuclear Energy Agency (NEA), & International Atomic Energy Agency. Uranium 2024: Resources, Production and Demand (NEA No.7683). www.oecd-nea.org/jcms/pl_103179/uranium-2024-resources-production-and-demand?details=true.

Omohwovo, E.J., 2024. Wastewater management in Africa: challenges and recommendations. Environ. Health Insights 18. https://doi.org/10.1177/11786302241289681.

Osipov, S., Yermenbai, A., Akylbekova, A., Livinsky, Y., Anarbekov, O., 2020. The negative impact of anthropogenic factors on the state of groundwater of Kazakhstan. N. Natl. Acad. Sci. Repub. Kazakhstan Ser. Geol. Tech. Sci. 2 (440), 132–140. https://doi.org/10.32014/2020.2518-170X.40.

Osman, A.I., Chen, Z., Elgarahy, A.M., Farghali, M., Mohamed, I.M.A., Priya, A.K., Hawash, H.B., Yap, P., 2024. Membrane technology for energy saving: principles, techniques, applications, challenges, and prospects. Adv. Energy Sustain. Res. 5 (5). https://doi.org/10.1002/aesr.202400011.

Padhi, M., Mukherjee, M., Baksi, S., Pal, P., 2023. Study of extent of global uranium contamination in groundwater. J. Surv. Fish. Sci. https://doi.org/10.53555/sfs.v10i1S.2167.

Patel, A.K., Singhania, R.R., Albarico, F.P.J.B., Pandey, A., Chen, C.-W., Dong, C.-D., 2022. Organic wastes bioremediation and its changing prospects. Sci. Total Environ. 824, 153889. https://doi.org/10.1016/j.scitotenv.2022.153889.

Pepin, S., Black, P., Koliabina, D., Paulley, A., Bruffel, L., Punt, A., Shubayr, N., Zhu, M., Yankovich, T., 2022. Intermodel comparison for the radiological assessment of the zapadnoe and tessenderlo case studies with implications for selection of remediation strategy. J. Radiol. Prot. 42 (2), 020510. https://doi.org/10.1088/1361-6498/ac66a4.

Pretorius, H.C.F., Tredoux, M., Andreoli, M.A.G., Vermeulen, P.D., 2020. A long term baseline and variability of natural radionuclides in groundwater at the vaalputs low-level radioactive waste disposal facility, namaqualand, South Africa: regional implications. South Afr. J. Geol. 123 (1), 105–116. https://doi.org/10.25131/sajg.123.0006.

Quinn, J.E., Sedger, D.S., Brennan, A.T., Ring, R.J., Soldenhoff, K., 2020. Recovery of uranium from carbonate solutions using lewatit TP 107 resin. Hydrometallurgy 194, 105360. https://doi.org/10.1016/j.hydromet.2020.105360.

Rajapakse, J., Rainer-Smith, S., Millar, G.J., Grace, P., Hutton, A., Hoy, W., Jeffries-Stokes, C., & Hudson, B. (2019). Unsafe drinking water quality in remote Western Australian Aboriginal communities 1*.

Raji, I.B., Hoffmann, E., Ngie, A., Winde, F., 2021. Assessing uranium pollution levels in the rietspruit river, far west rand goldfield, South Africa. Int. J. Environ. Res. Public Health 18 (16), 8466. https://doi.org/10.3390/ijerph18168466.

Raji, Z., Karim, A., Karam, A., Khalloufi, S., 2023. Adsorption of heavy metals: mechanisms, kinetics, and applications of various adsorbents in wastewater Remediation—A review. Waste 1 (3), 775–805. https://doi.org/10.3390/waste1030046.

Raklami, A., Meddich, A., Oufdou, K., Baslam, M., 2022. Plants—Microorganisms-Based bioremediation for heavy metal cleanup: recent developments, phytoremediation techniques, regulation mechanisms, and molecular responses. Int. J. Mol. Sci. 23 (9), 5031. https://doi.org/10.3390/ijms23095031.

Ralph, M.I., Cattani, M., 2021. A review of radiation doses and associated parameters in Western Australian mining operations (2018–20). J. Radiol. Prot. 42 (1), 012501. https://doi.org/10.1088/1361-6498/ac3c90.

Ralph, M.I., Chaplyn, A., Cattani, M., 2020. A review of radiation doses and associated parameters in Western Australian mining operations that process ores containing naturally occurring radionuclides for 2018–19. J. Radiol. Prot. 40 (4), 1476–1496. https://doi.org/10.1088/1361-6498/abc4eb.

Ralph, M.I., Koshy, J., Foley, P., 2024. A review of radiation doses and associated parameters in Western Australian mining operations (2020-23). J. Radiol. Prot. 44 (3), 032501. https://doi.org/10.1088/1361-6498/ad6f1a.

Redvers, N., Chischilly, A.M., Warne, D., Pino, M., Lyon-Colbert, A., 2021. Uranium exposure in American Indian communities: health, policy, and the way forward. Environ. Health Perspect. 129 (3). https://doi.org/10.1289/EHP7537.

Reid, A., 2019. The olympic Cu-Au province, gawler craton: a review of the lithospheric architecture, geodynamic setting, alteration systems, cover successions and prospectivity. Minerals 9 (6), 371. https://doi.org/10.3390/min9060371.

Ren, Y., Cui, M., Zhou, Y., Sun, S., Guo, F., Ma, J., Han, Z., Park, J., Son, Y., Khim, J., 2024. Utilizing machine learning for reactive material selection and width design in permeable reactive barrier (PRB). Water Res. 251, 121097. https://doi.org/10.1016/j.watres.2023.121097.

Richardson, D.B., Rage, E., Demers, P.A., Do, M.T., Fenske, N., Deffner, V., Kreuzer, M., Samet, J., Bertke, S.J., Kelly-Reif, K., Schubauer-Berigan, M.K., Tomasek, L., Zablotska, L.B., Wiggins, C., Laurier, D., 2022. Lung cancer and radon: pooled analysis of uranium miners hired in 1960 or later. Environ. Health Perspect. 130 (5). https://doi.org/10.1289/EHP10669.

Rossi, M.M., Dell'Armi, E., Lorini, L., Amanat, N., Zeppilli, M., Villano, M., Petrangeli Papini, M., 2021. Combined strategies to prompt the biological reduction of chlorinated aliphatic hydrocarbons: new sustainable options for bioremediation application. Bioengineering 8 (8), 109. https://doi.org/10.3390/bioengineering8080109.

Ruano-Ravina, A., Martin-Gisbert, L., Kelsey, K., Pérez-Ríos, M., Candal-Pedreira, C., Rey-Brandariz, J., Varela-Lema, L., 2023. An overview on the relationship between residential radon and lung cancer: what we know and future research. Clin. Transl. Oncol. 25 (12), 3357–3368. https://doi.org/10.1007/s12094-023-03308-0.

Sacré Regis, M., Mouhamed, D., Kouakou, L., Adeline, K., Arona, B., Houebagnon Saint. J., C, D., Koffi Claude, A., K., Talnan Jean, H., C., Salomon, O., Issiaka, S., 2020. Using the CHIRPS dataset to investigate historical changes in precipitation extremes in West Africa. Climate 8 (7), 84. https://doi.org/10.3390/cli8070084.

Sakr, M., El Agamawi, H., Klammler, H., Mohamed, M.M., 2023. A review on the use of permeable reactive barriers as an effective technique for groundwater remediation. In: In Groundwater for Sustainable Development, 21. Elsevier B.V. https://doi.org/10.1016/j.gsd.2023.100914.

Sánchez Hidalgo, G.C., Ábrego-Bonilla, J., Deago, E., Ortega Del Rosario, M.D.L.A., 2025. Global perspectives on groundwater decontamination: advances and challenges of the role of permeable reactive barriers. Hydrology 12 (4), 98. https://doi.org/10.3390/hydrology12040098.

Sanusi, Y.A., Ohadugha, C.B., Martins, V.I., Olaide, S.A., 2022. Energy resources of Southern Africa: potentials and sustainable energy delivery. J. Energy Res. Rev. 1–13. https://doi.org/10.9734/jenrr/2022/v12i230294.

Satyam, S., Patra, S., 2024. Innovations and challenges in adsorption-based wastewater remediation: a comprehensive review. Heliyon 10 (9), e29573. https://doi.org/10.1016/j.heliyon.2024.e29573.

Scott, S.R., Wiersma, A.K., Krinke, G., 2023. The importance of uranium isotope composition for gross alpha activity regulation. AWWA Water Sci. 5 (2). https://doi.org/10.1002/aws2.1329.

Shalaby, S.M., Sharshir, S.W., Kabeel, A.E., Kandeal, A.W., Abosheiasha, H.F., Abdelgaied, M., Hamed, M.H., Yang, N., 2022. Reverse osmosis desalination systems powered by solar energy: preheating techniques and brine disposal challenges – a detailed review. Energy Convers. Manag. 251, 114971. https://doi.org/10.1016/j.enconman.2021.114971.

Singh, R., Chakma, S., Birke, V., 2023. Performance of field-scale permeable reactive barriers: an overview on potentials and possible implications for in-situ groundwater remediation applications. Sci. Total Environ. 858, 158838. https://doi.org/10.1016/j.scitotenv.2022.158838.

Skinner, J., Delgado, A.G., Hyman, M., Chu, M.-Y.J., 2024. Implementation of in situ aerobic cometabolism for groundwater treatment: state of the knowledge and important factors for field operation. Sci. Total Environ. 925, 171667. https://doi.org/10.1016/j.scitotenv.2024.171667.

Smedley, P.L., Kinniburgh, D.G., 2022. Uranium in natural waters and the environment: distribution, speciation and impact. In: In Applied Geochemistry, 148. Elsevier Ltd. https://doi.org/10.1016/j.apgeochem.2022.105534.

Somu, P., Narayanasamy, S., Gomez, L.A., Rajendran, S., Lee, Y.R., Balakrishnan, D., 2022. Immobilization of enzymes for bioremediation: a future remedial and mitigating strategy. Environ. Res. 212, 113411. https://doi.org/10.1016/j.envres.2022.113411.

Soumaila, I., 2023. Uranium and the Macro-Economy in Niger: an empirical investigation. J. Dev. Areas 57 (2), 313–340. https://doi.org/10.1353/jda.2023.0036.

Stumpf, R., Budziak, D., Deus, N., Elbracht, J., 2020. Spatial anomalies of uranium background levels in groundwater of Lower Saxony. https://doi.org/10.5194/egusphere-egu2020-21458.

Subbotin, S.B., Krivitsky, P.E., Larionova, N.V., Aidarkhanova, A.K., Mamyrbayeva, A.S., Tleukanova, Zh.E., Aleksandrovich, I.A., Skripnikov, M.V., Bachurina, I.A., Ermakova, R.G., 2024. RECONNAISSANCE SURVEY OF MOTHBALLED URANIUM MINING FACILITIES AND SETTLEMENTS IN THE Southern PART OF THE NORTH-Kazakhstan REGION. NNC RK Bull. (1), 63–72. https://doi.org/10.52676/1729-7885-2024-1-63-72.

Tillman, F.D., Beisner, K.R., Anderson, J.R., Unema, J.A., 2021. An assessment of uranium in groundwater in the Grand Canyon region. Sci. Rep. 11 (1). https://doi.org/10.1038/s41598-021-01621-8.

Tisherman, R.A., Rossi, R.J., Shonkoff, S.B.C., DiGiulio, D.C., 2023. Groundwater uranium contamination from produced water disposal to unlined ponds in the san joaquin valley. Sci. Total Environ. 904, 166937. https://doi.org/10.1016/j.scitotenv.2023.166937.

Tleuova, Z., Snow, D.D., Mukhamedzhanov, M., Ermenbay, A., 2023. Relation of hydrogeology and contaminant sources to drinking water quality in Southern Kazakhstan. Water (Switz.) 15 (24). https://doi.org/10.3390/w15244240.

Torres, E., Gómez, P., 2020. Chapter 7. Permeable reactive barriers (PRBs) for environmental site remediation. In The Handbook of Environmental Remediation. Royal Society of Chemistry, pp. 191–228. https://doi.org/10.1039/9781788016261-00191.

Urošević, T., Trivunac, K., 2020. Achievements in low-pressure membrane processes microfiltration (MF) and ultrafiltration (UF) for wastewater and water treatment. In Current Trends and Future Developments on (Bio-) Membranes. Elsevier, pp. 67–107. https://doi.org/10.1016/B978-0-12-817378-7.00003-3.

Vengosh, A., Coyte, R.M., Podgorski, J., Johnson, T.M., 2022. A critical review on the occurrence and distribution of the uranium- and thorium-decay nuclides and their effect on the quality of groundwater. Sci. Total Environ. 808, 151914. https://doi.org/10.1016/j.scitotenv.2021.151914.

Verma, S., Kim, K.-H., 2022. Graphene-based materials for the adsorptive removal of uranium in aqueous solutions. Environ. Int. 158, 106944. https://doi.org/10.1016/j.envint.2021.106944.

Volberding, P., Warner, J., 2018. The uniqueness of uranium: the problematics of statecraft in Niger. Extr. Ind. Soc. 5 (3), 294–301. https://doi.org/10.1016/j.exis.2018.03.007.

Wang, J., Aghajani Delavar, M., 2023. Techno-economic analysis of phytoremediation: a strategic rethinking. Sci. Total Environ. 902, 165949. https://doi.org/10.1016/j.scitotenv.2023.165949.

Wang, Y., Wang, C., Feng, R., Li, Y., Zhang, Z., Guo, S., 2024. A review of passive acid mine drainage treatment by PRB and LPB: from design, testing, to construction. Environ. Res. 251, 118545. https://doi.org/10.1016/j.envres.2024.118545.

Warner, S.D., Bekele, D., Nathanail, C.P., Chadalavada, S., Naidu, R., 2023. Climate-influenced hydrobiogeochemistry and groundwater remedy design: a review. Remediat. J. 33 (3), 187–207. https://doi.org/10.1002/rem.21753.

Wilde, A., 2023. Towards a mineral systems model for surficial uranium mineralization based on deposits in the erongo district of Namibia (MDPI). Minerals 13 (2). https://doi.org/10.3390/min13020149.

Winde, F., Brugge, D., Nidecker, A., Ruegg, U., 2017. Uranium from Africa – an overview on past and current mining activities: Re-appraising associated risks and chances in a global context. In: In Journal of African Earth Sciences, 129. Elsevier Ltd, pp. 759–778. https://doi.org/10.1016/j.jafrearsci.2016.12.004.

World Nuclear Association. (2023). Uranium in Namibia. world-nuclear.org/information-library/country-profiles/countries-g-n/namibia.

Wu, Q., Sun, Y., Luo, Z., Li, X., Wen, Y., Shi, Y., Wu, X., Huang, X., Zhu, Y., Huang, C., 2024. Application and development of zero-valent iron (ZVI)-based materials for environmental remediation: a scientometric and visualization analysis. Environ. Res. 241, 117659. https://doi.org/10.1016/j.envres.2023.117659.

You, W., Peng, W., Tian, Z., Zheng, M., 2021. Uranium bioremediation with U(VI)-reducing bacteria. Sci. Total Environ. 798, 149107. https://doi.org/10.1016/j.scitotenv.2021.149107.

Zhanbekov, K., Akhmetov, A., Vundo, A., 2019. Twelve-year monitoring results of radioactive pollution in the Kazakh part of the syrdarya river basin. Environ. Nat. Resour. J. 17 (1), 44–53. https://doi.org/10.32526/ennrj.17.1.2019.05.

Zhang, R., Li, N., Lu, X., Shu, H., Li, H., Xu, Z., Wang, Q., 2024. Study on the characteristics and attribution analysis of runoff changes in the zuli river basin of northwest China. Water 16 (23), 3526. https://doi.org/10.3390/w16233526.

Zhang, X., Liu, Z., Qu, D., 2023. Proof-of-Concept study of ion-exchange method for the recycling of LiFePO4 cathode. Waste Manag. 157, 1–7. https://doi.org/10.1016/j.wasman.2022.12.003.

Zimmermann, K., Schoutteten, K., Liu, Z., Chen, W., Bérubé, P., Mohseni, M., Barbeau, B., 2025. Biological ion exchange for natural organic matter removal from drinking water. Water Res. 283, 123722. https://doi.org/10.1016/j.watres.2025.123722.