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Review

Environmental Impacts of In Situ Leaching Uranium Mining: A Review

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Abstract

In situ leaching (ISL) is the most popular method for uranium mining worldwide, particularly in arid and semi-arid regions. Despite its economic benefits, ISL raises concerns about radioactive migration and groundwater contamination. This review assesses the environmental impacts of ISL uranium mining, focusing on radionuclide transport pathways and key information gaps. This review, focusing on groundwater contamination, radionuclide migration, soil and sediment contamination, atmospheric impacts, vegetation responses, and ecosystem disturbances, summarizes current understanding of the hydrogeochemical, radiological, and environmental impacts of uranium mining. The analysis indicates that groundwater is the environmental component most vulnerable to contamination during ISL operations due to the injection of acidic or alkaline leaching solutions that may mobilize uranium, radium, sulfates, selenium, arsenic, and other potentially hazardous elements. In addition to impacts on groundwater, there have also been reports of soil contamination, airborne dust, radioactive accumulation in flora, and impacts on aquatic and microbiological resources, particularly in arid and semi-arid regions. Although cleanup methods and natural attenuation can minimize contamination to some extent, residual contamination can persist for decades after mine closure. Overall, ISL uranium mining emphasizes the need for effective groundwater management, long-term environmental monitoring, and improved reclamation methods, balancing surface disturbance with long-term hydrogeochemical and environmental concerns.

Keywords: in situ leaching; uranium mining; environmental monitoring; environmental impacts

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1. Introduction

1.1. Development of ISL Uranium Mining

Uranium remains a strategically important resource for nuclear energy production, especially when it comes to creating low-carbon energy. In situ leaching (ISL) has become the widespread uranium extraction method in arid and semi-arid zones [1]. Compared to traditional underground and open pit mining methods, ISL mining often provides higher operational safety, minimizes surface disturbance and produces less waste rock, making it economically viable [2]. ISL uranium mining has been applied since the 1950s in the Union of Soviet Socialist Republics (USSR) and 1960s in the United States of America (USA). Since 2014, it has accounted for above 50% of the world's uranium production [3]. In the past, alkaline carbonate systems gained popularity in the USA, while acid leaching systems were mainly used in the USSR [2]. Kazakhstan became the world's largest uranium producer

thanks to the extensive development of uranium deposits in the Chu-Sarysu and Syrdarya regions during the Soviet era [4]. The extensive ISL infrastructure that Kazakhstan acquired after the collapse of the Soviet Union was later updated and expanded by the national enterprise Kazatomprom [5]. By 2009, Kazakhstan was the leader of uranium producers, surpassing Canada and Australia.

The environmental and hydrogeological impacts of uranium mining in ISL are attracting increasing attention from scientists and regulators, despite its operational and economic benefits [6]. To mobilize uranium for extraction using pump wells, ISL mining involves injecting acidic or alkaline leachates into permeable ore-bearing aquifers [7].

1.2. Environmental Concerns Associated with ISL

1.2.1. Groundwater

Groundwater is considered to be the environmental component most at risk from contamination during uranium ISL mining, as leach solutions are injected directly into ore-bearing aquifers. The mobilization of uranium, radionuclides, and associated trace elements such as radium, arsenic, selenium, molybdenum, and vanadium is facilitated by the injection of acidic or alkaline leachates, which alter pH and redox conditions [8]. Therefore, post-mining aquifer restoration and groundwater contamination remain important environmental issues associated with ISL activities [9].

Studies have shown that uranium, nitrates, sulfates, and metals are more abundant in groundwater affected by mining operations [10–12]. Uranium migration is significantly influenced by oxidation–reduction conditions, carbonate complex formation, aquifer mineralogy, and groundwater flow dynamics [13]. In addition to hydrogeochemical processes, microbial populations can influence uranium mobility and uptake in ISL-affected aquifers. Acidic ISL systems can promote the growth of acidophilic and iron-oxidizing bacteria, which can increase contamination and delay aquifer recovery [14]. These microbes are similar to those found in acid mine drainage systems.

According to current research, uranium mining at ISL deposits directly impacts groundwater systems. The extent and duration of groundwater contamination depend on the chemical composition of the leachate, hydrogeological conditions, oxidation–reduction processes, and the effectiveness of remediation efforts. Therefore, groundwater conservation remains a significant environmental concern associated with ISL uranium mining.

1.2.2. Soil and Sediments

Soils and sediments are important secondary environmental elements that can be affected by radioactive contamination during ISL uranium mining. Unintentional leachate leaks from pipelines and boreholes, improper handling of drilling fluids, and leaks from evaporation ponds or storage tanks are common pathways for surface contamination [15]. Compared to conventional uranium mining, ISL uranium mining often produces less waste rock and requires less overburden removal, resulting in a comparatively lower direct mechanical impact on the surface environment [16]. However, soils can act as both secondary sources and sinks of radionuclides, depending on geochemical conditions [17,18]. Uranium mobility in soils and sediments is significantly influenced by organic matter, pH, redox conditions, mineral composition, and sorption processes [19]. Furthermore, sediments formed in drainage systems or retention ponds can serve as long-term reservoirs for particle-bound radionuclides, which can then be remobilized during hydrological disturbances [20].

Biogeochemical interactions can also influence the behavior of uranium in contaminated soils and sediments [21]. Although the surface area of ISL mining is typically smaller than that of conventional uranium mining, current research suggests that localized contam-

ination of soils and sediments can still occur as a result of industrial and hydrogeochemical processes. Because the current literature still focuses on groundwater systems, little is known about long-term radioactive stability and secondary contamination processes in surface ecosystems.

1.2.3. Biota

Examples of biota that can accumulate radionuclides and react acutely to environmental changes caused by uranium mining include plants, animals, and bacteria [22]. Thus, biological systems can act as both markers and accelerators of radionuclide migration in areas affected by mining. Despite their ecological importance, biological components are often overlooked in ISL environmental assessments, which primarily focus on groundwater and hydrogeochemical processes.

Microorganisms are among the most important biological elements in uranium biogeochemistry. Oxidation–reduction processes in microorganisms, particularly the conversion of soluble U(VI) to less mobile U(IV), can significantly influence the mobility and degradation of uranium in contaminated aquifers [23]. Furthermore, fish, terrestrial herbivores, benthic invertebrates, and aquatic organisms can contribute to the movement of radionuclides through aquatic and terrestrial food chains.

Although non-human biota is increasingly being considered in radiation protection systems, its use in ISL environmental assessments remains limited. Recent research suggests that microbes, plants, and animals can be important indicators of radionuclide transport and ecosystem response, highlighting the need for more comprehensive biological monitoring in ISL environmental studies.

Knowledge Gaps and Aim of the Review

In terms of hydrogeochemistry, microbiology, radiological assessment, and ecosystem monitoring, the environmental impacts of uranium mining at the ISL deposit remain poorly understood. Most recent studies focus on groundwater contamination, with far less attention paid to soils, sediments, air transport, vegetation, and environmental impacts. Environmental assessments are also less comparable, as different studies define radioactive material migration, mitigation, and the success of remediation differently.

Much remains to be learned about the long-term behavior of radionuclides, groundwater recovery after remediation, microbial feedback mechanisms, and ecosystem-level impacts. Therefore, further integration of hydrogeochemical, microbiological, and environmental data is required to improve environmental monitoring and remediation methods for uranium mining at the ISL deposit.

The purpose of this review is to assess the key environmental impacts of uranium mining, focusing on groundwater contamination, radioactive migration pathways, atmospheric transport, environmental impacts, and remediation.

2. Materials and Methods

This review is based on an analysis of a comprehensive body of research on the environmental impacts of uranium mining using ISL. International publications, technical articles, and relevant peer-reviewed studies focused on the hydrogeochemical, radiological, microbiological, and environmental aspects of ISL mining.

When selecting literature, special attention was given to studies that included field observations, groundwater monitoring data, hydrogeochemical analysis, reactive transport modeling, and assessment of remediation activities, as these can be used to study the environmental impacts of ISL uranium mining. To compare contamination pathways and

remediation outcomes at different ISL sites, preference was given to publications that described environmental impacts in various geological and operational situations.

Studies conducted in major uranium-producing regions, including Kazakhstan, the United States, China, Mongolia, and Uzbekistan, were analyzed to identify comparable environmental impacts, regulatory procedures, and existing knowledge gaps related to ISL uranium mining.

3. Results

3.1. Groundwater Contamination and Hydrogeochemical Impacts of ISL Uranium Mining

According to research, groundwater is the environmental component most susceptible to contamination during ISL uranium mining. Hydrogeochemical conditions in ore-bearing aquifers are dramatically altered by the injection of acidic or alkaline leachants, which also facilitate the mobilization of uranium, radium, sulfate, iron, arsenic, selenium, and other potentially hazardous elements (Table 1) [24]. Subsurface contamination remains a key long-term environmental concern in ISL uranium mining, despite its significantly lower surface impact than traditional uranium mining methods.

Table 1. Comparative hydrogeochemical impacts of acid and alkaline ISL systems.

ISL System	Representative Regions	Typical Hydrochemical Response	Main Contaminants	Groundwater Behavior	Restoration Outcome	References
Acid ISL systems	China, Kazakhstan, Mongolia	Strong groundwater acidification, sulfate enrichment, increased mineral dissolution and salinity	U, SO_4^{2-}, Fe, Mn, Ra, As, Cd	High contaminant mobility, persistent contaminant plumes, alteration of aquifer geochemistry	Restoration often difficult due to residual contamination and slow geochemical equilibration	[9,12,25–27]
Alkaline ISL systems	USA (Wyoming, Texas, Nebraska)	Moderate hydrochemical alteration under carbonate conditions; localized ore-zone contamination	U, Ra, sulfate, Se, Mn, Fe	Contamination commonly restricted to ore zone due to natural attenuation and reductive immobilization	Partial restoration achievable, although some contaminants remain above baseline	[28–31]

Studies conducted in Kazakhstan revealed varying hydrochemical conditions depending on the mining region and the level of ISL impact. Measurements in rivers, artesian wells, and groundwater in the Shu–Sarysu uranium region revealed relatively low gross alpha and beta activity, generally remaining below regulatory limits ($\alpha \leq 0.2$ Bq/L and $\beta \leq 1.0$ Bq/L) [4]. Researchers concluded that the radiation environment in this area was fairly constant. However, scientists noted the potential for uranium remobilization and the so-called "rebound effect," in which slow geochemical equilibration processes could lead to the spread of residual contaminants after the completion of ISL activities.

On the other hand, studies conducted in the Syr Darya River basin in Kazakhstan showed that uranium mining areas in the ISL were associated with severe radioactive contamination [32]. Total beta activity reached 408.1 Bq/L, several orders of magnitude higher than the intervention levels, while total alpha activity reached 158 Bq/L. The growth of ISL mining activities in the Syr Darya basin was linked to severe radionuclide pollution of surface waters and downstream transfer of radioactive elements, suggesting possible a hydrogeological relationship between mining zones and river systems. However, more research is required to identify the precise pathways and sources of contamination, including tracer experiments and thorough hydrogeological modeling.

Extremely high concentrations of ^{226}Ra, ^{230}Th, and ^{210}Pb were detected downstream of mining sites. Between 2008 and 2009, researchers observed an increase in radioactive contamination caused by increased industrial activity in the ISL area. This indicates a significant hydrogeological connection between surface water systems and mining zones. This contamination may pose a potential risk to household water consumption, livestock watering, and irrigation.

According to research conducted in the United States, hydrogeological isolation and groundwater remediation efficiency significantly influence the environmental impacts of ISL operations. Uranium concentrations in ore zone groundwater at the Smith Ranch–Highland ISL mine in Wyoming increased from background levels of approximately 10–70 ppm to post-mining concentrations reaching 13–40 ppm [28]. During mining, ^{226}Ra levels also increased significantly. However, due to natural attenuation mechanisms such as adsorption, reductive immobilization, and geochemical buffering, drawdown monitoring boreholes typically yielded significantly lower uranium concentrations. Consistent with previous studies, these results suggest that drawdown conditions and natural geochemical barriers can effectively prevent large-scale uranium migration beyond mining zones.

The importance of reductive immobilization procedures during uranium transport was demonstrated by additional field testing conducted at ISL units in Wyoming. While conservative chloride tracers achieved near-complete recovery, only approximately 39% of the injected dissolved U(VI) was recovered in low-grade wells, indicating significant uranium losses from solution through adsorption and reduction processes [28,33]. A significant amount of uranium was converted from soluble U(VI) to less mobile U(IV), according to co-reactive transport modeling and uranium isotope studies, highlighting the importance of redox-controlled attenuation processes in limiting uranium migration.

One of the best documented examples of groundwater alteration due to ISL extraction and reclamation is the Smith-Highland Ranch ISL site in Wyoming (Table 2).

Table 2. Hydrochemical evolution of groundwater during alkaline ISL mining and restoration at the Smith Ranch–Highland site (USA) [28].

Parameter	Pre-Mining Groundwater	Post-Mining Groundwater	Post-Restoration Groundwater	Drinking-Water Standard	Main Implication
U (mg/L)	0.05	40.19	3.53	0.03	After recovery, uranium levels remained above baseline and regulatory limits.
Ra-226 (pCi/L)	675	3286	1153	5	Radium contamination that persists after ISL operations
SO_4^{2-} (mg/L)	91	380.6	127.2	250	Sulfate enrichment is associated with changes in groundwater
Fe (mg/L)	0.05	0.05	1.3	0.3	Increasing iron levels after restoration
Mn (mg/L)	0.03	0.66	0.49	0.05	After restoration, manganese levels remained high.
Se (mg/L)	0.001	0.99	0.07	0.05	Selenium contamination persisted after remediation
TDS (mg/L)	330	1507	410	500	During mining operations, the salinity of groundwater increased.
pH	8.0	6.78	7.31	6.5–8.5	Partial recovery from moderate acidity during ISL

Groundwater remediation during ISL remains very challenging, despite evidence of natural attenuation, as contaminants can persist for years or decades after mining operations cease [28,34,35]. Uranium, radium, manganese, iron, and selenium concentrations in

remediated aquifers continued to increase, exceeding drinking water standards even after remediation [28]. While ^{226}Ra concentrations continued to increase, uranium concentrations decreased significantly after remediation but remained above baseline levels. These results highlight the long-term challenges associated with restoring groundwater systems damaged by mining and show that remediation methods such as chemical remediation, reverse osmosis, and groundwater treatment can reduce contamination but often fail to fully restore groundwater to pre-mining conditions [28,36].

Zones rich in pyrite and carbon were characterized by particularly high levels of residual uranium contamination. Even after reduction, uranium remained tightly bound to organic matter and sulfide minerals, and pyrite served as a trapping phase and reducing barrier for uranium, limiting its mobility but complicating recovery procedures [31]. While carbonaceous materials retained significant levels of residual uranium, deeper ore zones were more successfully leached. These results highlight the importance of mineralogical heterogeneity in regulating uranium migration and recovery efficiency.

Studies in China have found significant changes in groundwater chemistry associated with acidic ISL systems. Sulfuric acid leaching has led to severe acidification of groundwater in uranium deposits in Inner Mongolia and Xinjiang, resulting in pH values dropping to 1.5–1.9 [9,12,26]. In several wells, uranium concentrations exceeded 11,000 μg/L, while sulfate contents ranged from 11,900 to 26,132 mg/L. Iron concentrations exceeding 1300 mg/L indicated significant dissolution of iron-bearing materials [9,26]. According to reactive transport modeling [12], acid plumes can travel approximately 150 m beyond production zones and alter porosity and permeability through dissolution and precipitation processes.

Sulfuric acid injection promotes the breakdown of uranium-bearing minerals and improves uranium mobility by forming soluble uranyl complexes during pumping cycles, according to reactive transport modeling conducted by PHAST at the Bayan-Uul deposit [11].

Furthermore, studies have shown that sulfuric acid leaching significantly improves water–rock interactions by stimulating mineral dissolution, sulfate formation, and the mobilization of dissolved elements [35,37]. Major ions and trace elements enter groundwater through the dissolution of calcite, dolomite, feldspar, and clay minerals, significantly increasing the content of sulfates, sodium, calcium, iron, and total dissolved solids (TDS). Highly mineralized groundwater around mining areas has been found to be unsuitable for drinking by animals. Sulfates have been found to be one of the main markers used to distinguish contaminated groundwater from background water [9,25].

A notable discovery from the Chinese ISL experiments was that acid leaching significantly impacted groundwater microbial populations in addition to altering groundwater chemistry. Acidic conditions and high levels of uranium, sulfate, iron, manganese, arsenic, cadmium, and chromium altered the microbial community composition in contaminated aquifers of the Ili River Basin. Under acidic conditions, sulfate-reducing and uranium-reducing bacteria, such as *Desulfosporosinus* and *Sulfobacillus*, predominated, suggesting continuous biogeochemical adaptation and natural attenuation processes [26].

Similar results indicate that the growth of acidophilic and iron-oxidizing microbial communities, similar to those observed in acid mine drainage systems, was facilitated by sulfuric acid injection into active acid leach sites in Kazakhstan. These microbial populations were associated with consistently low pH and high concentrations of sulfates, iron, aluminum, and dissolved uranium, suggesting that biologically mediated feedback loops may be involved in long-term groundwater contamination and delayed aquifer regeneration [14,26].

The importance of hydrogeological control during mining operations was further emphasized by research conducted in Mongolia. Researchers found that inadequate hy-

drogeological control can cause acidic leachates to migrate 5–10 m beyond the ore zone. Seepage control and the prevention of pore blockages are essential to reduce contaminant migration, according to numerical groundwater transport models [27].

Following field testing of acid-leached uranium in Mongolia, long-term groundwater monitoring showed that dissolved uranium concentrations gradually decreased to levels close to background levels within a few years of leaching cessation. Under controlled operating conditions, hydrochemical anomalies remained largely limited, suggesting that lateral migration of contaminants can be significantly reduced through effective hydraulic control.

Overall, the studies reviewed indicate that the main environmental impact of ISL uranium mining is groundwater pollution [9,28,29]. Because acidic conditions significantly increase metal mobility, sulfate enrichment, and aquifer acidification, acid leach systems often have more detrimental environmental impacts than alkaline carbonate systems [12,25,26]. Although ISL mining results in less surface disturbance than conventional mining, slow desorption reactions, mineral dissolution, residual contamination, and redox imbalances make it difficult to restore groundwater to its original state [28,31]. Long-term hydrogeochemical monitoring and remediation management are crucial for uranium production in the ISL to be environmentally sustainable.

3.2. Soil Contamination and Radionuclide Migration Around ISL Uranium Mining Sites

Compared to traditional open-pit and underground mining, ISL uranium mining generally results in less direct soil disturbance. However, contaminated gravity wells, tailings ponds, ISL borehole fields, wastewater seepage zones, and processing plants can still be subject to significant soil contamination. Uranium-series radionuclides, radium, thorium, sulfate, uranium, and heavy metals such as cadmium, chromium, copper, lead, zinc, and iron are the primary soil contaminants detected in all the studies reviewed.

Research in the Shu–Sarysu uranium region of Kazakhstan revealed localized accumulation of radioactivity in surface soil layers around ISL deposits and contaminated sites [4]. ^{226}Ra concentrations reached 1729.6 ± 173 Bq/kg, significantly exceeding global background levels of 12–120 Bq/kg. The highest contamination levels were observed in previously contaminated areas near uranium mining sites. Most soils in nearby settlements were found to be below permissible radioactivity levels. However, localized contamination persisted near contaminated wells and ISL infrastructure. The authors also highlighted the potential for uranium remobilization during ISL activities, which could lead to infiltration processes and secondary contamination of groundwater.

Further studies in southern Kazakhstan revealed that the primary accumulation site of radioactive substances was the top 0–10 cm of soil [38]. Concentrations of ^{226}Ra ranged from 11 to 2350 Bq/kg, while concentrations of ^{40}K and ^{232}Th were also higher near contaminated sites. In an arid climate, vertical migration of radionuclides was likely very limited, but redistribution through wind erosion, dust transport, and surface runoff was considered important. Outside the buffer zones, the most contaminated sites were found near abandoned gravity wells, where gamma radiation levels ranged from 0.5 to 1.2 μSv/h. Through inhalation of contaminated dust and its possible entry into agricultural systems, the researchers identified potential problems related to exposure of local residents and livestock.

Uranium mining areas in China, particularly those affected by tailings ponds, wastewater leaks, and acid leaching operations, have been shown to have the most contaminated soils [9]. In soils exposed to wastewater, uranium concentrations ranged from 74.78 to 79.30 mg/kg, nearly 27 times higher than background levels. Furthermore, chromium, copper, lead, and zinc concentrations were several times higher than natural levels, while cadmium concentrations were nearly 946 times higher than background values. The

study found that while precipitation-induced leaching promoted vertical migration of contaminants to depths of up to 14 m, wind erosion transported contaminated particles approximately 4 km from the sources. The concentration of uranium contamination in the top 20 cm of soil indicates strong surface accumulation of uranium associated with airborne deposition and contaminated runoff.

Furthermore, Chinese studies have shown that acid leaching significantly improves the mobility of contaminants, as sulfuric acid dissolves silicate phases, carbonate minerals, and iron oxides, improving the transport of heavy metals and radionuclides into nearby soils and groundwater systems. The researchers concluded that wastewater leaks and contaminated waste storage sites were the main long-term causes of soil contamination around many ISL mining sites [9].

Studies conducted in China also showed that high levels of uranium-series radionuclides can be present in drilling fluids and other operational materials used in the construction of ISL wells. These results suggest that auxiliary materials introduced during mining operations may also be a source of surface contamination, in addition to the ore extraction itself.

According to hydrochemical studies of the Bayan-Uul uranium deposit in Inner Mongolia [25], the use of sulfuric acid treatment facilities increased water–rock interactions and the mobility of contaminants in nearby soils and groundwater systems. Sulfate enrichment and mineral dissolution were found to be the two main factors influencing radionuclide migration in acidic environments.

Studies conducted in Uzbekistan, the main sources of soil contamination in uranium mining areas are tailings ponds, landfills, and uranium drillhole deposits [39]. Man-made soils near uranium waste processing plants were found to contain elevated levels of uranium-series radionuclides. However, remediation efforts approximately doubled the uranium concentration, and after remediation, the remediated soils often met national radiological criteria. According to the study, carbonate ISL systems dissolved a higher percentage of radium, possibly increasing migration into nearby aquifers, while acidic ISL systems retained most of the radium in underground ore residues. The researchers emphasized that radioactive infiltration, tailings ponds, and spent ISL zones continue to pose long-term hazards even in locations where remediation has been successful.

According to research conducted in the South Texas uranium region in the United States, ISL deposits naturally enrich nearby soils and river sediments with uranium-related elements such as arsenic, molybdenum, selenium, vanadium, and chromium [8]. While some arsenic and vanadium concentrations exceeded environmental thresholds in Texas, uranium concentrations in soils ranged from 2.7 to 17.3 parts per million. Redistribution of uranium and related elements in nearby sediments and soils was shown to be primarily caused by wind erosion, groundwater movement, runoff, and leaching. The study highlighted that hydrogeological failures and uncontrolled migration of leachates can still lead to long-term environmental contamination, even though ISL has less impact on the surface than conventional mining.

Experimental studies have shown that microbial activity can significantly influence uranium immobilization in contaminated soils. In core leaching studies, the residual uranium fraction in biotic systems was significantly higher than in abiotic systems, indicating improved uranium retention due to microbial activity. These results suggest that, under appropriate geochemical conditions, soil bacteria can contribute to the long-term stabilization of uranium.

The reviewed studies demonstrated that soil contamination from ISL uranium mining is generally more localized than that from traditional uranium mining [8,14]. However, there are still significant environmental dangers in the vicinity of contaminated industrial

regions, restoration sites, wastewater leakage zones, and contaminated wells [4,39]. Acid ISL systems are linked to higher radionuclide mobility, more geochemical change, and more permanent contamination than alkaline carbonate systems, according to the analyzed research taken together [12,25]. Wind erosion and dust redistribution become particularly significant routes for radioactive transmission in dry and semi-arid climates. Long-term monitoring of soils, sediments, agricultural lands, and groundwater is still crucial since residual radionuclide pollution may continue for decades after mine closure, even though numerous studies have found that ISL is environmentally safer than open-pit mining [8,28].

3.3. Atmospheric Impacts of In Situ Leaching Uranium Mining

ISL uranium mining generally has a lower atmospheric impact than conventional open-pit and underground mining methods [8,9]. However, due to radon emissions, radioactive aerosols, dust transport, and gamma-ray anomalies near both active and abandoned mining areas, ISL operations continue to contribute to localized air pollution [38,39]. Along with radioactive aerosols and uranium-containing dust particles generated at processing plants, contaminated soils and waste storage sites, radon and its decay products have been found to be the main air pollutants associated with ISL activities [4,9]. A regional comparison of atmospheric contamination associated with ISL uranium mining is presented in Table 3.

Table 3. Regional comparison of atmospheric contamination associated with ISL uranium mining.

Country/ISL Site	Main Atmospheric Pollutants	Measured Levels/Concentrations	Main Findings	References
Kazakhstan—Shu–Sarysu uranium province	Radon, gamma radiation, radioactive dust	Radon: 1–191 Bq/m^3; gamma dose: 0.03–1.2 μSv/h	Near the ISL boreholes, radiation levels are mostly at background levels with isolated radon and gamma anomalies.	[4,38]
Uzbekistan—Navoi industrial region	Radon, radon progeny, LAN, radioactive aerosols	0.16–0.67 μSv/h; occupational dose: 5–8 mSv/year	The main sources of atmospheric pollution were industrial and buffer zones.	[39]
USA—South Texas ISL districts	Radon, radioactive aerosols, uranium-bearing dust	Not quantitatively specified	Radon has been identified as the main atmospheric risk associated with ISL activities.	[8,40]
China—Songliao, Ordos, Turpan–Hami and Ili Basins	Radon, radioactive dust, heavy metals	Elevated radionuclide and heavy metal contamination in mining areas	In arid areas, wind erosion has increased the airborne movement of contaminated dust and radionuclides.	[9,41]

According to studies conducted in Kazakhstan's Shu–Sarysu uranium district, atmospheric radiation levels near ISL deposits were often at natural background levels. While gamma dose rates typically ranged from 0.06 to 0.10 μSv/h, equilibrium radon equivalent volume activity (EEVA) ranged from 1 to 191 Bq/m^3. However, boreholes and localized anomalies were found near the deposit, where gamma emission rates reached 0.56–1.2 μSv/h. The existence of isolated radiation points suggests that residual contamination and radionuclide migration may continue around ISL sites, even though most measurements remain below the national radon limit of 200 Bq/m^3. The researchers also noted that these anomalous zones may be associated with secondary groundwater contamination and uranium remobilization [4,38].

Similar results were recorded in Uzbekistan, where ISL operations in the Navoi industrial sector were found to be significant sources of atmospheric radioactive contamination [39]. The main air pollutants were gamma radiation, radioactive aerosols, radon, and

long-lived alpha-emitting radionuclides. Measured equivalent dose rates ranged from 0.16 to 0.67 μSv/h, and the predicted annual occupational doses ranged from 5 to 8 mSv/year, which is less than the regulatory limit of 20 mSv/year for workers. The authors concluded that industrial facilities and buffer zones are the main sources of atmospheric pollution, suggesting that well-managed ISL operations can reduce regional atmospheric dispersion. However, old tailings ponds, contaminated industrial areas and associated landfills remain significant long-term sources of radioactive dust and aerosols [39].

According to research conducted in the South Texas uranium districts in the United States, radon is the primary air pollutant associated with ISL uranium mining. Because extensive excavation work is not conducted and the ore remains underground, ISL mining generates comparatively less dust than conventional mining. However, the production and transportation of uranium-containing resins and yellowcake products can still generate radioactive aerosols. Climatic factors such as stagnant air and semi-arid weather can also influence radon accumulation near ISL active areas. According to broader atmospheric studies [40,42], temperature, atmospheric pressure, wind, and other meteorological parameters significantly influence the transport, dispersion, and accumulation of radionuclides and radioactive aerosols in the air.

Chinese studies have shown that dust transport and wind erosion significantly contribute to air pollution near uranium mining sites, particularly in arid and semi-arid regions. In several uranium mining regions, wind dispersion and environmental migration of radionuclides and associated heavy metals from contaminated mining waste and radionuclide-enriched soils were found to be important contaminant transport pathways [9,41].

According to the reviewed literature, because ISL mining reduces blasting, excavation, ore processing, and waste rock generation, it generally results in less air pollution than traditional uranium mining. However, a number of significant environmental hazards still exist. Workers and surrounding communities may be exposed to localized radiation exposure due to radon emissions from boreholes, radioactive aerosol emissions during uranium processing, and wind-blown contaminated dust [38,39]. Strong winds and low precipitation increase dust transport and radioactive material redistribution in desert regions such as Kazakhstan, Uzbekistan, Mongolia, and northwest China, making these problems more serious [9]. The studies reviewed show that operating procedures, hydrogeological conditions, climate, and the effectiveness of remediation strategies all have a significant impact on air pollution at ISL facilities, varying by location.

3.4. Impacts of ISL Uranium Mining on Vegetation

The impacts of uranium mining at the ISL mine on vegetation remain largely unstudied compared to groundwater and hydrochemical impacts. However, existing research suggests that uranium mining at the ISL mine may impact vegetation through a number of interrelated mechanisms. These include the accumulation of heavy metals in plant tissue, soil contamination, acidification, radionuclide uptake, and atmospheric dust deposition. The primary pathways for plant contamination include uranium uptake by roots from contaminated soils and groundwater, as well as surface deposition of uranium-containing dust particles on leaves and stems [43]. Figure 1 shows the main pollution pathways and environmental impacts associated with ISL uranium mining.

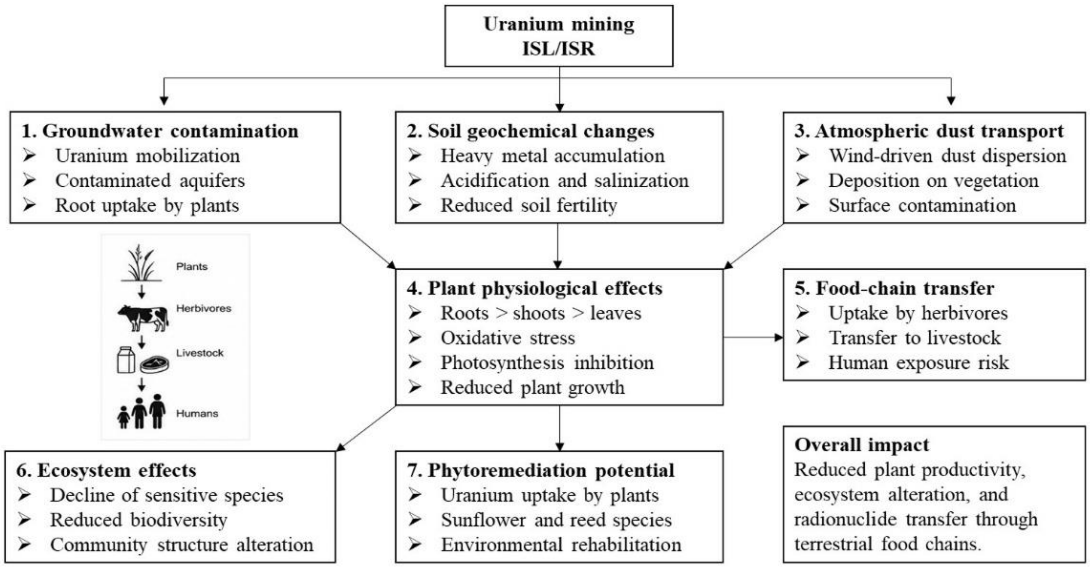


Figure 1. Potential pathways and ecological impacts of ISL uranium mining on vegetation.

Studies conducted in uranium mining areas in China have shown that wind erosion and airborne dust transport are important factors in the redistribution of uranium and associated heavy metals to nearby flora, particularly in arid and semi-arid climates [9]. High amounts of uranium, cadmium, chromium, lead, zinc, and copper were found in surface soil layers near uranium mining areas. These elements can subsequently be taken up by plants. According to studies, contaminated dust particles can travel several kilometers from contaminated waste storage areas and mining sites, increasing the likelihood of radioactive accumulation in grasses, shrubs, and crops growing near ISL sites.

Uranium accumulation in plants often follows a root-shoot-leaf pathway, suggesting that root tissues serve as the primary accumulation site, according to studies of uranium behavior in soil-plant systems [44]. Uranium uptake negatively impacts seed germination, root elongation, shoot growth, photosynthesis, and overall plant productivity [45]. In addition to causing chromosomal defects, elevated uranium concentrations can inhibit mitotic division in plant cells. Uranium toxicity negatively impacts plant growth, including seed germination, root development, photosynthesis, biomass production, and cell division processes [46].

According to research, acidic ISL systems can also have indirect effects on vegetation by significantly altering the geochemistry of soils and groundwater. Acid leaching increases salinity, promotes the mobilization of uranium and associated hazardous elements, and increases the acidity of nearby soils and groundwater systems [12,25]. Increased acidification, sulfate enrichment, and soil salinization can alter nutrient availability for plants and reduce soil fertility. Under such conditions, more metal-tolerant plant species may become dominant, while sensitive plant species may decline. Vegetation near other mining areas affected by heavy metal contamination and acid mine drainage exhibit similar biological responses.

Several studies have also highlighted the importance of radionuclide transfer through the food chain. Contaminated plants, through agricultural products and pasture systems, can act as a conduit for uranium and associated radionuclides to herbivores, animals, and ultimately humans. Plant properties, pH, organic matter content, and soil chemistry all significantly influence these transfer factors. Uranium bioavailability often increases in acidic environments, increasing its uptake by plants and causing environmental problems.

Using phytoremediation techniques, certain plant species can help clean up uranium-contaminated habitats. Radionuclides from contaminated water and soil can be taken up and immobilized by hyperaccumulator plants and aquatic species such as sunflower

(*Helianthus annuus*) and reed (*Phragmites australis*) [47,48]. Experiments have shown that, under controlled laboratory conditions, sunflower roots remove significant amounts of dissolved uranium from contaminated water. These results suggest that phytoremediation may be a useful complementary strategy for cleanup of uranium-contaminated areas surrounding ISL sites. However, plant species, uranium concentrations, soil chemistry, and climate significantly influence the effectiveness of remediation efforts.

Collectively, the conducted studies show that the impact of ISL operations on vegetation is primarily indirect and mediated by atmospheric dust transport, geochemical changes in soil, and groundwater contamination. The accumulation of radionuclides in plants and their movement through terrestrial food chains remains a serious environmental concern, even though ISL directly destroys fewer habitats than conventional mining. Therefore, it is crucial to monitor vegetation and pastures over long periods of time, especially in dry areas where dust is carried by the wind.

3.5. Impacts of ISL Uranium Mining on Biota and Ecosystems

Some biological and ecological reviews in this study are based on more general studies of uranium ecotoxicology and soil-plant-microbe interactions due to the lack of direct field studies of ecosystems surrounding active uranium mining sites using the ISL method. ISL uranium mining can harm not only habitats but also biota through contamination of groundwater, soils, sediments, and plants. Because the ore remains underground and surface excavation is reduced, ISL typically results in less severe environmental impacts than traditional open-pit and underground uranium mining [8,14]. However, contaminated dust, heavy metals, acidic sediment, and radionuclides can enter terrestrial and aquatic environments, posing long-term environmental threats to microbes, plants, invertebrates, livestock, and wildlife.

Microorganisms are crucial to ecological reactions to ISL contamination, as several studies have shown. Significant changes in groundwater microbial populations under acidic and metal-rich environments were found in Chinese studies of acid ISL systems in Xinjiang and Inner Mongolia [14,26]. The predominance of metal-tolerant and sulfate-reducing microbial communities, such as *Desulfosporosinus*, *Sulfobacillus*, *Pseudomonas*, and *Bacillus*, was encouraged by elevated concentrations of uranium, sulfate, iron, manganese, arsenic, cadmium, and chromium. By lowering soluble uranium species and encouraging mineral precipitation, these microbes may take part in natural attenuation processes and contribute to the biogeochemical cycle of uranium. Strong ecological adaptability to chemically harsh circumstances was demonstrated by the microbial communities linked to ISL systems, which resembled those in acid mine drainage environments, according to researchers.

Uranium pollution associated with mining can be particularly hazardous to aquatic habitats. Studies of uranium-contaminated freshwater systems have shown that uranium accumulates in organic matter, biofilms, macrophytes, and aquatic invertebrates; the highest amounts were found in leaf litter and macrophytes at contaminated sites [49]. Even at relatively low environmental uranium concentrations, pollution can alter the structure of aquatic communities and ecosystem functioning, as evidenced by reduced biodiversity and the predominance of pollution-tolerant taxa, such as chironomids, in contaminated areas.

In ISL-contaminated areas, microbial populations are critical for uranium mobility and natural degradation. Research has shown that under anaerobic conditions, sulfate-reducing bacteria, particularly Desulfovibrio species, can enzymatically convert soluble U(VI) to insoluble U(IV) uraninite, reducing uranium mobility in groundwater [50]. Environmental factors, particularly pH, sulfate, nitrate, and heavy metal concentrations, significantly influence the efficiency of uranium bioprecipitation. While nitrate acted as a powerful inhibitor, maintaining oxidizing conditions that were detrimental to sulfate-reducing bac-

teria, acidic conditions significantly reduced the microbial reduction of uranium. The study highlighted the importance of microbial processes for bioremediation and natural mitigation of uranium-bearing groundwater contamination associated with ISL mining.

Collectively, research suggests that the primary cause of environmental impacts from ISL uranium mining is hydrogeochemical contamination, rather than direct habitat destruction. Because acidic conditions increase radionuclide mobility, metal bioavailability, and geochemical instability, acid leach systems typically result in more severe environmental problems [12,25]. Long-term environmental monitoring of aquatic systems, soils, microorganisms, vegetation, livestock, and wildlife is critical, as residual contamination and radionuclide migration can persist for decades after mine closure, even though ISL uranium mining is generally considered more environmentally friendly than conventional uranium mining.

3.6. Strategies for the Remediation and Restoration of Uranium-Contaminated Sites

Following ISL uranium mining, remediation of uranium-contaminated sites remains a significant concern. Effective remediation typically requires physical, chemical, and biological methods tailored to the site's hydrogeological and environmental parameters. There is no single remediation approach suitable for all situations, as contamination can impact soil, sediment, plants, groundwater, and ecosystems [28,34].

Groundwater remediation often utilizes pump and treatment systems, groundwater flushing, ion exchange, reverse osmosis, and permeable reactive barriers to limit contaminant migration and reduce radionuclide mobility [28,29,34]. In addition, the use of reactive transport and observed natural attenuation modeling has increased to assess long-term remediation success and predict the evolution of groundwater chemistry under different hydrogeological conditions [11,35]. Furthermore, studies have shown that uranium immobilization can be facilitated by the inherent reductive capacity of host geological formations, which reduces the need for long-term active remediation [30,31].

Biological remediation methods are of increasing interest as additional recovery options. Enzymatic reduction and biomineralization mechanisms can facilitate the conversion of soluble U(VI) to less mobile U(IV) forms through biostimulation of local microbial communities [14,50]. The inclusion of electron donors such as acetate, lactate, or formate, which stimulate the growth of metal- and sulfate-reducing bacteria responsible for uranium immobilization, can enhance the effectiveness of these methods. However, successful implementation requires long-term monitoring of microbiological activity and groundwater quality, as well as careful characterization of the hydrogeochemical state.

Excavation of highly contaminated materials, engineered covers, containment systems, dust suppression, and land remediation methods are examples of methods for remediating contaminated soils and surface environments [8,39]. Another sustainable remediation option that has been studied is phytoremediation. Some plant species have been shown to accumulate or fix uranium and related contaminants, which may reduce their mobility in contaminated habitats [47,48]. In arid and semi-arid areas, restoration of vegetation can reduce wind erosion and the redistribution of contaminated particles in the atmosphere, in addition to removing contaminants.

In general, successful remediation of uranium-contaminated sites requires a combination of engineering controls, hydrogeological management, biological remediation procedures, and long-term environmental monitoring. Adaptive management and post-closure monitoring programs are critical, as residual contamination can persist for decades after mine closure, despite significant advances in cleanup technologies [28,35].

4. Discussion

Evaluated studies show that because ISL uranium mining minimizes large-scale excavation and keeps the ore underground, it generally results in less direct surface impact than traditional uranium mining. Despite these advantages, ISL operations can still have significant long-term negative environmental impacts, particularly when it comes to radionuclide migration and groundwater contamination.

The studies reviewed demonstrate that hydrogeological and geochemical conditions significantly influence the environmental impacts of uranium mining. The persistence of groundwater contamination suggests that lower impacts on surface waters do not necessarily translate into lower long-term environmental risks, despite the fact that ISL is often viewed as a less efficient alternative to conventional mining. Specifically, radionuclide mobility, aquifer acidification, and recovery difficulties were consistently higher in acidic ISL systems than in alkaline ones. These results suggest that post-closure groundwater management and hydrogeological isolation are important factors influencing the overall environmental sustainability of ISL operations.

Groundwater has been found to be the most vulnerable environmental element impacted by ISL mining. Injecting acidic or alkaline leach solutions mobilizes uranium, radium, sulfates, selenium, iron, and other hazardous elements, altering the geochemistry of the aquifer. Due to increased acidification, sulfate enrichment, and contaminant mobility, the studies reviewed consistently demonstrate that acidic ISL systems cause more severe environmental impacts than alkaline systems.

Groundwater movement, oxidation–reduction processes, mineral composition, and hydrogeological variables all significantly influence how radionuclides behave in the environment. Although uranium migration can be limited by natural attenuation and reductive immobilization, fully restoring groundwater levels to pre-mining levels often remains challenging. After mining ceases, residual contamination can persist for many years or decades.

The reviewed literature also shows that the impact of ISL is not limited to groundwater systems. Secondary pathways for radioactive material transfer may include contaminated soils, sediments, vegetation, biota, and airborne dust. Wind erosion and dust transport play a significant role in the redistribution of heavy metals and radioactive particles in arid and semi-arid regions.

Rather than directly destroying habitats, the environmental impacts of mining are primarily indirect and related to hydrogeochemical pollution. The accumulation of radionuclides and associated metals in plants, microbes, aquatic organisms, livestock, and wildlife can impact food chains and ecosystem functioning. Furthermore, microbial populations significantly influence uranium immobilization and natural degradation processes.

While far fewer studies address long-term ecological responses, radionuclide transfer through food webs, and ecosystem recovery after mine closure, most existing studies focus on groundwater contamination and hydrogeochemical processes. This limitation highlights the need for more comprehensive ecosystem-based monitoring methods and limits our ability to fully assess the environmental impacts of ISL uranium mining.

Overall, the studies reviewed demonstrate that ISL uranium mining represents a compromise between the long-term risk of hydrogeochemical contamination and reduced surface impact. Although ISL is generally considered more environmentally friendly than traditional uranium mining, long-term monitoring, improved reclamation methods, and effective groundwater management are still needed to reduce environmental impacts. The persistence of residual contamination and complex hydrogeochemical processes make it difficult to fully restore contaminated aquifers and ecosystems, despite the development of a number of solutions for their restoration.

5. Conclusions

While the ore remains underground and the volume of excavation is reduced, this review demonstrates that ISL uranium mining generally results in less direct surface damage than traditional uranium mining methods. Despite these advantages, ISL activities can still have significant negative environmental impacts due to groundwater contamination, radionuclide migration, soil and sediment contamination, atmospheric transport of radioactive dust, and biological disturbances.

According to research, groundwater is the environmental component most susceptible to ISL-related contamination. Due to increased acidification, sulfate enrichment, and mineral dissolution, acidic ISL systems typically result in more intense hydrogeochemical alterations and greater contaminant mobility than alkaline carbonate systems. Restoring groundwater systems to pre-mining conditions is often challenging, as residual radionuclides and dissolved contaminants can persist for many years after mining ceases, even though natural attenuation and remediation procedures can partially reduce contamination levels.

The reviewed literature also shows that the migration of radionuclides along interconnected ecological pathways can impact soil, vegetation, microorganisms, aquatic life, livestock, and wildlife. Wind erosion and airborne dust transport are important mechanisms for the redistribution of radioactive particles and associated heavy metals in arid and semi-arid regions.

Overall, ISL uranium mining represents a trade-off between reduced surface disturbance and long-term hydrogeochemical and ecological risks. Effective hydrogeological control, long-term environmental monitoring, and improved remediation technologies remain crucial to reduce environmental impacts and ensure sustainable growth of uranium mining at the ISL deposit. Future research should focus on integrated hydrogeochemical and environmental assessment methods, radionuclide behavior in biological systems, and long-term ecosystem responses.

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Abbreviations

The following abbreviations are used in this manuscript:

ISL	In situ leaching
USSR	Union of Soviet Socialist Republics
USA	United States of America
TDS	Total dissolved solids

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