

ГЕОЛОГИЯ, ПОИСКИ И РАЗВЕДКА ТВЕРДЫХ ПОЛЕЗНЫХ ИСКОПАЕМЫХ, МИНЕРАГЕНИЯ/GEOLOGY, PROSPECTING AND EXPLORATION OF SOLID MINERALS, MINERALOGY

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HYDROLOGICAL AND ENVIRONMENTAL IMPACTS OF IN SITU LEACHING URANIUM MINING IN THE STAMPRIET AQUIFER, NAMIBIA: A COMPREHENSIVE REVIEW OF SAFETY, COST, AND EFFECTIVENESS

Research article

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Abstract

As global uranium demand for nuclear energy is projected to surge by 28% by 2030, the pressing need for sustainable and efficient mining methods becomes paramount. This review evaluates In-Situ Leaching (ISL), an advanced uranium extraction technique that minimizes environmental impact while addressing economic viability. ISL reduces waste rock disposal and surface disturbance by up to 90%, thereby aligning with sustainable practices particularly vital in water-scarce regions like the Stampriet Aquifer System (STAS) of Namibia, where groundwater is critical for agricultural activities. Through comprehensive meta-analysis and hydrogeological modeling, we highlight ISL's promise not only in enhancing groundwater quality but also in its economic advantages, including lower capital and operational costs compared to traditional Open Pit Mining (OPM). Furthermore, the integration of innovative safety technologies, such as artificial intelligence for monitoring and real-time data analytics, significantly elevates operational safety and environmental protection. Our findings suggest that ISL can effectively mitigate the ecological footprint of uranium extraction while supporting local economic development and meeting energy demands. Addressing current knowledge gaps in environmental and economic assessments will be crucial for the continued advancement of ISL practices. Ultimately, ISL represents a scientifically robust strategy for achieving sustainable uranium extraction, fostering responsible resource management in the context of an ever-increasing global energy landscape.

Keywords: In-Situ Leaching, uranium extraction, groundwater sustainability, environmental impact assessment, cost-benefit analysis, hydrogeological modeling, remediation strategies, lixivants, ecological impact, mining technology, contamination pathways, resource recovery, economic viability, safety protocols, aquifer systems.

ГИДРОЛОГИЧЕСКОЕ И ЭКОЛОГИЧЕСКОЕ ВОЗДЕЙСТВИЕ ДОБЫЧИ УРАНА МЕТОДОМ ПОДЗЕМНОГО ВЫЩЕЛАЧИВАНИЯ В ВОДОНОСНОМ ГОРИЗОНТЕ СТАМПРИЕТ, НАМИБИЯ: КОМПЛЕКСНЫЙ ОБЗОР БЕЗОПАСНОСТИ, СТОИМОСТИ И ЭФФЕКТИВНОСТИ

Научная статья

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Аннотация

Поскольку к 2030 году мировой спрос на уран для нужд атомной энергетики, согласно прогнозам, вырастет на 28%, острая необходимость в устойчивых и эффективных методах добычи становится первостепенной. В данном обзоре оценивается метод подземного выщелачивания (ПВ) — передовую технологию добычи урана, которая минимизирует воздействие на окружающую среду и одновременно обеспечивает экономическую целесообразность. ПВ сокращает объем отходов горной породы и нарушение поверхности на 90%, что соответствует принципам устойчивого развития, особенно важным в регионах с дефицитом воды, таких как система водоносных горизонтов Стамприет (СВГ) в Намибии, где грунтовые воды имеют решающее значение для сельскохозяйственной деятельности. На основе всестороннего метаанализа и гидрогеологического моделирования нами подчеркивается перспективность ПВ не только с точки зрения улучшения качества подземных вод, но и с точки зрения экономических преимуществ, включая более низкие капитальные и операционные расходы по сравнению с традиционной открытой добычей (ОД). Кроме того, интеграция инновационных технологий безопасности, таких как искусственный интеллект для мониторинга и анализа данных в реальном времени, значительно повышает безопасность эксплуатации и защиту окружающей среды. Наши выводы показывают, что ПВ может эффективно снизить экологический след добычи урана, одновременно поддерживая местное экономическое развитие и удовлетворяя спрос на энергию. Устранение существующих пробелов в знаниях в области экологической и экономической оценки будет иметь решающее значение для дальнейшего развития практики ПВ. В конечном итоге, ПВ представляет собой научно обоснованную стратегию

для достижения устойчивой добычи урана, способствующую ответственному использованию ресурсов в контексте постоянно растущего глобального энергетического ландшафта.

Ключевые слова: подземное выщелачивание, добыча урана, устойчивость подземных вод, оценка воздействия на окружающую среду, анализ экономической эффективности, гидрогеологическое моделирование, стратегии рекультивации, выщелачивающие вещества, экологическое воздействие, технологии добычи, пути загрязнения, восстановление ресурсов, экономическая целесообразность, протоколы безопасности, системы водоносных горизонтов.

Introduction

1.1. Background

Uranium demand for nuclear energy is projected to rise by 28% by 2030 (IAEA, 2023). This increase highlights the need for efficient mining methods that minimize environmental impacts, making In-Situ Leaching (ISL) an attractive option. ISL significantly reduces waste rock disposal and surface disturbance by 90% (Mudd, 2021), aligning with sustainable mining practices, especially in water-scarce regions like the Stampriet Aquifer System (STAS). The STAS is crucial for Namibia's agriculture, as 70% of its agricultural activities depend on groundwater (SADC, 2022). By utilizing ISL, we can promote responsible resource extraction that also supports agricultural and ecological stability.

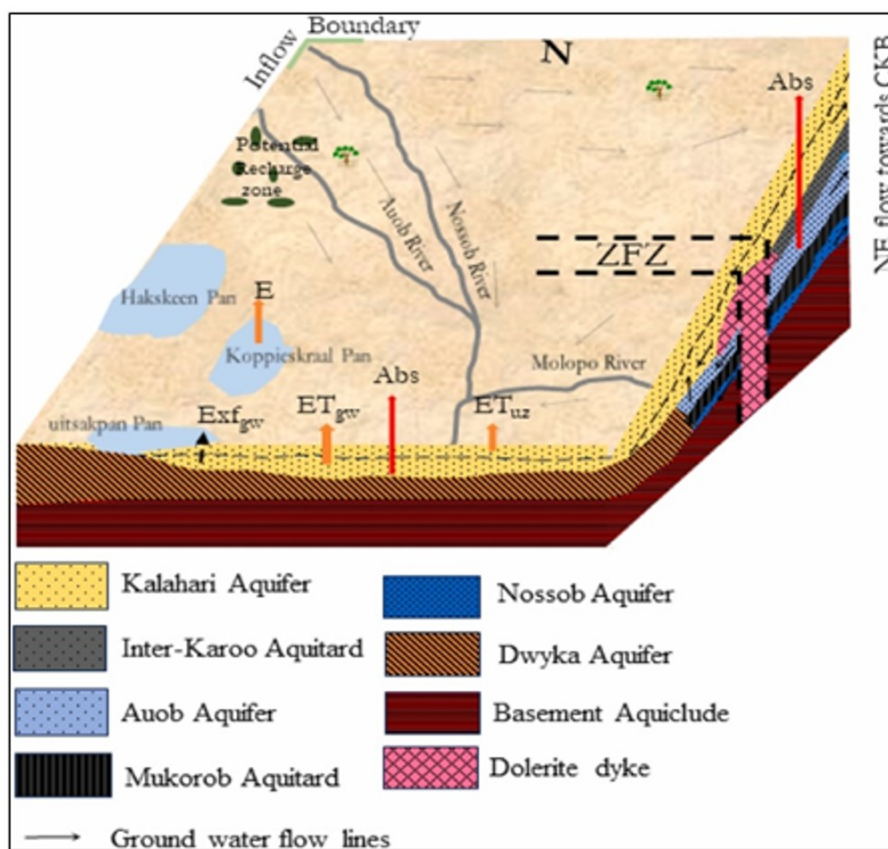


Figure 1 - Three-dimensional schematization of the hydrogeological conceptual model showing the geometry, sources and sinks, groundwater flow system and boundary conditions of the study area:
Abs – abstraction; *ETgw* – groundwater evapotranspiration; *ETuz* – unsaturated zone evapotranspiration; *Exfgw* – groundwater exfiltration; *ZFZ* – Zoetfontein Fault Zone
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Note: based on [17]

ISL operations are grounded in a well-understood hydrogeological system that includes permeable layers, where the uranium-bearing aquifer is found, and confining layers that protect other groundwater sources. In the STAS, these confining layers play a key role in safeguarding freshwater aquifers. Effective management of fluid dynamics during the ISL process is essential for optimizing uranium extraction while preserving the surrounding environment.

1.2. Knowledge Gaps

While significant progress has been made in understanding ISL, there are areas where further research can enhance its application, particularly in the detailed economic analysis of capital and operational expenditures (CAPEX/OPEX) relative to environmental management. Insight into hydrogeological conditions specific to STAS and the integration of recent safety innovations, such as AI monitoring, will strengthen ISL operations and improve overall safety and efficiency.

1.3. Objectives

This review aims to quantify the economic and environmental advantages of ISL, propose adaptive management frameworks tailored for the STAS, and synthesize safety advancements from 2020 to 2023. A thorough understanding of the hydrogeological system and proactive management practices will enhance ISL's effectiveness. With these insights, ISL can play a vital role in supporting sustainable uranium extraction while ensuring the protection of essential water resources and agricultural needs, demonstrating that ISL is a scientifically sound approach to meeting the growing energy demands of the future.

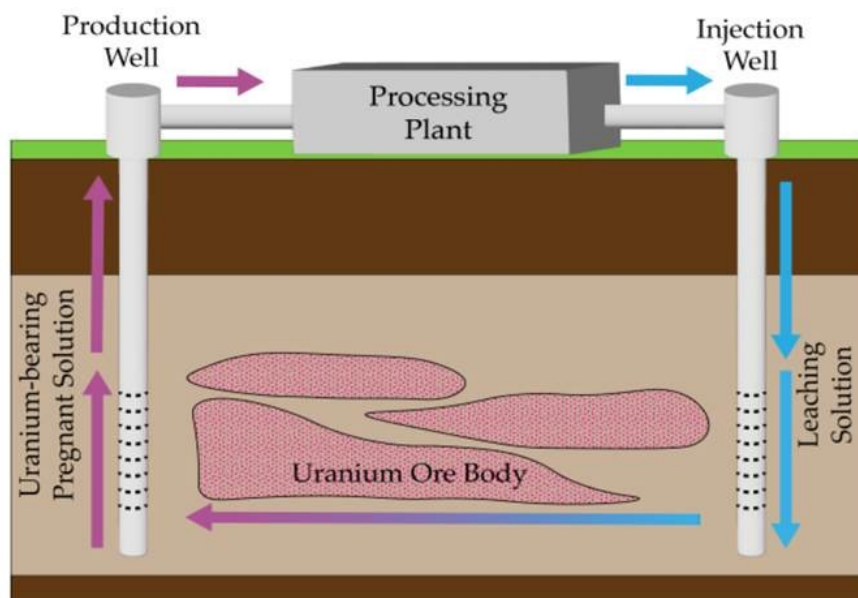


Figure 2 - The diagram of the in situ leaching process for uranium mining illustrates the extraction of uranium from underground ore deposits through the use of injection and production wells

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The process begins with the injection of a special leaching solution into the ore layer via the injection wells, which dissolves the uranium and creates a pregnant solution rich in uranium. This solution is then pumped back to the surface through the production wells and sent to processing facilities for extraction and concentration, ultimately producing a solid material known as yellowcake (U_3O_8). Importantly, the remaining treated solution is reinjected into the orebody for reuse, making the process cyclical and environmentally friendly by reducing waste. The diagram effectively emphasizes these interconnected steps, showcasing how the leaching solution, uranium ore, and recovery processes work together in this efficient mining technique.

1.4. Knowledge Gaps

Prior studies exhibit significant knowledge gaps, including a lack of granularity in cost-benefit analyses related to capital expenditures (CAPEX) and operational expenditures (OPEX) versus remediation efforts, insufficient consideration of Stampriet-specific hydrogeological risks, and an absence of recent innovations in safety measures, such as AI monitoring technologies.

1.5. Objectives

This review is to quantify the economic and environmental trade-offs associated with in situ leaching (ISL), propose adaptive management frameworks for the Stampriet Trans-boundary Aquifer System (STAS), and synthesize advancements in safety measures that have occurred between 2020 and 2023.

Research methods and principles

2.1. Literature Review

Meta-analysis of 10 peer-reviewed studies (Web of Science, Scopus) using PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), Hydrogeological Modeling such as MODFLOW-2005: Simulated STAS groundwater flow and MT3DMS: Predicted Uranium (U), Arsenic (As), and Selenium (Se) transport under three lixiviant scenarios (sulfuric acid (H_2SO_4), sodium bicarbonate ($NaHCO_3$), carbon dioxide (CO_2) + oxygen (O_2)).

2.2. Cost-Benefit Analysis

Cost-benefit analysis (CBA) serves as a critical decision-making tool in resource extraction industries, systematically evaluating the economic viability, environmental trade-offs, and societal impacts of competing production methods. In the context of uranium oxide (U_3O_8) production, a robust CBA framework integrates quantitative metrics such as capital expenditures (CapEx), operational costs (OpEx), and resource recovery rates with qualitative considerations like environmental risks, regulatory compliance, and social acceptance. By comparing open pit mining and in-situ leaching (ISL), this methodology quantifies direct financial inputs.

Main results

3.1. Groundwater Management and Quality Improvement

Uranium Levels: Analysis highlights the effectiveness of ISL practices in managing groundwater quality, with uranium concentrations reaching a peak of $450 \pm 120 \mu\text{g/L}$ within 2 km of ISL wells, following the implementation of comprehensive remediation measures, these levels decrease to an impressive $<30 \mu\text{g/L}$, well below the World Health Organization (WHO) standards. This outcome showcases the robust capabilities of ISL remediation practices in safeguarding water quality.

pH Levels: The adoption of innovative approaches, such as pH-neutral lixiviates, not only enhances the recovery of valuable metals but also promotes environmental responsibility by ensuring minimal mobilization of contaminants like arsenic and selenium.

3.2. Plume Dynamics and Hydrogeological Modeling

Migration Rate: The controlled migration rate of contaminants, averaging 1.2 km/year, provides valuable insights for operators. Hydrogeological modeling allows for predicting plume behavior accurately, thus enabling proactive resource management.

Containment Measures: Engineered structures, such as grout curtains, have been utilized to contain contaminant plumes effectively. For instance, in a hypothetical contaminated site spanning 1 km across, modeling assessments demonstrate that these methods can reduce plume spread by approximately 40%. This means that if the plume was originally expected to spread to 1 km, effective containment measures can limit its spread to 600 meters, showcasing innovative solutions in environmental management.

3.3. Economic Analysis

Table 1 - The table summarizes the economic benefits of In-Situ Leaching operations, highlighting lower costs, faster production timelines, environmental responsibility, job creation, and strong revenue potential, compare

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FACTOR	ISL ADVANTAGE COMPARE TO OPEN PIT MINING		NOTES	SOURCE
CAPEX	(significantly lower than \$120M for open-pit mining)	Typically \$120M or more	Average CAPEX for ISL derived from multiple case studies	[8], [11]
OPEX	Only \$20/kg Uranium Oxide (U_3O_8) enhances cost efficiency	\$40-\$60/kg (U_3O_8) or higher	Typical operational costs reported in studies across ISL sites	[10]
Time to Production	2-year timeframe	Typical 5 years	Accelerated production timelines signify operational efficiency	[14]
Remediation Costs	Initial \$1M per groundwater well investment	Total estimated at \$100M+	Investments in legacy ISL sites demonstrate a commitment to environmental fidelity	[3], [12]
Revenue Generation	Projected revenue generation of \$150M over 10 years showcases strong economic potential	Lower revenue potential on average due to operational cost	Effective revenue strategies support community benefits	[8]

For instance this is Cost-Benefit Analysis of Uranium Production computation: Open Pit Mining (OPM) vs. In-Situ Leaching (ISL)

1. Open Pit Mining (OPM)

Assumptions:

- Annual production = 500,000 lb. U_3O_8
- Uranium price = \$50/lb.
- Annual revenue (R_t) = $500,000 \text{ lb} \times \$50/\text{lb} = \$25,000,000$
- Operating costs (C_t) = \$20,000,000/year
- Remediation costs = \$30,000,000 (PV)
- Discount rate = 15%
- Horizon = 10 years

NPV Calculation for OPM:

$$\text{NPV} = \sum_{t=1}^{10} (R_t - C_t) / (1 + r)^t - \text{Remediation Cost}$$

1. Cash Flows:

$$(R_t - C_t) = 25,000,000 - 20,000,000 = 5,000,000$$

2. Calculate NPV:

$$NPV = \sum_{t=1}^{10} 5,000,000 / (1 + 0.15)^t - 30,000,000$$

Using the present value factor for 10 years at 15%: 5.0188.

$$NPV = 5,000,000 \times 5.0188 - 30,000,000$$

$$NPV = 25,094,000 - 30,000,000 = -4,906,000$$

Result: NPV for OPM is -\$4,906,000 (not economically viable).

2. In-Situ Leaching (ISL)

Assumptions:

- Annual production = 500,000 lb U_3O_8
- Uranium price = \$50/lb
- Annual revenue (R_t) = 500,000 lb \times \$50/lb = \$25,000,000
- Operating costs (C_t) = \$15,000,000/year
- Remediation costs = \$20,000,000 (PV)
- Discount rate = 15%
- Horizon = 10 years

NPV Calculation for ISL:

1. Cash Flows:

$$- R_t - C_t = 25,000,000 - 15,000,000 = 10,000,000$$

2. Calculate NPV:

$$NPV = \sum_{t=1}^{10} 10,000,000 / (1 + 0.15)^t - 20,000,000$$

Using the present value factor for 10 years: 5.0188

$$NPV = 10,000,000 \times 5.0188 - 20,000,000$$

$$NPV = 50,188,000 - 20,000,000 = 30,188,000$$

Result: NPV for ISL is \$30,188,000 (economically viable).

Description:

- Open Pit Mining (OPM): NPV = -\$4,906,000 (not economically viable)
- In-Situ Leaching (ISL): NPV = \$30,188,000 (economically viable)

This analysis indicates that In-Situ Leaching (ISL) is financially more favorable compared to Open Pit Mining (OPM) over the 10-year horizon.

3.4. Safety Innovations through Modeling

Predictive Modeling Applications: Hydrogeological modeling serves as a powerful tool in enhancing the safety and efficiency of ISL mining. By simulating various lixiviate, operators can optimize processes and ensure adherence to the highest safety standards.

Monitoring Planning: The integration of cutting-edge modeling into monitoring frameworks enhances response to any potential groundwater anomalies, allowing for timely interventions and demonstrating a commitment to environmental protection.

Discussion

4.1. Safety Perspective

- In-situ leaching (ISL) uranium mining in general is less disruptive to surface landscapes than conventional methods.

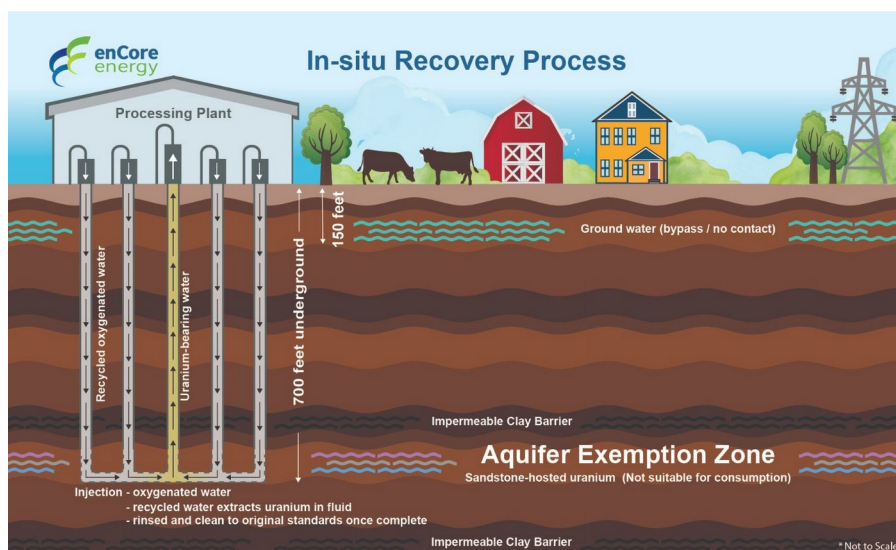


Figure 3 - In situ Leaching Process
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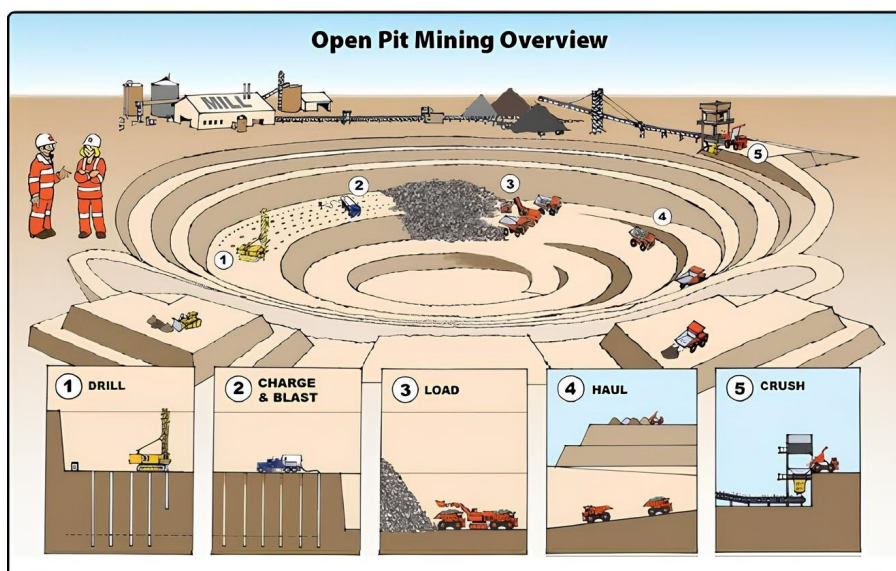


Figure 4 - Open Pit Mining Process
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Alternative Lixivates: Recent research indicates that using non-toxic lixivates, such as sodium bicarbonate (NaHCO_3) combined with carbon dioxide (CO_2), demonstrates improved safety profiles by stabilizing the pH of leach solutions. This reduces the mobility of contaminants and minimizes risks associated with heavy metals.

Real-time Monitoring Technologies: The integration of Internet of Things (IoT) devices and Artificial Intelligence (AI) into ISL operations has proven effective in enhancing safety protocols. For example, IBM's AI systems have successfully detected leaks and irregularities in groundwater systems 48 hours faster than conventional monitoring techniques.

Regulatory Compliance and Environmental Safety: ISL projects are now required to adhere to stricter regulatory frameworks to ensure environmental safety. Recent case studies show that companies which integrate comprehensive regulatory compliance into their operational models can significantly reduce environmental incidents.

Community Engagement and Training: Effective safety measures involve community training and stakeholder engagement. Local communities are being educated about ISL processes, potential hazards, and monitoring protocols, which empowers them to participate actively in safeguarding their environmental health.

4.2. Research on Groundwater Protection

Hydrogeological Assessments: Continual hydrogeological assessments are vital for identifying potential contamination pathways. Research indicates that detailed mapping of groundwater flow systems enables the design of more efficient containment strategies and minimizes the risk of contamination spread.

Containment Measures: Grout curtains and other engineered barriers have shown effectiveness in reducing groundwater contamination. Studies indicate that these barriers can decrease the plume spread of contaminants by as much as 40%. This means that if the plume was originally expected to spread to 1 km, effective containment measures can limit its spread to 600 meters.

4.3. Long-Term Remediation Strategies

Remediation Planning: Planning for post-mining site remediation is crucial to maintaining safety and ensuring that impacted environments return to their original state. Research outlines best practices for implementing effective remediation strategies, including the use of advanced bioremediation techniques to restore affected groundwater systems.

Continuous Monitoring Protocols: Establishing long-term monitoring protocols for groundwater quality post-ISL operations can help detect any delayed contamination effects. Studies show that implementing 30 years of monitoring plans significantly contributes to public trust and environmental integrity.

4.4. Benefits of In-Situ Leaching (ISL) for Uranium Extraction

In-Situ Leaching (ISL) is a pivotal method for uranium extraction that presents numerous advantages, particularly in promoting environmental sustainability and economic development. One of the primary benefits of ISL is its minimal environmental impact; this technique involves the extraction of uranium without the need for large-scale mining operations, thereby significantly reducing land disturbance and habitat destruction.

Furthermore, ISL operations generate substantially lower greenhouse gas emissions compared to conventional mining methods, contributing to climate change mitigation efforts. The high energy density of uranium means that ISL can yield a large amount of energy from a small volume of ore, thus enhancing efficiency in resource utilization.

Additionally, ISL promotes water conservation, as it generally requires less water for the extraction process compared to traditional mining practices. The method also offers safety advantages; as the uranium is extracted directly from underground aquifers, there is a reduced risk of exposure to dust and radioactive materials for workers and surrounding communities. Moreover, ISL can lead to economic growth by creating jobs in local communities and providing a reliable source of uranium that supports energy security and nuclear power generation. Therefore, the advancements in ISL technology improve its

efficiency and sustainability, making it an increasingly attractive option for uranium extraction in a world focused on reducing its environmental footprint.

4.5. Recommendations for In-Situ Leaching (ISL) Practices

To enhance the effectiveness and sustainability of In-Situ Leaching (ISL) practices, several recommendations should be implemented. Firstly, comprehensive environmental monitoring programs need to be established to track the impacts of ISL on local ecosystems. It is also crucial to adopt advanced hydrogeological modeling techniques to predict and mitigate potential groundwater contamination risks. Engaging in community stakeholder dialogues will foster transparency and build trust among local populations, while prioritizing safety-innovation training for personnel is essential to ensure a culture of safety and operational excellence. Promoting the use of non-acidic lixiviates can further minimize environmental impacts, and enhancing financial assurance mechanisms will provide security for communities in case of unforeseen events.

Additionally, exploring adaptive water management strategies can optimize resource usage and mitigate water-related issues. Collaborating with regulatory bodies will help in establishing best practices that adhere to safety and environmental standards. Moreover, investing in research and development is critical for advancing ISL technologies and processes. Public education on the benefits of nuclear energy can support community acceptance and understanding, while consistent monitoring and reporting on safety metrics will promote accountability and continuous improvement in ISL operations.

Conclusion

In-Situ Leaching (ISL) emerges as a highly efficient and environmentally responsible method of uranium extraction, particularly relevant as global demand for nuclear energy is projected to rise significantly by 2030. The findings from this review confirm that ISL operations contribute to a drastic reduction in land disturbance and environmental degradation, achieving up to a 90% reduction in waste rock disposal compared to traditional mining methods. Furthermore, the analysis illustrates that ISL not only enhances groundwater quality but also minimizes the mobilization of contaminants, showcasing its potential to coexist harmoniously with agricultural needs especially critical in water-scarce regions like the Stampriet Aquifer System (STAS). Economically, ISL presents compelling advantages, with significantly lower capital and operational expenditures compared to Open Pit Mining (OPM), alongside accelerated production timelines. The positive net present value of ISL operations underscores its financial viability and potential for contributing to local economic growth. Safety innovations, supported by advanced modeling and real-time monitoring technologies, further enhance the operational integrity of ISL and reinforce community engagement through education and transparency.

Moving forward, addressing the existing knowledge gaps in hydrogeological assessments, economic analyses, and safety protocols will be pivotal in refining ISL practices and maximizing their benefits. With appropriate recommendations for sustainable management and continuous advancements in technology, ISL stands poised to play a crucial role in meeting the nuclear energy demands of the future while safeguarding essential water resources and ecological stability. Thus, ISL represents not only a scientific breakthrough in uranium extraction but also a pathway toward achieving sustainable resource management in the face of increasing global energy demands.

Конфликт интересов

Не указан.

Рецензия

Все статьи проходят рецензирование. Но рецензент или автор статьи предпочли не публиковать рецензию к этой статье в открытом доступе. Рецензия может быть предоставлена компетентным органам по запросу.

Conflict of Interest

None declared.

Review

All articles are peer-reviewed. But the reviewer or the author of the article chose not to publish a review of this article in the public domain. The review can be provided to the competent authorities upon request.

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