Global Accidents in Solution Mining: Causes, Mechanisms, Consequences and Lessons Learned

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ABSTRACT

Original Research Article

Solution mining has expanded globally as an alternative to conventional mining for salt, potash, trona, lithium brines, sulfur, and uranium; however, it is inherently associated with geotechnical, hydrogeological, and environmental risks. This review critically examines major global accidents in solution mining, focusing on failure mechanisms, root causes, and consequences. Drawing on a systematic analysis of peer-reviewed literature, regulatory reports, and documented industrial incidents, the review classifies accidents into geomechanical failures (cavern collapse and subsidence), well integrity failures, uncontrolled brine migration, groundwater contamination, and operational or regulatory deficiencies. Representative case studies from North America, Europe, Asia, and South America highlight recurring patterns and region-specific challenges. The review shows that inadequate cavern design, insufficient monitoring, geological heterogeneity, and weak regulatory oversight are the dominant contributors to severe accidents. Environmental impacts often include irreversible aquifer salinization, land subsidence, and long-term social and economic damage. Finally, the paper discusses lessons learned, advances in monitoring and risk assessment technologies, and future research needs, providing a comprehensive framework to improve the safety, sustainability, and governance of solution mining operations worldwide.

Keywords: Solution mining, Mining accidents, Cavern collapse, Brine leakage, Groundwater contamination, In-situ leaching, Geomechanical failure, Environmental risk.

Highlights

- Reviews major global accidents in solution mining across commodities and regions.
- Identifies geomechanical, hydrogeological, and well-integrity failures as dominant accident mechanisms.
- Demonstrates the role of design, monitoring, and regulatory gaps in severe incidents.
- Discusses the environmental, social, and economic consequences of solution-mining failures.
- Proposes lessons learned and preventive strategies to enhance operational safety and sustainability.

Graphical Abstract

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Introduction

Solution mining involves extracting materials by dissolving them in situ and pumping the pregnant solution to the surface for processing. This review broadly covers evaporites, soluble salts (e.g., halite, potash, trona), salt-cavern creation, lithium brines, uranium in situ leaching (ISL), and the Frasch sulfur process—showing the common subsurface fluid-driven recovery method (Jeremic, 2020; Xu et al., 2024; Yi et al., 2023).

Solution mining's global relevance stems from two ongoing drivers. First, some strategic commodities naturally occur with soluble deposits or brines, making fluid-based extraction attractive. Second, it can reduce surface-operation impacts, enable continuous production, and support underground storage (Yi et al., 2023; Zhang et al., 2023). However, these benefits come with risks that differ from traditional open-pit and underground mining. The system is highly interconnected: hydrogeology, dissolution, cavern stability, and surface deformation evolve together, and small operational deviations can lead to large geotechnical issues (Duffy et al., 2022; Jeremic, 2020; Zhang et al., 2021).

Compared with traditional mining, solution mining concentrates risks in failure modes that are often spread out in space and depend on time. These include progressive irregularities in cavern shape, roof instability, brine migration or leakage, and surface subsidence that may lead to sinkholes. Recent studies and field analyses show how these interconnected processes can create complex deformation patterns and damage infrastructure, especially in heavily populated areas (Busetti, 2024; Chen et al., 2025; Minkley et al., 2025; Zhang et al., 2025; Zhang, Li, et al., 2024). Monitoring and early warning are therefore essential, with satellite interferometry, GNSS, UAV data, and fiber-optic sensing increasingly used to enhance detection sensitivity and improve decision-making time (Chen, Yu, et al., 2021; Fan et al., 2021; Gutierrez et al., 2023; Intrieri et al., 2023; Zhao, Yang, et al., 2023; Zhu et al., 2024).

This review is motivated by practical concerns. Accident analyses in mining show that severe outcomes often stem from compound hazards, organizational blind spots, and delayed recognition. These themes are relevant to solution mining, where early instability signs are subtle and diffuse (Al Heib & Franck, 2024; Agarwal et al., 2025; Valluru et al., 2020; Zeqiri et al., 2022). Post-event salt and evaporite studies also show how induced and microseismic activity can serve as warnings and reveal the development of failure (Contrucci et al., 2023; Namjesnik et al., 2021; Ni et al., 2026).

This review aims to (i) define solution-mining methods and contexts; (ii) synthesize accident mechanisms, focusing on subsidence, sinkholes, cavern instability, and fluid migration; (iii) evaluate monitoring and warning tools and their limits; and (iv) discuss risk management and prevention for operators and regulators (Bastida, 2020; Warhurst & Noronha, 2024). The scope is cross-commodity since similar physical mechanisms occur in salt, potash, trona, brines, and ISL systems, despite different surface processing (Jeremic, 2020; Xu et al., 2024; Yi et al., 2023).

Section 2 covers the review methodology, including the search strategy, screening criteria, and categorized, the categorization of evidence by solution-mining method and commodity, failure mechanism and triggers, and monitoring approach. This ensures all references are cited in the relevant sections, not just in the introduction.

Methodology

This review employed a structured, transparent methodology to ensure reproducibility, coverage, and adherence to best practices in mining and geohazard research. It combines

database literature retrieval with screening focused on industrial-scale solution mining and related accidents.

To enhance methodological transparency, the literature review followed a structured selection procedure inspired by systematic review principles. Publications were screened based on three main criteria: (i) direct relevance to solution mining technologies or accidents, (ii) availability of documented evidence regarding failure mechanisms, monitoring strategies, or environmental consequences, and (iii) applicability to industrial-scale operations.

Studies were categorized according to mining technology (salt, potash, trona, ISL uranium, lithium brines, sulfur), dominant accident mechanism (geomechanical, well integrity, hydrogeological, chemical–environmental, and operational), and geographic context. This classification enabled cross-comparison of accident mechanisms and risk patterns across technologies and regions.

Literature Search Strategy

A comprehensive literature search was conducted using Scopus, Web of Science, and Google Scholar, complemented by government, regulatory, and technical reports from recognized institutions and industry bodies.

The search strategy combined controlled terms and free-text keywords related to solution mining and accident mechanisms, including solution-mining accidents, brine leakage, salt-cavern collapse, sinkhole formation, well failure, ground subsidence, and in situ leaching (ISL) contamination.

Search queries were iteratively refined to capture multidisciplinary studies across geomechanics, hydrogeology, monitoring technologies, environmental risk, and safety management.

Inclusion and Exclusion Criteria

The review considered publications from 2020 to 2025, reflecting the historical development and industrial consolidation of solution-mining technologies.

Only studies on industrial-scale operations were included. Eligible sources included peer-reviewed journal articles, conference proceedings, and official government or technical reports.

Studies that focused exclusively on artisanal mining, conducted laboratory-scale experiments lacking field relevance, or examined conventional mining methods unrelated to artisanal mining were excluded. Papers that lacked sufficient technical detail on mechanisms, monitoring, or accident characterization were also excluded.

PRISMA Flow Diagram

To ensure transparency, reproducibility, and rigor, this review follows a structured process aligned with PRISMA 2020 guidelines. Figure 1 shows the flow of studies through identification, screening, eligibility, and inclusion related to solution-mining accidents and risks.
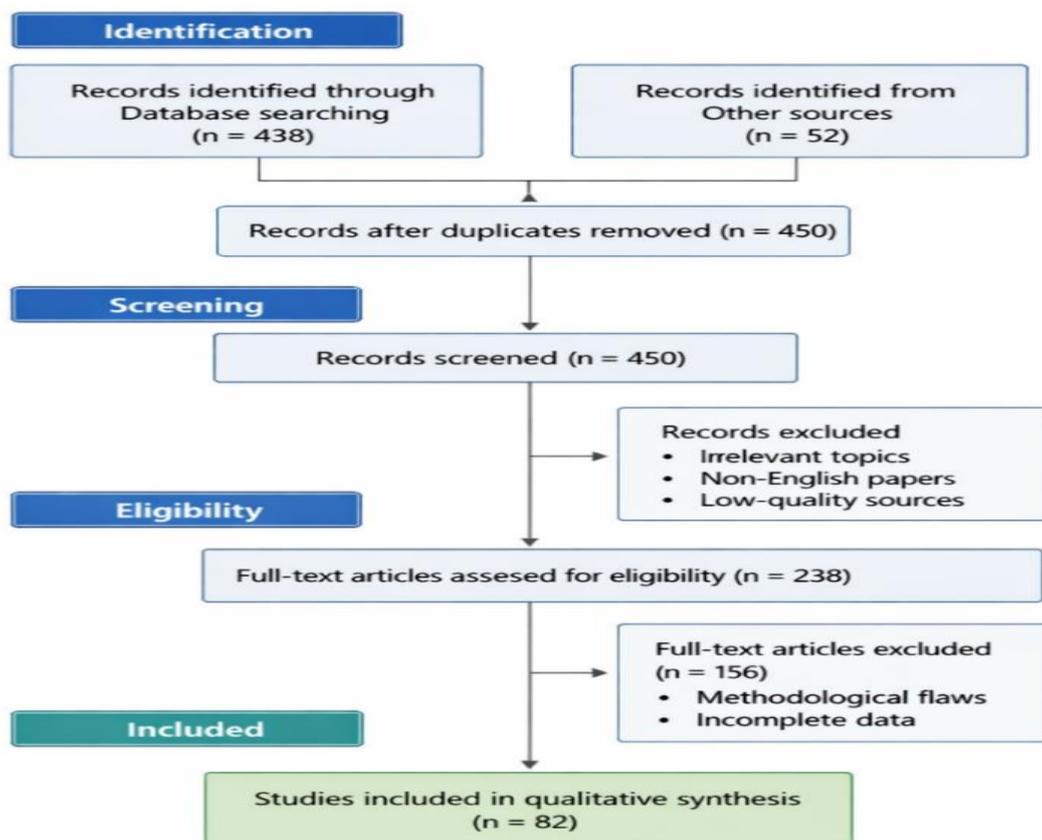
Figure 1. Systematic flow diagram of the literature selection process adopted in this review. Adapted from Page et al. (2021).

The PRISMA-based workflow enabled transparent documentation of record identification, duplicate removal, abstract and full-text screening, and the justification for exclusions. This approach ensured methodological rigor while allowing the inclusion of high-quality technical reports that are particularly relevant to solution-mining accidents.

The accident mechanisms, environmental impacts, and socio-economic consequences discussed later rely on understanding the technological diversity and operational principles of solution mining. Different methods involve specific geological settings, fluid–rock interactions, cavern geometries, and well configurations, which influence risks and failure modes.

Before analyzing accidents and causes, it is necessary to overview the main solution-mining technologies like salt and potash extraction, trona mining, lithium brine recovery, uranium leaching, and sulfur production by the Frasch process. This establishes the technical baseline for understanding accident types, monitoring, and regulations.

Overview of Solution Mining Technologies

Solution mining comprises a family of extractive techniques that rely on the controlled injection of fluids to dissolve target minerals in situ, followed by recovery of the pregnant solution for surface processing. Although the basic principle is shared, substantial differences in geological settings, operational configurations, chemical agents, and containment strategies lead to markedly different risk profiles across applications (Jeremic, 2020; Wagner & Mori, 2024).

Salt and Potash Solution Mining

Salt and potash solution mining represent the most mature and widespread applications of the technology. Caverns are developed within halite or potash-bearing formations through controlled water injection and brine extraction, creating large subsurface voids whose geometry evolves (Jeremic, 2020; Zhang et al., 2021).

Operational risks with cavern stability, roof collapse, interbed failure, and long-term subsidence. These risks are strongly influenced by stratigraphy, cavern geometry, extraction rates, and pressure management (Lord et al., 2021; Zhang et al., 2023).

Salt and potash solution mining share similar principles but differ in cavern shape, extraction methods, and main risks. Table 1 summarizes key operational parameters, caverns, and risks for both.

Table 1. Summary of typical operational parameters, cavern geometries, and dominant risk mechanisms associated with salt and potash solution mining operations. Adapted from Jeremic (2020); Gutierrez et al. (2023); Solari et al. (2020); Zhang et al. (2021, 2023); Minkley et al. (2025); and Wagner & Mori (2024).

| Parameter	Salt Solution Mining	Potash Solution Mining	Dominant Risk Implications
Typical cavern depth	300–2,000 m	500–1,500 m	Stress redistribution and roof stability
Cavern geometry	Large, vertical, bottle- or bulb-shaped	Layered or elongated caverns	Roof span and pillar instability
Leaching medium	Freshwater or undersaturated brine	Saturated or controlled brine	Over-leaching and shape loss
Roof thickness	Highly variable	Often thinner due to stratification	Roof collapse and subsidence
Interbedded layers	Common (anhydrite, shale)	Frequent (clay, marl)	Differential dissolution
Extraction control	Flow and density control	Flow, density, and temperature control	Irregular cavern growth
Typical monitoring	Pressure, sonar, microseismic	Pressure, sonar, InSAR	Delayed failure detection
Main failure modes	Cavern collapse, sinkholes	Subsidence, pillar failure	Surface and aquifer impacts

Trona and Soda Ash

Trona solution mining is commonly used where conventional mining is uneconomic or environmentally constrained. The process involves injecting hot water or alkaline solutions to dissolve sodium sesquicarbonate, followed by crystallization of soda ash at surface facilities (Yi et al., 2023).

Compared with halite caverns, trona operations typically involve thinner beds and more complex stratigraphy, increasing susceptibility to roof instability and localized subsidence. Thermal stresses and dissolution kinetics further complicate cavern evolution, particularly during cyclic operations (Xue et al., 2024).

Fresh water is injected into subsurface trona beds via wells, producing sodium carbonate–bicarbonate brine. The brine is pumped to surface reservoirs, then sent to a recovery plant for clarification and chemical adjustment. Evaporation stages crystallize soda ash (Na_2CO_3), while residual brines (bitterns) are recycled or managed as secondary streams. The process links subsurface leaching, brine chemistry, and surface crystallization, which influence production and operational risk in trona solution mining.
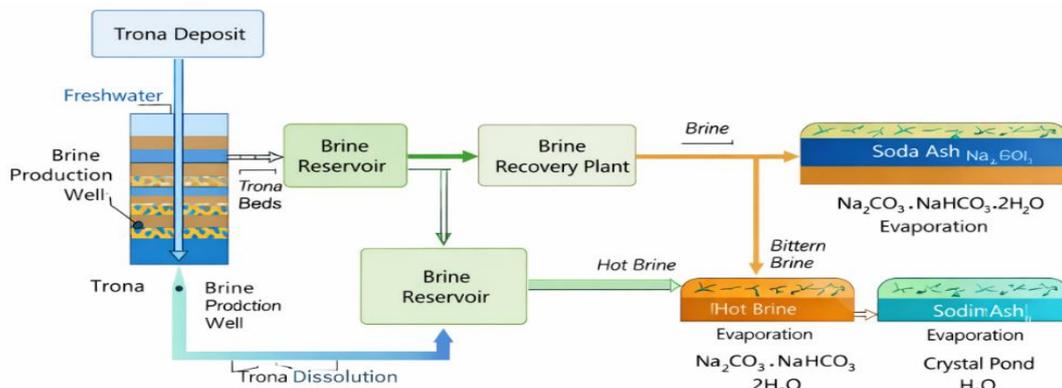
Figure 2. Process flow diagram illustrating trona dissolution, brine recovery, surface processing, and soda ash crystallization in solution mining operations. Adapted from Jeremic (2020); Wagner and Mori (2024); Xue et al. (2024).

Fresh water is injected into subsurface trona beds via wells, producing sodium carbonate–bicarbonate brine through selective dissolution. The brine is pumped to surface reservoirs, clarified, and chemically adjusted at a recovery plant. Evaporation then crystallizes soda ash (Na_2CO_3), while residual brines (bitterns) are recycled or managed. This process links subsurface leaching, brine chemistry, and surface crystallization, determining production and risk in trona solution mining.
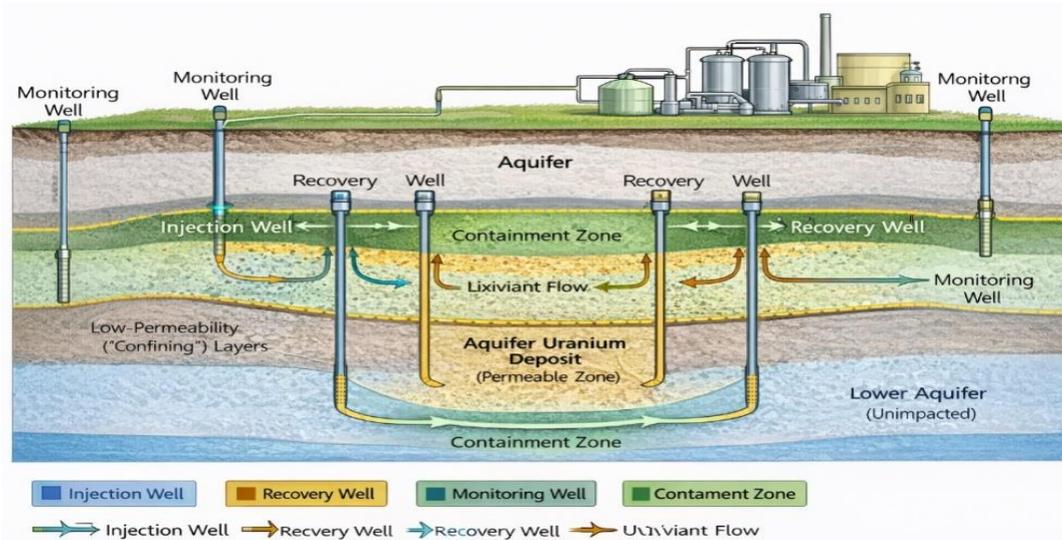
Uranium In-Situ Leaching (ISL)

Uranium ISL differs fundamentally from cavern-based solution mining, as it relies on permeable ore bodies rather than the creation of voids. Leaching solutions, typically acidic or alkaline with oxidants, are injected to mobilize uranium, which is recovered through production wells (Iskakov, 2020; Son et al., 2023).

The dominant risk profile is environmental rather than geomechanical, involving groundwater contamination, well integrity failure, lixiviant migration, and long-term challenges in aquifer restoration (Asylbekova, 2021; Aumalikova, 2025).

Figure 3 presents a conceptual diagram of an in-situ leaching (ISL) wellfield, illustrating the hydraulic flow paths, leaching zones, and containment mechanisms that govern uranium recovery and environmental protection.

Figure 3. Conceptual diagram of an in-situ leaching (ISL) wellfield, highlighting injection and recovery wells, subsurface flow paths, containment zones, and monitoring networks. Adapted from Iskakov (2020); Lord et al. (2021); Muntendam-Bos et al. (2022); Saifulina et al. (2023).

ISL operations use a controlled well pattern to circulate lixiviant through a uranium formation. The solution mobilizes uranium, ideally confined by low-permeability layers and hydraulic gradients. Recovery wells extract the solution while monitoring wells track pressure, flow, and potential excursions. Loss of hydraulic control, well failure, or unexpected geology can cause lixiviant migration beyond containment zones, posing a key risk in ISL mining.
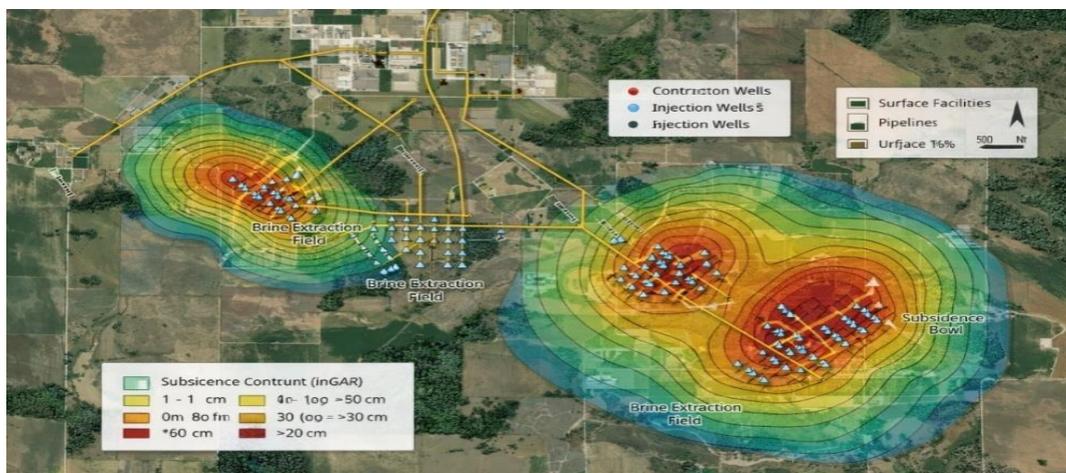
Lithium Brine Extraction

Lithium brine extraction exploits naturally occurring saline aquifers, primarily in arid, closed basins. Brines are pumped to surface evaporation ponds or processed via direct lithium extraction technologies (Xu et al., 2024).

Key risks include land subsidence from brine withdrawal, disruption of regional hydrogeological balances, and conflicts

over water resources and with local communities. Unlike cavern-based systems, deformation is often diffuse and delayed, complicating monitoring and attribution (Solari et al., 2020; Warhurst & Noronha, 2024).

To complement hydrogeological and geomechanical risk discussions in solution mining, a spatial view is vital for visualizing how subsurface extraction causes surface responses. Map-based representations combining wellfield layouts with deformation data link operations to ground behavior.

Figure 4. Spatial representation of brine extraction systems. Adapted from published InSAR-based subsidence studies and solution mining case analyses. Adapted from Solari et al. (2020); Orhan et al. (2023); Minkley et al. (2025).

The figure illustrates the relationships among brine wells, surface facilities, and subsidence bowls identified by satellite InSAR. Maximal surface deformation aligns with high-extraction zones, indicating the cumulative effects of long-term withdrawal and cavern growth. Concentric patterns show differential compaction and roof convergence, while outer zones suggest stress redistribution outside the wellfield. These spatial insights aid early detection of ground movement, optimize extraction, and guide land-use planning in solution-mining areas.

Sulfur (Frasch Process)

The Frasch process injects superheated water and compressed air to melt and lift elemental sulfur to the surface. Although largely phased out in many regions, legacy operations still pose residual geotechnical and environmental risks (Jeremic, 2020).

Thermal weakening of host formations, loss of well integrity, and subsidence over abandoned fields have been documented, particularly when long-term monitoring was inadequate (Wagner & Mori, 2024).

Across solution-mining technologies, risk profiles are governed by a combination of void-creation versus porous-flow mechanisms, the chemical aggressiveness of injected fluids, pressure and temperature regimes, and long-term cavity or reservoir evolution. Geomechanical hazards dominate cavern-based systems, whereas ISL and brine extraction pose higher risks of fluid migration and environmental contamination (Minkley et al., 2025; Xue et al., 2024).

Given the diversity of solution mining technologies, a framework links each method to its hazard mechanisms. A matrix allows comparison across technologies and hazard types, highlighting shared and specific risks. Figure 5 maps main mining methods to geomechanical, well integrity, hydrogeological, chemical–environmental, and operational hazards, summarizing relative risks across contexts.

Solution Mining Technologies	Comparative Matrix				
	Geomechanical Failure	Well Integrity Issues	Hydrogeological Accidents	Chemical/ Environmental Impacts	Operational/ Human-Induced Risks
Salt & Potash Solution Mining	●●●	●●●	●	●●●	●●●
Trona Dissolution	●●●	●●●	●	●●●	●●●
Uranium In-Situ Leaching (ISL)	●	●●●	●●●	●●●	●●●
Lithium Brine Extraction	●	●●●	●●●	●●●	●●●
Sulfur Recovery (Frasch Process)	●●●	●●●	●●●●	●●●	●●●

● Major Hazard   ● Moderate Hazard   ● Minor Hazard

Hazard levels indicate the relative risk prominence in each solution mining technology.

Figure 5. Comparative matrix linking major solution mining technologies to dominant hazard categories. Adapted from Jeremic, (2020); Solari et al. (2020); Muntendam-Bos et al. (2022); Minkley et al. (2025).

The matrix links major solution-mining technologies—salt and potash solution mining, trona dissolution, uranium in situ leaching (ISL), lithium brine extraction, and sulfur recovery via the Frasch process—to key hazard categories. Geomechanical hazards, such as cavern collapse and subsidence, are common in salt, potash, and trona mining, whereas hydrogeological and chemical risks dominate in ISL and lithium brine mining due to fluid migration and aquifer interactions. Operational and well-integrity failures affect all technologies differently. The matrix shows that risks vary and require technology-specific design, monitoring, and regulation.

The technological diversity outlined above results in distinct accident mechanisms, failure modes, and temporal signatures across solution-mining operations. Understanding these technological foundations is essential for interpreting why certain accident types recur in specific mining contexts, while others remain rare or site-specific.

Accordingly, the next section presents a systematic classification of solution-mining accidents, organizing historical events by dominant mechanisms, triggering factors, and consequences. This classification provides the analytical framework for comparing incidents across technologies and for identifying common lessons for risk mitigation and policy development.

Classification of Accidents in Solution Mining

Accidents in solution mining arise from interactions among geological conditions, engineered systems, chemical processes, and human decision-making. Unlike conventional mining, failures often propagate invisibly in the subsurface, with delayed or spatially displaced surface manifestations. For analytical clarity, solution mining accidents can be classified into five major categories based on their dominant failure mechanisms and consequences.

Figure 6 presents a conceptual framework for classifying solution mining accidents based on dominant failure mechanisms and resulting impacts. The framework provides a structured overview of how geomechanical, well integrity, hydrogeological, chemical–environmental, and operational factors interact to generate distinct accident pathways.
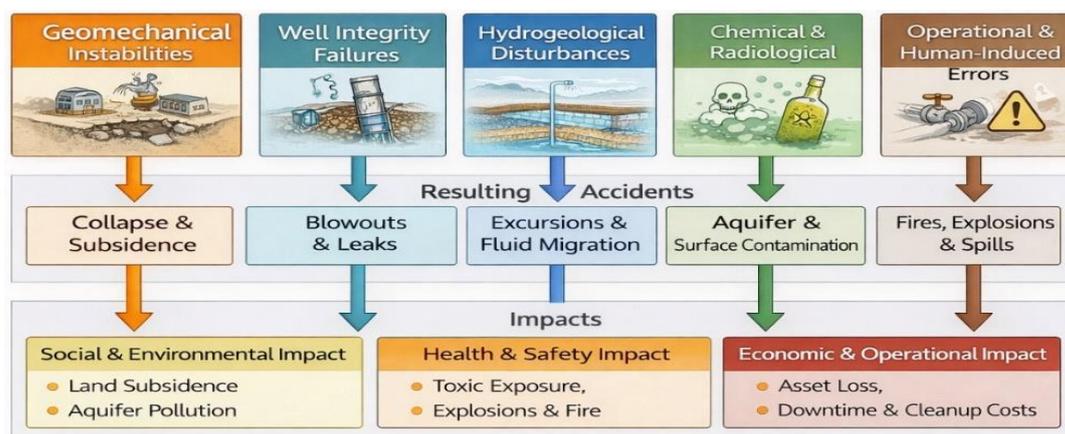
Figure 6. Conceptual classification framework of solution mining accidents. Adapted from Jeremic (2020); Gutierrez et al. (2023); Contrucci et al. (2023); da Silva and Kormann (systematic review); Muntendam-Bos et al. (2022).

Geomechanical Failures

Geomechanical failures are the most widely documented accident class in cavern-based solution mining. These events are typically associated with a progressive loss of structural stability in the host rock.

Cavern roof collapse occurs when tensile or shear stresses exceed rock strength, caused by over-enlargement, unfavorable stratigraphy, or insufficient pressure control. Such collapses may remain confined initially but can evolve into large-scale ground deformation (Jeremic, 2020; Lord et al., 2021).

Pillar instability is especially relevant in bedded evaporite formations, where interlayers of weaker material reduce load-bearing capacity. Progressive pillar failure can lead to asymmetric cavern deformation and localized subsidence (Zhang et al., 2021; Zhang et al., 2023).

Subsidence and sinkholes are the most visible manifestations of geomechanical failure. These processes can develop gradually or abruptly, depending on cavern depth, roof thickness, and overburden properties. Sinkhole formation often marks the final stage of long-term cavern degradation (Gutierrez et al., 2023; Intrieri et al., 2023).

Well Integrity Failures

Well integrity failures represent a critical interface between subsurface processes and surface impacts. They are common across all solution-mining technologies, including cavern mining, ISL, and brine extraction.

Casing corrosion results from prolonged exposure to aggressive brines, acidic or alkaline leaching agents, and temperature gradients. Undetected corrosion can compromise zonal isolation and cause fluid leakage (Iskakov, 2020; Wagner & Mori, 2024).

Cement failure is often associated with inadequate cement placement, thermal cycling, or chemical degradation. Microannuli formation can create preferential pathways for fluid migration even when casings remain intact (Liu et al., 2020; Ugarte & Salehi, 2022).

Blowouts and uncontrolled brine flow are acute well integrity failures. These events may be triggered by overpressure, mechanical damage, or loss of wellhead control, posing immediate environmental and safety risks (Qian et al., 2022; Wang et al., 2025).

Hydrogeological Accidents

Hydrogeological accidents involve unintended interactions between mining fluids and surrounding groundwater systems. These failures often develop slowly and are difficult to detect in early stages.

Freshwater aquifer contamination occurs when leaching solutions or saline brines migrate beyond the intended mining zone. In ISL operations, this risk is strongly influenced by permeability contrasts and hydraulic gradients (Asylbekova, 2021; Aumalikova, 2025).

Brine migration may occur laterally or vertically through faults, fractures, or improperly sealed wells. Such migration can alter regional groundwater chemistry and compromise water resources located far from the mining site (Solari et al., 2020; Li et al., 2022).

Loss of confinement layers is a critical failure mode in both cavern and ISL operations. Breaches of caprock or aquitards can couple geomechanical and hydrogeological processes, accelerating subsidence and contaminant transport (Zhang et al., 2024; Minkley et al., 2025).

Although accident categories in solution mining are often discussed separately, real-world incidents frequently unfold along interconnected failure pathways. Figure 7 depicts a simplified yet representative propagation sequence linking initial engineering failures to cascading hydrogeological, chemical, and socio-environmental impacts.
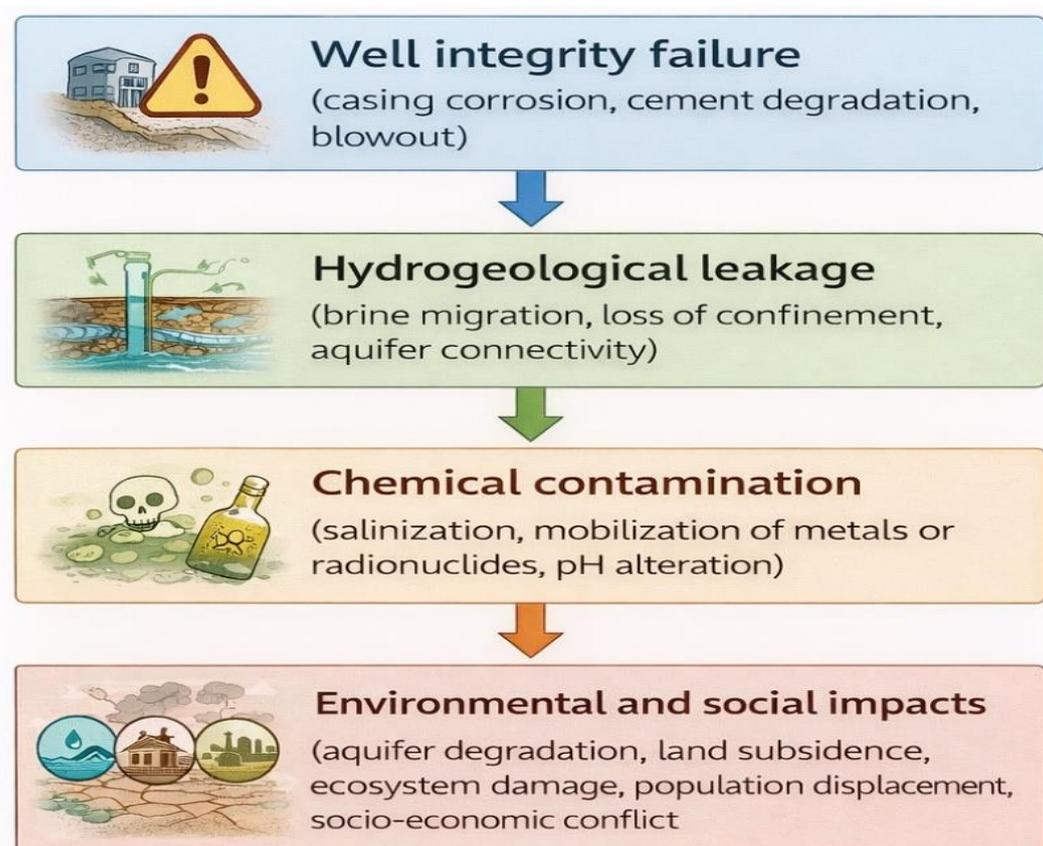
Figure 7. Conceptual flow diagram illustrating typical failure propagation pathways in solution mining systems. Adapted from Gutierrez et al. (2023); Contrucci et al. (2023); Minkley et al. (2025); Muntendam-Bos et al. (2022); Yi et al. (2023); Zhao et al. (2021, 2025).

The propagation pathway shown in Figure X underscores that solution-mining accidents rarely remain confined to a single technical domain. Initial well-integrity failures often serve as trigger events, creating unintended hydraulic connections between the leaching zone and surrounding geological formations. Once hydrogeological containment is compromised, chemical plumes may migrate beyond operational boundaries, causing long-term environmental degradation and, in many cases, significant social and economic consequences.

This cascading structure explains why several solution-mining incidents escalate rapidly from localized engineering failures into regional environmental and governance

challenges. From a policy perspective, the figure underscores the importance of integrated regulatory frameworks that address not only technical design standards but also long-term environmental monitoring, emergency response capacity, and social risk management.

Chemical and Environmental Accidents

Chemical and environmental accidents are especially common in solution-mining systems that involve reactive fluids or radioactive materials.

Acid or alkaline plume migration is characteristic of ISL uranium mining and certain metal leaching operations. These plumes may persist for decades, complicating site remediation and regulatory closure (Saifulina et al., 2023; Sydykov et al., 2025).

Radioactive contamination is specific to uranium ISL and legacy mining sites. Accidents may involve the mobilization of radionuclides, radon emissions, or the contamination of soils and water bodies (Asylbekova, 2021; Kashkinbayev et al., 2025).

Soil and surface water salinization commonly results from brine spills, leakage from evaporation ponds, or uncontrolled discharge. These impacts are often cumulative and socially contentious, particularly in arid regions (Warhurst & Noronha, 2024; Yi et al., 2023).

Operational and Human Errors

Operational and human factors are cross-cutting contributors across all accident categories. While rarely the sole cause, they often trigger or exacerbate failures.

Over-leaching causes excessive cavern growth, thinning of roof spans, and destabilization of confinement layers. This practice is often driven by short-term production targets (Jeremic, 2020; Zhang et al., 2023).

Poor control of cavern geometry, including irregular shapes and sharp corners, increases stress concentrations and undermines long-term stability (Duffy et al., 2022; Xue et al., 2024).

To support a systematic understanding of the diverse accident mechanisms in solution mining, a structured classification is needed to link failure modes to their technical origins and observable consequences. Table 2 synthesizes the main categories of solution mining accidents, organizing them by dominant failure mechanisms, representative accident types, and typical environmental, social, and operational impacts reported in the literature.

Table 2. Classification of accidents in solution mining and associated impacts. Adapted from: Jeremic (2020); Contrucci et al. (2023); Solari et al. (2020); Gutierrez et al. (2023); Minkley et al. (2025); Muntendam-Bos et al. (2022); Zhang et al. (2023, 2025); Yi et al. (2023); Zhao et al. (2021, 2025).

Accident category	Typical failure modes	Main consequences
Geomechanical failures	Roof collapse, pillar instability, sinkholes	Subsidence, infrastructure damage
Well integrity failures	Casing corrosion, cement failure	Brine leakage, blowouts
Hydrogeological accidents	Aquifer contamination, brine migration	Water resource degradation
Chemical & environmental	Acid plume, radioactive release	Long-term contamination
Operational & human errors	Over-leaching, poor monitoring	Accident escalation

Table 2 shows accidents in solution-mining systems result from multiple factors. Geomechanical failures like roof collapse and subsidence are linked to poor cavern design, geological heterogeneity, or lack of deformation monitoring. Well-integrity issues, such as casing corrosion and cement degradation, often trigger uncontrolled brine migration and aquifer contamination.

Hydrogeological accidents are particularly critical because of their long-term, often irreversible impacts, especially when loss of confinement contaminates freshwater aquifers. Chemical and radiological incidents are most prominent during uranium in situ leaching operations, where deviations in redox conditions or hydraulic control can mobilize contaminants beyond the intended leaching zone. Operational and human-induced errors, such as over-leaching, insufficient pressure control, or delayed responses to early warning indicators, frequently exacerbate technical failures and amplify their consequences.

Overall, the table underscores that most severe accidents stem from the interaction of multiple failure mechanisms rather than from isolated technical deficiencies, reinforcing the need for integrated geomechanical, hydrogeological, and operational risk management strategies.

Inadequate monitoring remains a recurring issue, particularly in older operations or regions with limited regulatory oversight. Delayed detection of deformation, leakage, or pressure anomalies significantly worsens the severity of accidents (Hu et al., 2021; Sun et al., 2023).

Global Case Studies of Major Accidents

Large-scale accidents in solution mining have been reported across multiple regions, involving various commodities, geological settings, and regulatory frameworks. This section reviews representative international case studies to highlight recurring failure mechanisms, contextual factors, and regulatory responses. Rather than providing an exhaustive

inventory, the focus is on emblematic events that illustrate systemic vulnerabilities in solution-mining operations worldwide.

North America

One of the most widely documented solution-mining accidents is the Bayou Corne sinkhole in Louisiana, USA. The event, which began in 2012, was linked to the collapse of a salt cavern used for hydrocarbon storage, developed using solution-mining techniques. Progressive cavern instability led to surface subsidence, sinkhole formation, gas migration, and a long-term evacuation of the local population. Subsequent investigations highlighted deficiencies in cavern geometry control, insufficient monitoring, and delayed regulatory intervention (Jeremic, 2020; Lord et al., 2021).

In addition to salt-related incidents, uranium in-situ leaching (ISL) operations in North America have raised concerns about groundwater contamination. Several documented cases report the migration of lixiviant beyond the intended ore zone, mobilizing uranium, radium, and associated trace metals into adjacent aquifers. These incidents are often linked to well integrity failures, inadequate hydraulic confinement, and incomplete baseline hydrogeological characterization (Iskakov, 2020; Namjesnik et al., 2021).

Europe

In Europe, solution-mining accidents have been reported primarily in potash and salt-mining districts, particularly in Germany and France. Historical collapses in German potash mines underscore the long-term geomechanical risks of cavern convergence, pillar dissolution, and delayed roof failure. Several cases resulted in surface subsidence, infrastructure damage, and irreversible loss of mine workings (Jeremic, 2020; Zhang et al., 2021).

France and the Netherlands have also experienced incidents involving solution mining and post-mining cavern instability. Studies of post-operational caverns show that time-dependent deformation, coupled with brine-pressure changes, can trigger seismicity and delayed collapses years after closure. These cases underscore the importance of long-term monitoring and post-closure risk management (Contrucci et al., 2023; Muntendam-Bos et al., 2022).

Asia

Asia accounts for an increasing share of documented accidents, reflecting the rapid expansion of solution mining and underground storage operations. In China, solution mining of salt and nitrate deposits has been linked to extensive land subsidence and brine migration. Remote sensing and InSAR-based studies show that uncontrolled cavern growth and over-leaching are major contributors to ground deformation, affecting urban infrastructure and transportation networks (Solari et al., 2020; Chen et al., 2025).

In Kazakhstan, uranium ISL operations have raised significant environmental concerns. Multiple studies report changes in groundwater chemistry, elevated radionuclide concentrations, and long-term exposure risks in mining regions. These impacts are often attributed to the loss of confinement, legacy well-integrity issues, and inadequate restoration of leached zones (Aumalikova, 2025; Kashkinbayev et al., 2025; Saifulina et al., 2023).

South America

In South America, large-scale lithium brine extraction in arid regions has triggered environmental and social conflicts rather than sudden catastrophic failures. Although sinkholes and collapses are less frequent, progressive impacts related to changes in water balance, brine migration, and surface ecosystem degradation have been widely reported. These issues are particularly critical in closed-basin systems, where freshwater resources are limited (Tsalidis et al., 2020; Lai et al., 2021).

Subsidence and hydrogeological imbalances have also been observed in salt solution mining and brine extraction projects, raising concerns about cumulative impacts rather than isolated accidents. Regulatory responses in the region remain heterogeneous, with limited harmonization of monitoring standards and impact thresholds (Warhurst & Noronha, 2024).

Figure 5 presents a comparative matrix that links the main solution-mining technologies to their dominant accident and hazard categories. This integrative representation supports cross-technology risk assessment and highlights both shared and technology-specific vulnerability patterns.
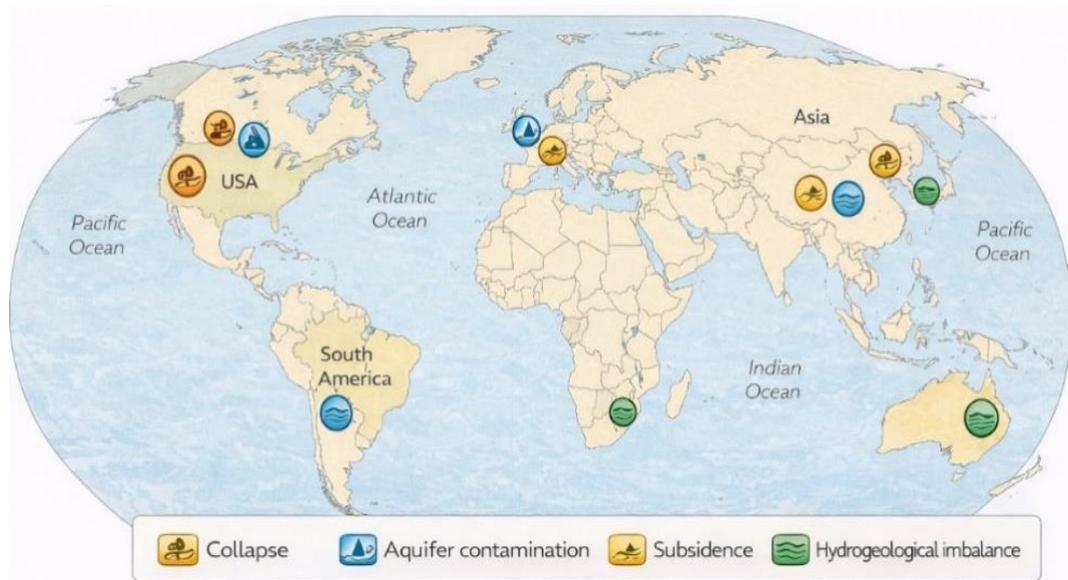
Figure 8. Comparative matrix linking solution mining technologies to dominant hazard categories. Adapted from: Jordá-Bordehore et al. (2017); Bureau & Genter (2020); Bérest et al. (2021); World Nuclear Association (2022); Flexer et al. (2023); Chen et al. (2024).

The comparative framework in Figure 5 shows that, despite significant differences in geological settings, operational objectives, and regulatory maturity, solution mining technologies share a limited set of recurring failure mechanisms. Geomechanical instability and hydrogeological connectivity are cross-cutting risk factors, particularly when cavern geometry control, leaching envelopes, or confinement integrity are insufficiently managed.

At the same time, the matrix highlights technology-specific vulnerabilities. Uranium ISL operations are disproportionately associated with groundwater contamination risks related to well integrity and redox control, whereas lithium brine extraction is more strongly linked to regional hydrogeological imbalance and socio-environmental conflicts. Salt and potash solution mining exhibit a higher frequency of cavern collapses and

subsidence, reflecting the long-term creep behavior of evaporitic formations.

By synthesizing engineering, geological, and environmental dimensions, this matrix supports the development of targeted regulatory strategies and risk-based monitoring frameworks. It also underscores the need for integrated assessment approaches that go beyond single-discipline analyses to address the complex risk landscape of solution mining.

Comparative Summary of Major Accidents

To contextualize the diversity of failure mechanisms and regulatory outcomes associated with solution-mining operations, Table 3 presents a comparative overview of major accidents reported worldwide. The table synthesizes representative case studies across minerals, regions, and technological settings, highlighting common root causes, consequences, and post-incident regulatory responses.

Table 3. Comparative overview of major solution mining accidents worldwide. Adapted from Jin et al. (2022); Chen et al. (2025); Minkley et al. (2025); Wagner & Mori (2024).

Location	Mineral	Failure type	Root cause	Consequences	Regulatory response
USA (Bayou Corne)	Salt	Cavern collapse	Poor cavern geometry control	Sinkhole, evacuation	Post-event regulation 강화
USA / Kazakhstan	Uranium (ISL)	Aquifer contamination	Well integrity failure	Long-term groundwater impact	Monitoring and remediation
Germany	Potash	Pillar instability	Time-dependent creep	Mine collapse, subsidence	Mine closure policies
China	Salt / Nitrate	Subsidence	Over-leaching	Urban infrastructure damage	Enhanced monitoring
South America	Lithium brine	Hydrogeological imbalance	Excessive brine extraction	Ecosystem stress	Emerging regulatory frameworks

Table 3 shows that despite variations in mineral types and regulations, solution-mining accidents often result from

recurring technical and organizational failures. The main causes include poor cavern design, inadequate control of

leaching envelopes, and poor well integrity. Severe environmental and social impacts are often associated with delayed detection and weak oversight, underscoring the importance of proactive monitoring and careful design.

A critical comparison of these case studies indicates that accident severity is rarely determined solely by geological conditions. Instead, the interaction between engineering design choices, monitoring capacity, and regulatory oversight plays a decisive role. In several documented cases, early warning signals such as abnormal pressure fluctuations, minor deformation trends, or chemical anomalies were detected but not adequately interpreted or acted upon

Despite regional differences in geology, commodities, and regulatory environments, the reviewed case studies reveal recurring patterns of failure. Cavern geometry mismanagement, loss of hydraulic confinement, inadequate well integrity, and insufficient monitoring repeatedly emerge as critical contributors to accidents. These observations underscore the need for a systematic root-cause analysis that

extends beyond individual events and focuses on underlying technical, organizational, and regulatory drivers. Accordingly, the next section synthesizes these findings into a structured root cause framework for solution-mining accidents.

Root Cause Analysis

Accidents in solution-mining systems rarely stem from a single failure mechanism. Instead, they arise from the interplay of technical design limitations, geological uncertainties, and organizational or regulatory shortcomings. Evidence from global case studies indicates that these factors often act in concert, amplifying risks and accelerating the propagation of failure (Contrucci et al., 2023; Minkley et al., 2025; Zhao et al., 2025).

Figure 9 synthesizes the primary root causes of solution-mining accidents, organizing them into interconnected technical, geological, and organizational layers that collectively govern the initiation and propagation of failures.
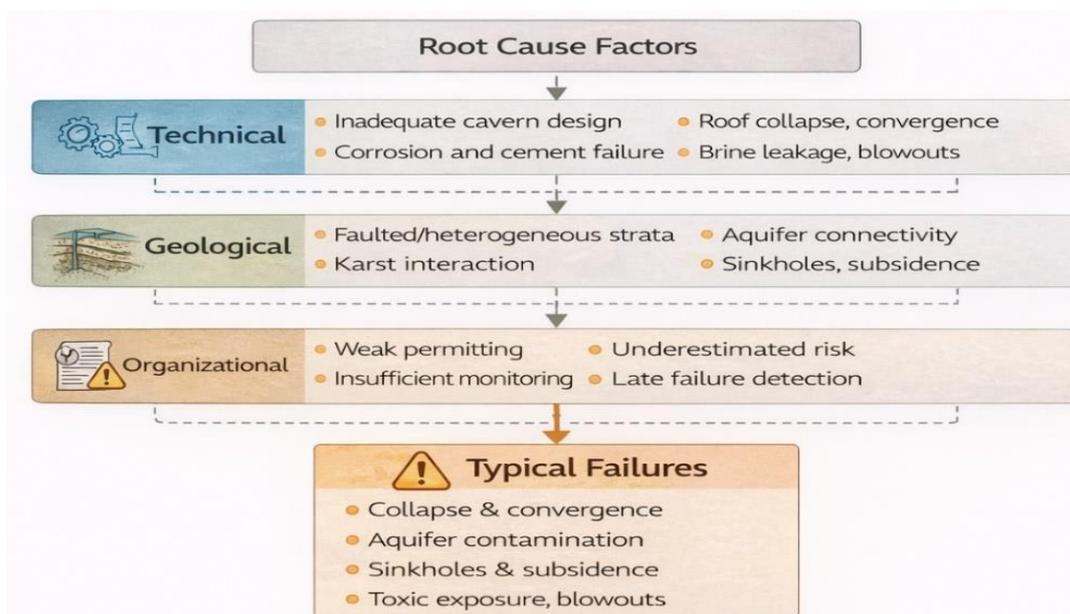
Figure 9. Multi-layer root-cause framework for solution-miningaccidents. Adapted from Jeremic (2020); Lord et al. (2021); Contrucci et al. (2023); Minkley et al. (2025); Sánchez and Franks (2022); Zhang et al. (2025).

This framework highlights that solution-mining accidents rarely have a single cause. Failures usually result from interactions among design limits, geological challenges, and organizational weaknesses. Technical issues such as cavern geometry or well-integrity problems may remain hidden until geological features increase hydraulic connectivity. Coupled with poor monitoring, weak permits, or slow responses, these can lead to large collapses, brine leaks, or environmental damage. The layered approach emphasizes integrated risk management across engineering, regulation, and decision-making.

This section synthesizes the dominant root causes reported in the literature and organizes them into three main categories: technical, geological, and organizational–regulatory drivers.

Technical Causes

Technical deficiencies are among the most frequently reported root causes of solution-mining accidents. Inadequate cavern design, particularly the underestimation of roof-span stability and pillar load transfer, has been directly linked to large-scale collapses and subsidence events (Jeremic, 2020; Jin et al., 2022). Simplified geomechanical models that fail to capture the time-dependent creep behavior of evaporites further exacerbate long-term instability risks (Minkley et al., 2025; Zhang et al., 2021).

Well integrity failures represent another critical technical pathway. Corrosion of casings, poor cement placement, and material incompatibility with aggressive brines have been widely documented in both salt cavern operations and

uranium ISL systems, resulting in uncontrolled brine flow and cross-aquifer contamination (Iskakov, 2020; Wang et al., 2025; Zhao et al., 2025).

Insufficient monitoring resolution and delayed detection of early deformation signals also contribute to accident escalation, particularly when real-time microseismic or deformation monitoring is absent or poorly integrated into operational decision-making (Fan et al., 2021; Liu et al., 2024).

Geological Causes

Geological complexity is a defining risk factor in solution mining. Stratigraphic heterogeneity, interbedded insoluble layers, and undetected faults or fractures frequently act as preferential pathways for brine migration and pressure redistribution (Duffy et al., 2022; Zhang et al., 2023).

Karst interactions are especially critical in evaporitic environments. Several studies report that the hydraulic connection between solution-mined caverns and pre-existing karst systems significantly increases the likelihood of sinkholes and delayed surface collapse (Gutierrez et al., 2023; Intrieri et al., 2023; Orhan et al., 2023). These processes are often progressive, with surface manifestations appearing years after active leaching has ceased.

In uranium ISL operations, geological confinement failure is a recurring theme. Weak or discontinuous aquitards allow lixiviants and mobilized radionuclides to migrate beyond the target ore zone, contaminating surrounding groundwater systems (Asylbekova, 2021; Aumalikova, 2025; Saifulina et al., 2023).

Figure 10 illustrates a failure escalation pathway in solution-mining systems, highlighting how geological uncertainty propagates through design, monitoring, and operational decisions, ultimately resulting in accidents and broader environmental and social impacts.
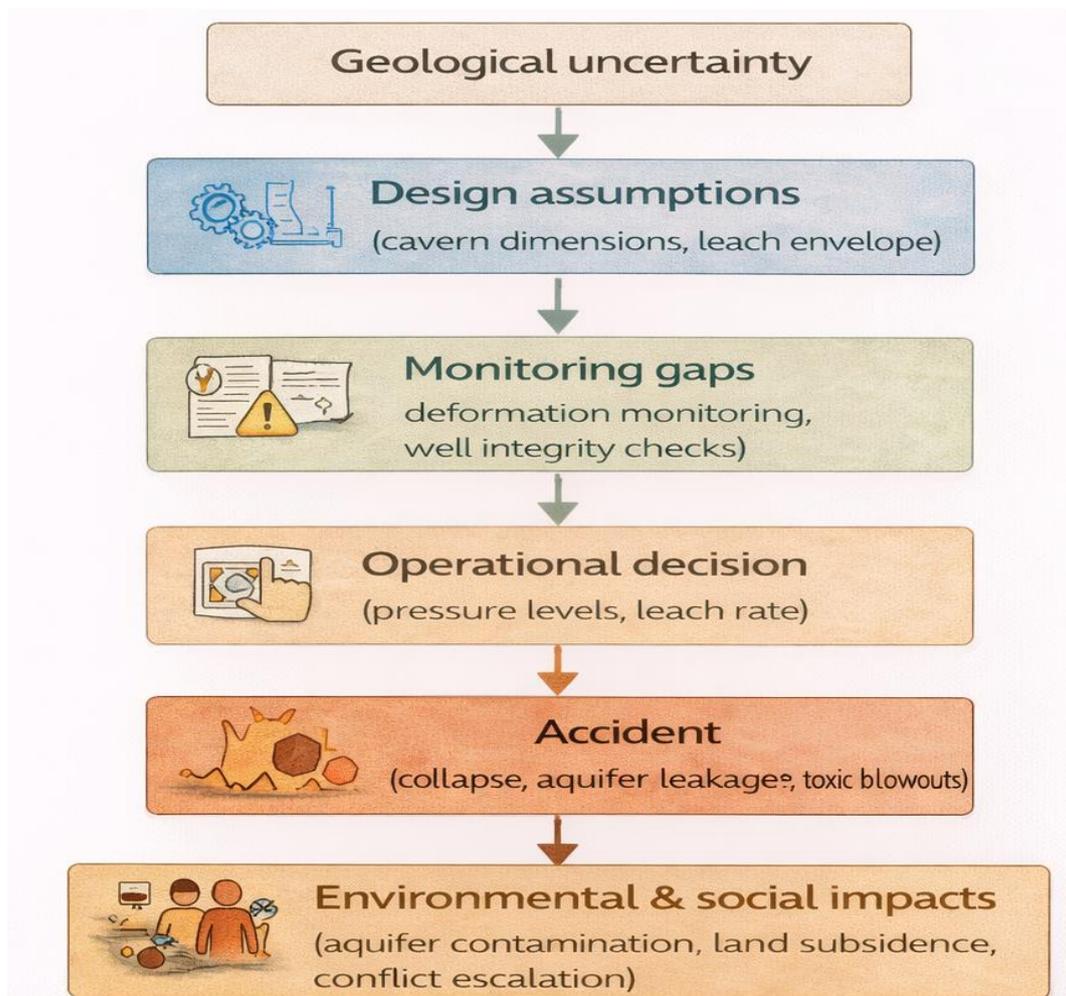
Figure 10. Failure-escalation pathway in solution-mining systems. Adapted from Jeremic (2020); Contrucci et al. (2023); Minkley et al. (2025); Zhang et al. (2025); Sánchez & Franks (2022).

Solution-mining accidents rarely stem from a single failure but from cumulative weaknesses like incomplete geological knowledge, simplified design assumptions, monitoring issues, and operational pressures. Once an accident happens, its impacts extend beyond the mine, affecting aquifers, surface stability, ecosystems, and social dynamics. This highlights the need for integrated risk governance linking engineering, environmental, and social considerations.

Organizational and Regulatory Causes

Beyond technical and geological drivers, organizational and regulatory factors are decisive in shaping accident outcomes. Weak permitting frameworks and insufficient site-specific geological characterization have been identified as systemic vulnerabilities, particularly in rapidly expanding solution-mining regions (Bastida, 2020; Sánchez & Franks, 2022).

Economic pressures and cost-cutting practices often lead to reduced monitoring density, extended cavern lifetimes beyond design assumptions, and delayed remediation, thereby increasing the probability of catastrophic failure (Kowalewski & Śpiewanowski, 2020; Valluru et al., 2020). In several documented cases, early warning signs were identified but not acted upon because of organizational inertia or regulatory ambiguity (Contrucci et al., 2023; Zhao et al., 2021).

The literature also highlights governance challenges related to transparency, community engagement, and enforcement capacity, which can magnify social and environmental consequences once technical failures occur (Oh et al., 2023; Warhurst & Noronha, 2024).

Table 4 summarizes the primary root-cause categories associated with solution-mining accidents, linking technical, geological, and organizational factors to their typical failure manifestations and to representative case studies worldwide.

Table 4. Root cause categories, specific contributing factors, typical failure manifestations, and representative solution mining accident cases. Adapted from: Bérest et al. (2012, 2021); Jordá-Bordehore et al. (2017); U.S. EPA (2019); World Nuclear Association (2022); Bureau & Genter (2020); Chen et al. (2024).

Root cause category	Specific factors	Typical manifestations	Representative cases
Technical	Inadequate cavern design	Roof collapse, convergence	Bayou Corne (USA)
Technical	Corrosion and cement failure	Brine leakage, blowouts	ISL uranium wells
Geological	Faulted/heterogeneous strata	Aquifer connectivity	China salt mines
Geological	Karst interaction	Sinkholes, subsidence	Europe (evaporites)
Organizational	Weak permitting	Underestimated risk	Multiple regions
Organizational	Insufficient monitoring	Late failure detection	Global ISL cases

Root cause analysis reveals that solution-mining accidents rarely result from a single factor. They usually involve technical issues, geological uncertainties, and organizational weaknesses. Cavern design flaws and material degradation, such as corrosion and cement failure, often trigger failures, that are exacerbated by geological conditions, including faulted strata or karst systems.

Organizational factors such as weak permitting and limited monitoring contribute to underestimating risks and delaying early-warning detection. This allows small issues to escalate into major accidents. The repeated failure patterns across regions suggest that many solution-mining incidents are systemic rather than site-specific.

This integrated perspective underscores the need to move beyond purely technical mitigation measures toward governance frameworks that embed conservative design, adaptive monitoring, and institutional accountability throughout the full lifecycle of solution-mining operations.

These root causes form a coupled risk system where failures spread across physical and institutional boundaries. Understanding this is key to assessing environmental, social, and economic impacts, as discussed later.

Environmental, Social, and Economic Impacts

Solution mining accidents often have impacts that extend well beyond the immediate operational boundary and persist for decades. Environmental degradation, social disruption, and substantial economic losses are recurrent, particularly where regulatory oversight is weak, hydrogeological settings are complex, or intervention is delayed.

Environmental Damage

Solution mining accidents can cause long-term aquifer degradation through loss of hydraulic confinement, casing failures, or uncontrolled brine migration, leading to persistent freshwater contamination often beyond remediation. In uranium ISL, the release of radionuclides and metals adds long-term risks to groundwater and health (Asylbekova, 2021; Aumalikova, 2025; Iskakov, 2020; Saifulina et al., 2023).

Irreversible salinization of soils and surface waters has been documented at salt, potash, and trona operations following cavern collapse or well-integrity failure. Once salinity thresholds are exceeded, ecological recovery is often unfeasible on human timescales, resulting in permanent loss of agricultural productivity and ecosystem services (Gutierrez et al., 2023; Orhan et al., 2023; Solari et al., 2020).

Figure 11 illustrates the conceptual pathways by which contaminants released during solution-mining accidents migrate across interconnected environmental compartments, including aquifers, soils, surface waters, and the atmosphere.
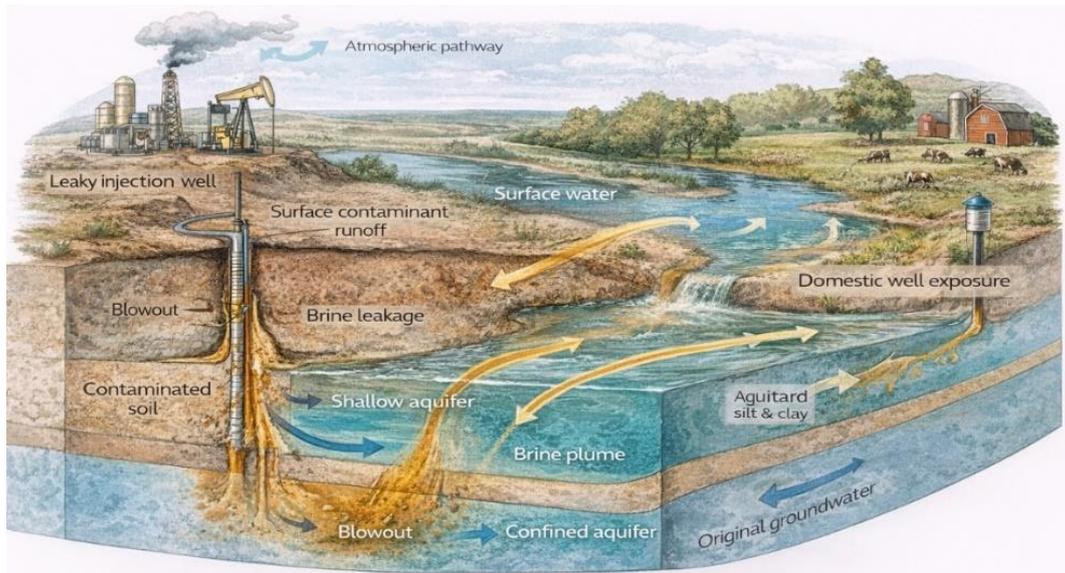
Figure 11. Conceptual pathways of contaminant migration following solution mining accidents (aquifers, soils, surface waters). Adapted from Lord et al. (2021); Liu et al. (2020); Chen et al. (2025); Muntendam-Bos et al. (2022).

The diagram emphasizes how a localized failure at the well or cavern scale can rapidly evolve into a multi-compartment contamination problem. Vertical migration driven by pressure gradients allows contaminants to breach confining layers, while lateral transport through shallow aquifers and surface runoff spreads salinity, radionuclides, or chemical reagents beyond the operational footprint. The diagram also highlights exposure pathways affecting domestic water wells, agricultural soils, and surface water bodies, reinforcing the long-term environmental and social consequences of inadequate containment and monitoring strategies.
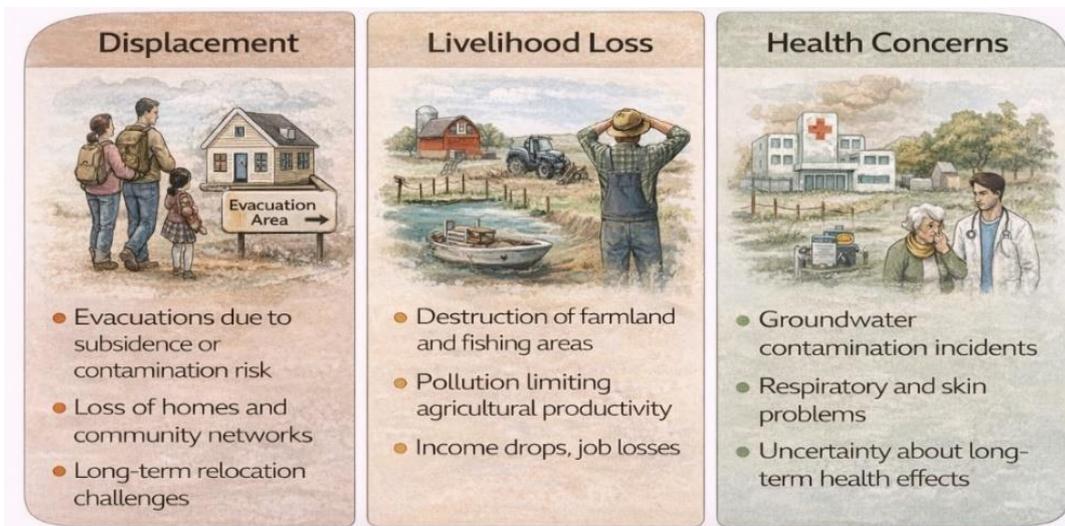
Social Impacts

Environmental damage frequently translates into severe social consequences, particularly in densely populated or agriculturally dependent regions. Population displacement has been reported during major subsidence and sinkhole events, in which ground instability renders residential areas uninhabitable for extended periods (Intrieri et al., 2023; Minkley et al., 2025).

The loss of land and livelihoods is particularly pronounced in rural communities that rely on agriculture, grazing, or local water resources. In the contexts of lithium brine extraction and uranium ISL, conflicts between mining operators and local populations have intensified due to perceived inequities in the distribution of risks and benefits (Kowszyk et al., 2023; Oh et al., 2023). These impacts often persist even after technical stabilization, undermining long-term social acceptance of solution-mining projects.

Figure 12 synthesizes the key social impacts documented in major solution-mining accidents, emphasizing population displacement, livelihood disruption, and public health concerns reported across diverse geographic and regulatory contexts.

Figure 12. Summary of documented social impacts associated with major solution mining accidents (displacement, livelihood loss, health concerns). Adapted from Bastida (2020); Warhurst & Noronha (2024); Sánchez & Franks (2022); Kowalewski & Śpiewanowski, (2020); Solari et al. (2020).

Solution mining accidents often cause social issues beyond technical or environmental failures, including population displacement due to subsidence, sinkholes, or groundwater contamination, leading to evacuations and relocations. Livelihoods are affected by degraded land, fisheries, and water resources, resulting in income loss and instability. Health risks include exposure to contaminated water and airborne pollutants, as well as long-term health effects, underscoring the need for social risk assessment in mining governance.

Economic Consequences

The economic consequences of solution-mining accidents are often underestimated during project planning. Remediation costs for groundwater treatment, land stabilization, and long-term monitoring can exceed initial project capital expenditures, particularly in complex geological settings (Jeremic, 2020; Wagner & Mori, 2024).

In addition to direct remediation costs, operators may face legal liabilities, compensation claims, and regulatory penalties. Stock market reactions to major mining disasters show significant, sustained declines in value, reflecting investors' sensitivity to environmental and governance risks (Kowalewski & Śpiewanowski, 2020).

In severe cases, accidents can lead to partial or total project shutdowns, with cascading economic impacts on regional employment and public finances. These outcomes underscore the systemic nature of solution-mining risks, in which technical failures propagate into social and economic domains (Sánchez & Franks, 2022; Warhurst & Noronha, 2024).

Figure 13 synthesizes the typical cost escalation pathways associated with solution-mining accidents, illustrating how initial technical failures propagate into environmental damage, health impacts, community disruption, and ultimately long-term socioeconomic losses.

Figure 13. Cost-escalation pathways following solution-mining accidents: from technical failure to socioeconomic losses. Adapted from Bastida (2020); Gutiérrez et al. (2023); Kowalewski & Śpiewanowski (2020); Sánchez & Franks (2022); Solari et al. (2020); Tsalidis et al. (2020); Warhurst & Noronha (2024); Minkley et al. (2025).

The diagram illustrates how accident costs in solution mining cascade from well failures to environmental, health, displacement, and legal issues, with long-term costs exceeding initial remediation costs. This highlights the need for preventive design, early detection, and robust governance to mitigate engineering and socioeconomic risks.

The cumulative environmental, social, and economic impacts discussed in this section underscore the need for robust risk assessment frameworks and advanced monitoring technologies. The following section examines state-of-the-art approaches to hazard detection, early warning, and risk mitigation in solution-mining operations, with an emphasis on integrating geomechanical, hydrogeological, and real-time monitoring data.

Risk Assessment and Monitoring Technologies

The growing complexity and depth of solution mining operations have increased the need for integrated risk assessment and monitoring frameworks. Advances in numerical modeling, real-time sensing, and remote monitoring now allow earlier detection of instability, provided that data are properly interpreted and operational thresholds are enforced.

Cavern Design and Modeling

Risk mitigation in solution mining begins at the cavern design stage, where numerical geomechanics plays a central role. Modern models couple rock mechanics, creep behavior, and

fluid flow to predict cavern evolution, roof stability, and pillar integrity under long-term operational conditions (Jeremic, 2020; Zhang et al., 2021; Yu et al., 2022).

Shape control and leaching strategies are critical parameters influencing cavern stability. Irregular cavern geometries, uncontrolled leaching fronts, or excessive vertical growth significantly increase the likelihood of roof collapse and subsidence. Recent studies emphasize the importance of controlled injection–production schemes, staged leaching, and adaptive geometry correction to limit stress concentration and asymmetric dissolution (Xue et al., 2024; Zhang et al., 2024; Zhang et al., 2026).

Figure 14 illustrates the conceptual evolution of cavern geometry during solution-mining operations and the associated development of geomechanical risk zones, highlighting how progressive enlargement can progress from stable conditions to critical failure states.
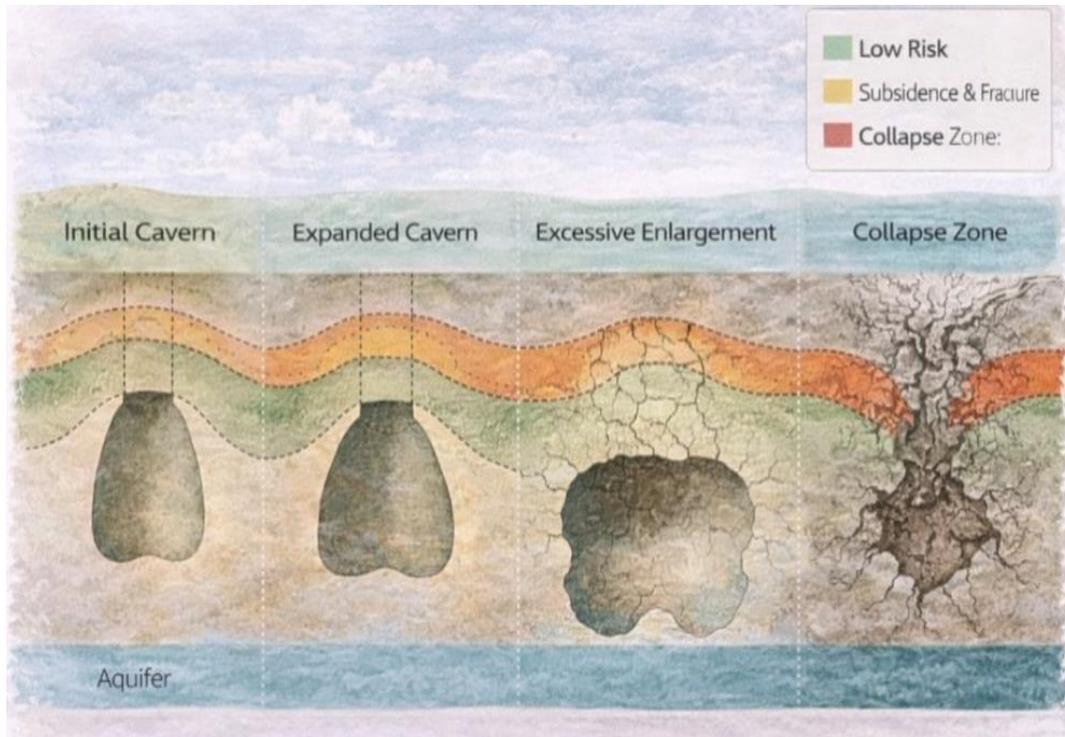
Figure 14. Conceptual illustration of cavern geometry evolution and associated geomechanical risk zones. Adapted from Duffy et al. (2022); Jeremic (2020); Minkley et al. (2025); Chen et al. (2025); Lord et al. (2021); Zhang et al. (2021).

The schematic shows how geomechanical instability in solution-mining caverns develops gradually, starting with controlled dissolution and low stress changes. As the cavern grows, stress concentrates in the roof and surrounding areas, leading to fractures, subsidence risks, and confinement loss, which can connect deep formations with aquifers and surface environments. This highlights the need for conservative cavern design, monitoring, and adaptive strategies.

Monitoring Systems

Continuous monitoring is essential for bridging the gap between modeled behavior and real-world conditions. Microseismic monitoring has become a key tool for detecting fracture initiation, stress redistribution, and early-stage roof instability, particularly in deep or heterogeneous salt formations (Contrucci et al., 2023; Liu et al., 2024; Yu et al., 2025).

In SAR and satellite deformation analysis allow regional monitoring of surface changes, detecting slow trends that may lead to sinkholes or collapses (Chen et al., 2021; Solari et al., 2020; Zhao et al., 2023; Zhu et al., 2024). Combining with GNSS and UAV photogrammetry improves spatial resolution and reliability (Fan et al., 2021; Sun et al., 2023).

Chemical monitoring complements other methods by helping identify leakage pathways, mixing with freshwater aquifers, and loss of confinement layers, especially in ISL uranium and lithium brine operations (Iskakov, 2020; Wang et al., 2024; Ye et al., 2024).

To support a comparative assessment of risk management practices in solution mining, Table 5 summarizes the primary monitoring technologies currently used across operations, highlighting their spatial scales, detection capabilities, response times, and inherent limitations.

Table 5. Comparison of monitoring technologies used in solution mining: scale, detection capability, response time, and limitations. Adapted from Solari et al. (2020); Hu et al. (2021); Contrucci et al. (2023); Gutierrez et al. (2023); Minkley et al. (2025).

Monitoring technology	Spatial scale	Primary detection capability	Typical response time	Main limitations
Microseismic monitoring	Cavern to regional	Rock fracturing, cavern roof instability, stress redistribution	Near real-time	Limited sensitivity to slow deformation; requires dense sensor networks
InSAR (satellite radar)	Regional to basin scale	Surface deformation, subsidence, sinkhole precursors	Days to weeks	Low temporal resolution; decorrelation in vegetated or wet areas
GNSS / GPS stations	Local to regional	Surface displacement trends	Near real-time	Point-based measurements; requires long-term installation
Well integrity logging	Well-scale	Casing corrosion, cement failure, leaks	Periodic (inspection-based)	Not continuous; failures may occur between inspections
Pressure and flow monitoring	Cavern / wellfield	Over-leaching, pressure anomalies, loss of confinement	Real-time	Limited spatial insight; indirect indicators of failure
Brine chemistry and tracers	Cavern–aquifer interface	Brine migration, aquifer contamination pathways	Days to months	Delayed detection; interpretation affected by hydrogeological complexity
Distributed fiber optic sensing (DAS/DTS)	Wellbore to cavern	Strain, temperature anomalies, leakage zones	Near real-time	High installation cost; data interpretation complexity

The comparison shows that no single monitoring technique is sufficient to capture the full spectrum of failure mechanisms in solution mining. Effective risk management, therefore, relies on integrated monitoring systems that combine geomechanical, hydrogeological, and operational data, enabling early detection of abnormal behavior and timely intervention.
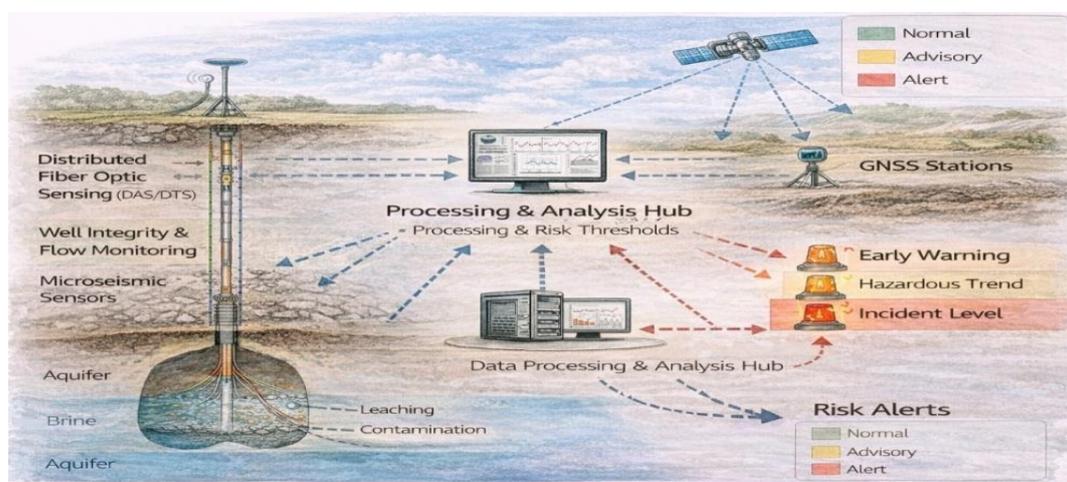
Early Warning Indicators

Effective monitoring must be paired with quantifiable early-warning indicators. Among the most reliable signals are pressure anomalies, such as unexpected drops or oscillations that may indicate a cavern breach, casing failure, or inter-cavern communication (Lord et al., 2021; Wagner & Mori, 2024).

Changes in brine composition, such as dilution, shifts in ion ratios, or tracer loss, often precede detectable mechanical failure and can serve as early indicators of leakage or unintended dissolution zones (Wang et al., 2025; Yi et al., 2023).

At the surface, deformation thresholds derived from InSAR time series and GNSS data are increasingly used to trigger alerts and operational interventions. However, their effectiveness depends on conservative threshold definitions and integration with subsurface data to avoid delayed responses (Hu et al., 2021; Intrieri et al., 2023; Zhang & Dong, 2025).

Figure 15 presents an integrated early-warning framework for solution-mining operations, illustrating how subsurface geomechanical signals, chemical indicators, and surface deformation monitoring can be integrated into a unified risk-assessment and alert system.

Figure 15. Integrated early warning framework linking subsurface signals, chemical indicators, and surface deformation. Adapted from Intrieri et al. (2023); Al Heib & Franck (2024); Chen et al. (2021); Solari et al. (2020); Zhao et al. (2023); Chen et al. (2021); Solari et al. (2020); Zhao et al. (2023).

The framework emphasizes integrating multiple data sources to enable proactive risk management in solution mining. Subsurface tools such as microseismic sensors, fiber-optic sensors, and well-integrity measurements provide early indicators of instability and fluid movement. These are complemented by chemical monitoring of brine and tracers, as well as surface deformation data from GNSS and InSAR.

Centralizing diverse datasets in a hub enables the application of thresholds and trend analyses to classify conditions as normal, advisory, or alert. This helps detect hazards early, supports prompt decisions, and reduces the risk of failures that affect the environment and society.

Although advanced modeling and monitoring technologies reduce technical uncertainty, their effectiveness depends on regulation, discipline, and governance. The next section examines how regulatory frameworks and best practices shape risk management in solution-mining worldwide.

Regulatory Frameworks and Best Practices

The safety and sustainability of solution mining operations are strongly influenced by the regulatory frameworks under which they operate and by the degree to which industry best practices are implemented. Unlike conventional mining, solution mining involves subsurface processes that are often invisible at the surface, increasing reliance on regulation-driven monitoring, reporting, and preventive controls.

International Regulations

In the United States, solution mining activities are regulated through a combination of federal and state agencies. The Environmental Protection Agency (EPA) oversees groundwater protection under the Safe Drinking Water Act, particularly for injection wells, while the Nuclear Regulatory Commission (NRC) regulates uranium in-situ leaching (ISL) operations, focusing on radiation protection, aquifer restoration, and long-term site stewardship (Iskakov, 2020; Lord et al., 2021). Regulatory requirements typically include baseline hydrogeological characterization, multi-barrier well integrity, and post-closure groundwater monitoring.

Within the EU, solution mining is regulated by directives on groundwater, emissions, and environmental liability. The Water Framework and Mining Waste Directives control brine migration, subsidence, and long-term impacts. Case studies highlight regulatory gaps and legacy permits that delay responses to subsidence and sinkholes (Contrucci et al., 2023; Minkley et al., 2025).

For uranium ISL operations, the IAEA offers guidelines on wellfield design, lixiviant control, radiation monitoring, and aquifer restoration, emphasizing the importance of confinement integrity and demonstrating that groundwater can be restored after mining (Iskakov, 2020; Sydykov et al., 2025).

Table 6 compares the main regulatory requirements for solution mining in the USA, the EU, and the IAEA (2021), highlighting similarities and differences in permitting, monitoring, closure, and post-closure. It supports Section 9 by placing regulatory controls in a risk management framework.

Table 6. Comparison of regulatory requirements for solution mining across major jurisdictions (USA, EU, IAEA): permitting, monitoring, closure, and post-closure obligations. Adapted from Bastida (2020); Jeremic (2020); Page et al. (2021); Sánchez & Franks (2022); Warhurst & Noronha (2024); Wagner & Mori (2024); Xu et al. (2024).

Regulatory aspect	USA (federal + state frameworks)	European Union (EU directives + national law)	IAEA (ISL uranium – international guidance)
Permitting and licensing	Multi-agency permitting (environmental, mining, water); site-specific conditions; financial assurance typically required.	Authorization by national competent authorities under EU environmental, water, and industrial safety directives; site-specific permits.	Licensing of uranium mining/milling using a graded approach; a safety case is required demonstrating radiological and environmental protection.
Baseline characterization	Mandatory hydrogeological and groundwater quality baseline; well integrity and, where relevant, subsidence risk assessment.	Environmental baseline required under EIA/SEA and water protection frameworks, with a focus on groundwater and ecosystems.	Radiological and hydrogeological baseline (groundwater, soils, radon); definition of reference conditions for restoration.

Operational monitoring	Groundwater monitoring (upgradient/downgradient), well integrity (pressure, casing/cement), brine chemistry; reporting defined by permit.	Monitoring requirements defined nationally, aligned with groundwater protection and non-deterioration principles.	Continuous monitoring of radiological parameters, groundwater chemistry, wellfield performance, and containment excursions.
Containment and excursion control	Hydraulic control and excursion detection are commonly required for ISL; corrective action plans are mandated.	Containment obligations are embedded in national permitting and groundwater protection regimes.	Central requirement: demonstrate confinement, define excursion thresholds, and implement rapid corrective actions.
Well integrity requirements	Mechanical integrity testing, pressure tests, cement evaluation, repair, and shutdown criteria are defined in permits.	Integrity standards are implemented through national mining and industrial safety regulations.	Strong emphasis on design, construction, verification, and lifecycle integrity of wells in ISL operations.
Subsidence and stability control	Geomechanical assessment and monitoring are required where dissolution caverns pose stability risks.	Managed through national mining law and land-use planning; monitoring is required where ground instability is credible.	Considered within the safety case if stability affects radiological or environmental pathways.
Incident reporting and emergency response	Mandatory reporting of releases, integrity failures, and excursions; emergency response plans required.	Incident reporting is required under national environmental liability and safety frameworks.	Mandatory reporting of radiological or environmental incidents; predefined response and mitigation procedures.
Closure planning	Closure and reclamation plan required at permitting stage; includes well plugging, site restoration, and monitoring.	Closure obligations are defined nationally, aligned with waste, water, and environmental liability requirements.	Closure and decommissioning integral to licensing; explicit groundwater restoration objectives for ISL.
Post-closure monitoring	Duration and scope defined by permit; may include long-term groundwater and deformation monitoring.	Post-closure monitoring is required where residual risks remain; duration is defined nationally.	Post-closure verification is required until restoration and safety objectives are demonstrated.
Financial assurance and liability	Bonds or other financial assurance instruments are widely required; long-term liability is defined by federal/state law.	Financial liability is guided by EU environmental liability principles and implemented nationally.	Emphasizes responsibility and documentation; financial assurance is addressed through national regulatory systems.

Industry Best Practices

Beyond formal regulation, industry experience has led to the consolidation of best practices to reduce accident frequency and severity. Double or multiple casing systems, combined with high-integrity cementation, are widely recognized as a primary barrier to brine leakage and cross-aquifer contamination (Jeremic, 2020; Wagner & Mori, 2024).

Controlled leaching envelopes are another critical practice. By carefully managing injection rates, solution chemistry, and cavern geometry, operators can limit uncontrolled dissolution and reduce the risk of roof instability and subsidence. Numerical feedback loops that link monitoring data to leaching control strategies are increasingly used in modern operations (Xue et al., 2024; Zhang et al., 2026).

Equally important are closure and post-closure monitoring programs, which address long-term risks that may persist decades after active mining ends. Best practice guidelines recommend extended monitoring of groundwater chemistry, surface deformation, and pressure conditions, particularly in densely populated or environmentally sensitive areas (Lecomte et al., 2023; Minkley et al., 2025).

Figure 16 presents a lifecycle risk management framework for solution mining that integrates technical, environmental, and regulatory controls from design through post-closure. It emphasizes proactive risk identification, continuous monitoring, and adaptive management to prevent accidents and reduce long-term liability.

Figure 16. Lifecycle risk management framework for solution mining: design, operation, closure, and post-closure. Adapted from Bastida (2020); Jeremic (2020); Lord et al. (2021); Solari et al. (2020); Sánchez & Franks (2022); Minkley et al. (2025); Wagner & Mori (2024); Page et al. (2021).

This lifecycle view shows that risks in solution mining evolve over time rather than remaining static at a single stage. Design impacts stability, and monitoring informs closure plans and future duties. Early warning systems and controls prevent minor failures from becoming major environmental and social issues.

Despite strict regulations and best practices, major accidents occur, showing that compliance alone is insufficient without technical knowledge, culture, and adaptive risk management. The next section summarizes lessons from past failures and strategies for future solution mining projects.

Lessons Learned and Preventive Strategies

The analysis of global case studies reveals that accidents in solution mining are rarely random events. Instead, they reflect recurrent systemic weaknesses involving engineering design assumptions, geological uncertainty, monitoring limitations, and institutional governance gaps. Lessons learned from these incidents provide valuable guidance for improving future risk management frameworks and preventing similar failures.

Global solution mining accidents show consistent patterns across minerals, geology, and regulations. Failures result from the interplay of technical issues, geological uncertainty, operational choices, and governance, rather than from a single cause (Jeremic, 2020; Minkley et al., 2025).

A key lesson is adopting a design-for-failure approach. Many accidents occurred because systems were based on idealized assumptions that ignored deviations in pressure, cavern geometry, or hydrogeology. Studies show early warning signs often existed but weren't linked to mitigation thresholds (Lord et al., 2021; Muntendam-Bos et al., 2022). Designing for failure entails incorporating redundant well barriers, conservative operating limits, and emergency protocols into daily work, not merely as exceptions.

A key lesson emphasizes conservative cavern geometries to prevent roof instability, pillar failure, and subsidence, as excess enlargement and irregular dissolution fronts cause risks years after peak production. Controlling cavern shape throughout its life, including post-closure, is essential. (Jin et al., 2022; Zhang et al., 2021; Minkley et al., 2025; Yi et al., 2023)

Preventive strategies need integrated geomechanical–hydrogeological modeling. Traditional decoupled methods can't capture feedback between stress, permeability, and brine flow. Recent advances show the benefits of coupled models, especially when calibrated with microseismic data and surface measurements (Li et al., 2022; Zhu et al., 2024). Incorporating monitoring data into adaptive models enhances predictions and supports proactive decisions.

Several accidents indicate that technical robustness alone is insufficient without transparent governance and stakeholder engagement. Delayed anomaly disclosures, fragmented oversight, and poor community communication exacerbate social and economic impacts, particularly in densely populated and sensitive areas (Kowalewski &Śpiewanowski, 2020; Kowszyk et al., 2023). Transparent reporting, independent audits, and inclusive decision-making are now regarded as risk-prevention measures rather than merely post-accident remedies (Sánchez & Franks, 2022; Warhurst & Noronha, 2024).

Figure 17 presents a framework that links engineering design, monitoring, governance, and social engagement as vital pillars of accident prevention in solution mining. It highlights

that accident prevention is not merely technical but depends on coordinated efforts across engineering, institutions, and society.
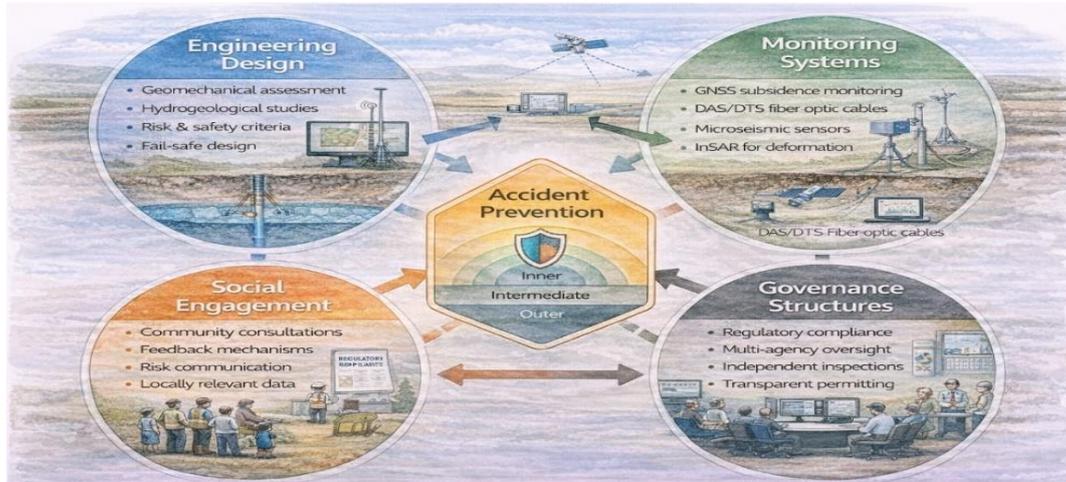
Figure 17. Conceptual framework linking engineering design, monitoring systems, governance structures, and social engagement in accident prevention, adapted from Jeremic (2020); Sánchez & Franks (2022).

The framework illustrates accident prevention from four interconnected dimensions. Engineering design creates the technical foundation with conservative cavern geometries, hydrogeological data, and fail-safe principles. Monitoring provides continuous feedback on subsurface behavior, detecting deviations early through geomechanical, geochemical, and deformational signals. Governance guarantees compliance, oversight, and accountability. Social

engagement enhances transparency, risk communication, and trust among operators, regulators, and communities. Together, these elements form a layered system to reduce the risk, impact, and societal effects of solution mining accidents.

Table 8 summarizes the core pillars of solution-mining accident prevention, highlighting their main components, primary functions, and typical risk-reduction outcomes.

Table 7. Lessons learned from major solution mining accidents and corresponding preventive strategies. Adapted from Jeremic (2020); Sánchez and Franks (2022).

Pillar	Key components	Primary function	Typical risk mitigation outcomes
Engineering design	Conservative cavern geometry; hydrogeological characterization; geomechanical modeling; fail-safe design criteria	Establish intrinsic system stability and design margins	Reduced the likelihood of collapse, subsidence, and uncontrolled leakage
Monitoring systems	Microseismic sensors; DAS/DTS fiber-optic cables; InSAR and GNSS deformation monitoring; brine chemistry surveillance	Early detection of abnormal subsurface behavior	Timely intervention before failure escalation
Governance structures	Transparent permitting; regulatory oversight; independent inspections; lifecycle compliance	Ensure accountability and enforcement of safety standards	Prevention of systemic and organizational failures
Social engagement	Community consultation; risk communication; grievance mechanisms; local participation	Build trust and social legitimacy	Reduced conflict escalation and improved emergency response
Integrated decision-making	Data integration platforms, risk thresholds, and cross-disciplinary review	Translate signals into operational action	Coordinated and proactive risk management

The table shows that effective accident prevention in solution mining depends on the coordinated performance across technical, institutional, and social dimensions. While engineering design and monitoring systems address physical failure mechanisms, governance structures and social engagement determine how risks are perceived, managed, and communicated. Integrating these pillars enables a shift from reactive incident management to preventive, risk-informed decision-making across the full project lifecycle.

Despite the consolidation of these lessons, emerging applications of solution mining—such as deeper caverns, energy storage, and expanded ISL operations—introduce new uncertainties. These challenges define a forward-looking research agenda, which is addressed in the following section.

Key Cross-Cutting Lessons

Across different commodities and regions, four cross-cutting lessons emerge from the global accident record in solution mining.

First, conservative cavern design and strict geometry control remain fundamental to preventing geomechanical instability.

Second, robust well integrity management—including corrosion-resistant materials, high-quality cementation, and continuous integrity testing—is essential to prevent uncontrolled fluid migration.

Third, monitoring systems must be integrated rather than isolated, combining geomechanical, hydrogeological, and chemical indicators into unified early-warning frameworks.

Finally, effective governance and transparent regulatory oversight are critical to ensure that technical warnings are translated into timely operational decisions.
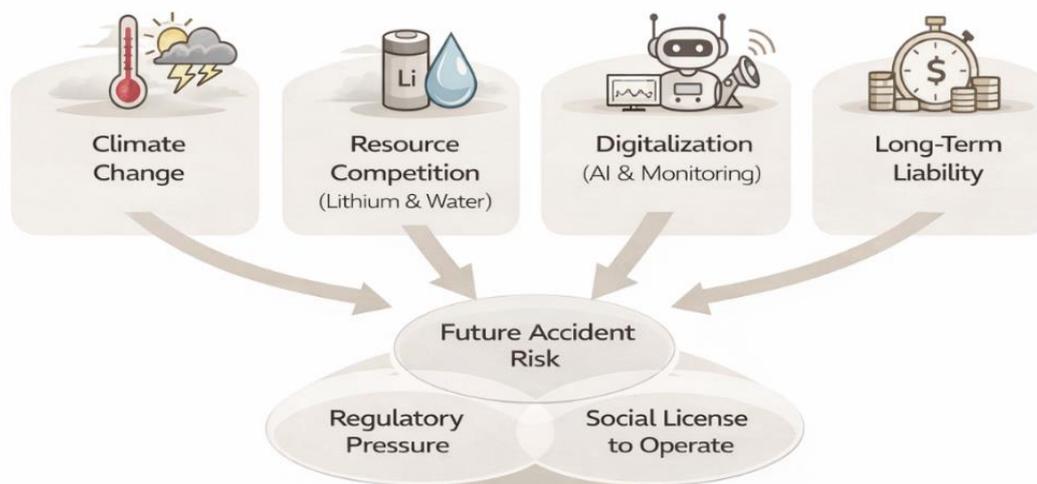
Future Challenges and Research Needs

Despite the technological maturity achieved in several solution-mining applications, the growing complexity of operating environments and societal expectations pose a new set of challenges that require coordinated advances in science, engineering, and governance. These challenges are particularly relevant in scenarios of climate change, resource competition, digital transformation, and long-term environmental liability.

Climate Change Effects on Brine Balance

Climate change is expected to alter precipitation patterns, evapotranspiration rates, and groundwater recharge, directly affecting brine balance and cavern stability in solution-mining systems. Changes in hydrological regimes may exacerbate pressure fluctuations, accelerate subsidence, and increase the likelihood of brine migration beyond designed containment boundaries (Solari et al., 2020; Zhang et al., 2024; Ye et al., 2024). However, climate-related impacts remain underrepresented in current cavern design standards and risk assessment frameworks, underscoring the need for integrated climate–hydrogeological modeling approaches.

To address uncertainties beyond traditional geomechanical and hydrogeological risks, a broader perspective is needed. Figure 18 presents an integrative framework that combines climate stressors, resource competition, digital transformation, and long-term liability, illustrating how these factors influence future risks, regulation, and social license in solution mining.

Figure 18. Conceptual framework illustrating emerging challenges and research priorities in solution mining. Adapted from Jeremic (2020); Sánchez & Franks (2022); Warhurst & Noronha (2024).

This framework highlights that accident prevention in solution mining is driven by interactions among environmental variability, technology, institutions, and stakeholders. Effective risk strategies must be adaptive, interdisciplinary, and integrated into long-term regulatory and social accountability systems.

Lithium Brines and Water Scarcity

The rapid expansion of lithium brine extraction has intensified conflicts over water use in arid and semi-arid regions. Unlike traditional salt and potash operations, lithium brine systems interact strongly with shallow aquifers and surface ecosystems, thereby amplifying socio-environmental risks (Yi et al., 2023; Tsalidis et al., 2020). Current monitoring practices often lack the temporal and spatial resolution needed to capture cumulative impacts on water balance, underscoring the need for improved tracer studies, basin-scale modeling, and transparent data-sharing mechanisms to support sustainable governance of brine resources.

AI-Based Monitoring and Predictive Analytics

Advances in artificial intelligence, machine learning, and data fusion offer significant opportunities to improve accident prevention and early warning in solution mining. Recent studies demonstrate the potential of AI-based systems to identify precursors of geomechanical failure, classify microseismic patterns, and automate root cause analysis from large accident databases (Agarwal et al., 2025; Jian et al., 2024; Yu et al., 2025). Nevertheless, the deployment of such tools remains fragmented, often limited by data quality, interoperability issues, and regulatory uncertainty. Future

research should prioritize explainable AI models and their integration into regulatory-compliant monitoring systems.

Long-Term Liability and Mine Closure

Long-term environmental liability represents one of the most critical unresolved challenges in solution mining. Cavern instability, delayed subsidence, and post-closure brine leakage may manifest decades after operations cease, transferring risks to future generations and public institutions (Lecomte et al., 2023; Busetti, 2024; Lord et al., 2021). Existing closure frameworks frequently underestimate these delayed effects, underscoring the need for extended post-closure monitoring, financial assurance mechanisms, and adaptive regulatory models to address long-term uncertainty.

Table 8 synthesizes the key emerging challenges in solution mining, highlighting key uncertainties, current technical and institutional limitations, priority research needs, and associated policy implications.

Table 8. Future Challenges and Research Gaps in Solution Mining, Adapted from Sydykov, Y., Sailaubay, Y., Maslov, K., & Zhanbossinova, A. (2025); Sánchez, L. E., & Franks, D. M. (2022).

Challenge Area	Key Uncertainties	Current Limitations	Research Needs	Policy Implications
Climate change impacts	Brine balance variability	Static design assumptions	Coupled climate–hydro models	Adaptive permitting
Lithium brines	Water–ecosystem interaction	Limited basin-scale data	Tracer + long-term monitoring	Water governance reform
AI-based monitoring	False positives / opacity	Fragmented datasets	Explainable AI models	Regulatory acceptance
Long-term liability	Delayed failures	Short closure horizons	Post-closure risk modeling	Financial assurance

The challenges indicate a shift in solution-mining risks driven by climate change, resource competition, digitalization, and longer liability periods. Tackling these needs calls for technological advances and regulatory changes in permitting, data transparency, and accountability. Without them, risks may be underestimated during project approval and closure.

Preventing accidents in solution mining needs more than better design or monitoring. An integrated approach that combines technical expertise, environmental stewardship, digital tools, and strong governance is essential. This section summarizes key findings and recommends safer, sustainable practices.

Conclusions

This review examined solution mining across multiple commodities, focusing on accident mechanisms, systemic vulnerabilities, and regulatory responses. The analysis demonstrates that, although solution mining is often perceived as a lower-impact alternative to conventional extraction methods, it presents distinctive risk profiles characterized by delayed failures, poorly observable subsurface processes, and complex interactions between geomechanical, hydrogeological, and operational factors. These characteristics demand analytical frameworks that extend beyond traditional mining safety paradigms.

The findings indicate that the primary drivers of accidents are structural and systemic rather than purely technical. Inadequate cavern design, insufficient geological characterization, and limited integration between geomechanical and hydrogeological models frequently contribute to instability. These technical weaknesses are often exacerbated by operational practices such as aggressive leaching, insufficient cavern geometry control, and delayed responses to early warning signals. Importantly, several documented accidents have occurred long after peak operation or even after mine closure, highlighting the long-term and often underestimated risk profile of solution-mining systems.

The review also reveals a persistent gap between technological development and regulatory frameworks. Existing regulatory systems are typically focused on permitting and operational compliance, while long-term monitoring, environmental liability, and post-closure risks receive comparatively less attention. Moreover, regional comparisons show that effective accident prevention depends not only on technical standards but also on institutional capacity, regulatory enforcement, transparency, and stakeholder engagement.

From an engineering perspective, the findings reinforce the importance of adopting failure-aware design approaches that explicitly account for geological uncertainty, long-term cavern evolution, and potential irreversible environmental impacts. Integrated monitoring systems—combining geomechanical, hydrogeological, chemical, and surface-deformation data—are essential for detecting early signs of instability and enabling proactive operational responses. As digital monitoring tools and data-driven systems become increasingly integrated into mining operations, ensuring transparency, interpretability, and regulatory oversight will be critical to avoid new forms of operational opacity.

Overall, the sustainability of solution mining depends less on the intrinsic characteristics of the technology and more on the effectiveness of its governance, monitoring, and risk management frameworks. Without these safeguards, solution mining risks reproducing the delayed environmental impacts

and underestimated liabilities historically associated with other extractive industries.

Ultimately, preventing future solution-mining accidents requires moving beyond reactive regulatory approaches toward integrated risk-governance frameworks that combine conservative engineering design, continuous monitoring, transparent decision-making, and long-term environmental stewardship.

Declarations

Ethics Approval and Consent to Participate

Not applicable. This study is a review article based exclusively on previously published literature, publicly available reports, and regulatory documents. No human participants or animals were involved.

Availability of Data and Materials

All data supporting the findings of this study are derived from publicly available sources cited in the reference list. No new datasets were generated or analyzed during the current study.

Competing Interests

The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Authors' Contributions

The author was solely responsible for the conception of the study, literature review, analysis and interpretation of the data, and writing of the manuscript.

References

1. Food security: A survey of selected counties in Kenya. International Journal of Economics and Management Studies, 7(8), 115-124.

2. Agarwal, S., Chugh, Y. P., Singh, A., Sakinala, V., Mukherjee, A., Prasad, B., ... & Zou, Y. (2025). Application of natural language processing and machine learning for analyzing mining accident reports and automating the process of root cause analysis. International Journal of Coal Science & Technology, 12(1), 91. https://doi.org/10.1007/s40789-025-00822-0

3. Al Heib, M., & Franck, C. (2024). A methodology for multi-hazard interaction assessment of abandoned mines. Journal of Industrial Safety, 1(2), 100018. https://doi.org/10.1016/j.jinse.2024.100018

4. Arrighi, S., Franceschini, F., Petrini, R., Fornasaro, S., & Ghezzi, L. (2024). The legacy of Hg contamination in a past mining area (Tuscany, Italy): Hg speciation and health risk assessment. Toxics, 12(6), 436. https://www.mdpi.com/2305-6304/12/6/436#

5. Asylbekova, A. A. (2021). Radioecological situation of contamination of the semipalatinsk test site. География и водныересурсы, (2), 56-61.

6. Aumalikova, M. (2025). Impact of uranium mining on radiation levels in Kazakhstan: a case study of two major provinces. Bulletin of the L.N. Gumilyov Eurasian National University. physics. astronomy series, 151(2), 45-59.

7. Bastida, A. E. (2020). The law and governance of mining and minerals: A global perspective. Bloomsbury Publishing.

8. Busetti, A. (2024). Sinkholes of the Friuli Venezia Giulia region: characterization, data collection, and hazard definition. https://hdl.handle.net/20.500.14242/63313

9. Cai, M., Li, P., Tan, W., & Ren, F. (2021). Key engineering technologies to achieve green, intelligent, and sustainable development of deep metal mines in China. Engineering, 7(11), 1513-1517.

10. Chen, J., Liu, X., Liu, J., & Wang, P. (2025). Study on the mechanism and control of ground subsidence induced by solution mining in Guangzhou Longgui Nitrate-Salt Mine. Frontiers in Materials, 12, 1630238. https://doi.org/10.3389/fmats.2025.1630238

11. Chen, Y., Yu, S., Tao, Q., Liu, G., Wang, L., & Wang, F. (2021). Accuracy verification and correction of D-InSAR and SBAS-InSAR in monitoring mining surface subsidence. Remote Sensing, 13(21), 4365. https://www.mdpi.com/2072-4292/13/21/4365#

12. Contrucci, I., Namjesnik, D., Niemz, P., Primo, P., Kotyrba, A., Mutke, G., ... & Cesca, S. (2023). European feedback on post-mining seismicity. Journal of Sustainable Mining, 22(3), 195-218. https://doi.org/10.46873/2300-3960.1385

13. da Silva, R. F. da, & Kormann, A. (2020). *Subsidence control in solution mining areas: A systematic review.* In *Proceedingsofthe XX Congresso Brasileiro de Mecânica dos Solos e Engenharia Geotécnica, IX Simpósio Brasileiro de Mecânica das Rochas, IX Simpósio Brasileiro de Engenheiros Geotécnicos Jovens, and VI Conferência Sul-Americana de Engenheiros Geotécnicos Jovens* (pp. xx–xx). Campinas, SP, Brazil, September 15–18.. https://doi.org/10.4322/cobramseg.2022.0795

14. Duffy, O. B., Moscardelli, L., Hudec, M. R., Dooley, T. P., Peel, F., Looff, K., ... & Shuster, M. W. (2022). Potential controls on the origin, nature and distribution of shear zones in salt stocks: Salt tectonic insights with a solution mining perspective. *In Solution Mining Research Institute, Technical Conference.*

15. Fan, H., Lian, X., Yang, W., Ge, L., Hu, H., & Du, Z. (2021). Mining large-gradient subsidence monitoring using D-InSAR optimized by GNSS. *The Imaging*

Science Journal, 69(1-4), 207-218 https://doi.org/10.1080/13682199.2022.2156667.

16. Ferentinou, M., Grobler, M., Malinowska, A., Farina, P., &Yumba, J. (2023). *Smart Monitoring & Early Warning System of Sinkhole with Fibre Optic Sensors and InSAR*. http://www.wrc.org.za/

17. Gutiérrez, F., Sevil, J., Sevillano, P., Preciado-Garbayo, J., Martínez, J. J., Martín-López, S., & González-Herráez, M. (2023). The application of distributed optical fiber sensors (BOTDA) to sinkhole monitoring. Review and the case of a damaging sinkhole in the Ebro Valley evaporite karst (NE Spain). *Engineering Geology*, 325, 107289 https://doi.org/10.1016/j.enggeo.2023.107289.

18. Hu, B., Chen, L., Zou, Y., Wu, X., & Washaya, P. (2021). Methods for monitoring fast and large gradient subsidence in coal mining areas using SAR images: A review. *Ieee Access*, 9, 159018-159035 https://doi.org/10.1109/ACCESS.2021.3126787.

19. Intrieri, E., Confuorto, P., Bianchini, S., Rivolta, C., Leva, D., Gregolon, S., ... & Fanti, R. (2023). Sinkhole risk mapping and early warning: the case of Camaiore (Italy). *Frontiers in Earth Science*, 11, 1172727https://doi.org/10.3389/feart.2023.1172727.

20. Iskakov, M. M. (2020). 217-*Overview Of The Radiation Protection System And Radiation Monitoring At Uranium Mining Enterprises Using Isl Method*. . They have not been edited., 349.

21. Jeremic, M. L. (2020). Rock mechanics in salt mining. *CRC Press*.

22. Jian, Z., Zhao, G., Wang, P., Liu, X., Jiang, M., Liu, L., & Ma, J. (2024). Identification of the mining accidents by a two-step clustering method for the mining-induced seismicity. *Frontiers in Earth Science*, 12, 1348698 https://doi.org/10.3389/feart.2024.1348698.

23. Jin, C., Zhao, F., Liu, L., Shangguan, S., Zhang, B., Zhang, X., & Gao, S. (2022). Subsidence of strata overlying salt mines: a case study in Northern China. *Environmental Earth Sciences*, 81(12), 334https://doi.org/10.1007/s12665-022-10451-4.

24. Jones, C. (2024). Sinkholes. In Remote Sensing for Characterization of Geohazards and Natural Resources (pp. 371-387). *Cham: Springer International Publishing*. https://link.springer.com/book/10.1007/978-3-031-59306-2.

25. Kapusta, M., Bąk, P., & Sukiennik, M. (2025). Mine safety and personal health–in terms of mining accidents and disasters in the Polish coal mining industry—frontiers *in Earth Science*, 13, 1690436 https://doi.org/10.3389/feart.2025.1690436.

26. Kashkinbayev, Y., Ibrayeva, D., Aumalikova, M., Saifulina, E., Bizhanova, D., Mussayeva, E., ... & Bakhtin, M. (2025). Radon Concentration Survey in Settlements Located in Uranium Mining Territory in Northern Kazakhstan. *International Journal of Environmental Research and Public Health*, 22(5), 723 https://www.mdpi.com/1660-4601/22/5/723#.

27. Kazbekova, D., Ogami, A., Ando, H., Baigabylov, N., & Yensebayeva, A. (2025). Mining, Health, And Society: A Comparative Analysis of Occupational Accidents in Kazakhstan and Japan. *Eurasian Research Journal*, 7(1), 73-99 https://izlik.org/JA62TJ89WG.

28. Konuk, C. N. (2023). Numerical Analysis of Destressing to Mitigate the Sudden Collapse Risk of Stiff Layers in Solution Mining (Master's thesis, Middle East Technical University (Turkey)).

29. Kowalewski, O., &Śpiewanowski, P. (2020). Stock market response to potash mine disasters. *Journal of Commodity Markets*, 20, 100124 https://doi.org/10.1016/j.jcomm.2020.100124.

30. Kowszyk, Y., Vanclay, F., & Maher, R. (2023). Conflict management in the extractive industries: A comparison of four mining projects in Latin America. *The Extractive Industries and Society*, 13, 101161 https://doi.org/10.1016/j.exis.2022.101161.

31. Lecomte, A., Charmoille, A., Laoufa, F., Rupasinghe, S., & Gombert, P. (2023, October). An example of a comprehensive technical and administrative mine closure process on the Urcuit mining site (France). *In Mine Closure 2023: Proceedings of the 16th International Conference on Mine Closure. Australian Centre for Geomechanics*https://doi.org/10.36487/ACG_repo/2315_092.

32. Li, Y., Deng, H., Wen, L., Qin, Y., & Xu, X. (2022). Method for identifying and forecasting mining-induced earthquakes based on spatiotemporal characteristics of microseismic activities in Fankou lead/zinc mine.*Minerals*,12(3), 318.

33. Liou, C. S., & Tsai, C. M. (2020). The Governing Paradox in a Transition Economy: Repeated Institutional Reforms and Increasing Regulatory Capture in China's Energy Sector. *Problems of Post-Communism*, 67(2), 156-168 https://doi.org/10.1080/10758216.2019.1604144.

34. Liu, F., Wang, Y., Kou, M., & Liang, C. (2024). Applications ofmicroseismic monitoring technique in coal mines: A state-of-the-art review. *Applied Sciences*, 14(4), 1509 https://www.mdpi.com/2076-3417/14/4/1509#.

35. Liu, W., Zhang, Z., Fan, J., Jiang, D., Li, Z., & Chen, J. (2020). Research on gas leakage and collapse in the cavern roof of underground natural gas storage in thinly bedded salt rocks—Journal *of Energy Storage*,31, 101669 https://doi.org/10.1016/j.est.2020.101669.

36. Lord, A. S., Moriarty, D. M., & Sobolik, S. R. (2021).Bryan Mound Abandoned Cavern 3 Stability Analysis-2021 Review (No. SAND2021-6650).

Sandia National Lab. (SNL-NM), Albuquerque, NM (United States) https://doi.org/10.2172/1813647.

37. Ludeling, C., Minkley, W., Naumann, D., Brandt, M., & Taghichian, A. (2025). Geomechanical investigation of a solution mining field in northeast Brazil. *The Mechanical Behavior of Salt XI*, 360.

38. Minkley, W., Lüdeling, C., Brückner, D., & Naumann, D. (2025). Subsidence and Sinkhole Risk Over a Solution Mining Cavern Field in Maceió, Brazil: Analysis of the Geomechanical Processes—Part I. *Rock Mechanics and Rock Engineering*, 1-26 https://doi.org/10.1007/s00603-025-05149-5.

39. Mudimu, G. (2021). *The effectiveness of codes of conduct of selected South African mining companies in regulating labour standards: window dressing or genuine regulatory instruments.* http://hdl.handle.net/11427/37821

40. Muntendam-Bos, A. G., Hoedeman, G., Polychronopoulou, K., Draganov, D., Weemstra, C., van der Zee, W., ... & Roest, H. (2022). An overview of induced seismicity in the Netherlands. *Netherlands Journal of Geosciences*, 101, e1 https://doi.org/10.1017/njg.2021.14.

41. Ni, R., Liu, C., Meng, M., Wu, Z., Ren, Z., Li, G., & Zhang, C. (2026). Multistage rupture mechanism of gypsum mine collapse seismicity revealed by moment tensor inversion and surface deformation monitoring. *Geomechanics and Geophysics for Geo-Energy and Geo-Resources*, 12(1), 16 https://doi.org/10.1007/s40948-025-01096-1.

42. Namjesnik, D., Kinscher, J., Gunzburger, Y., Poiata, N., Dominique, P., Bernard, P., & Contrucci, I. (2021). Automatic detection and location of microseismic events from sparse network and its application to post-mining monitoring. *Pure and Applied Geophysics*, 178(8), 2969-2997https://doi.org/10.1007/s00024-021-02773-4.

43. Oh, C. H., Shin, J., & Ho, S. S. H. (2023). Conflicts between mining companies and communities: Institutional environments and conflict resolution approaches. *Business Ethics, the Environment & Responsibility*,32(2), 638-656 https://doi.org/10.1111/beer.12522.

44. Orhan, O., Haghshenas Haghighi, M., Demir, V., Gökkaya, E., Gutiérrez, F., & Al-Halbouni, D. (2023). Spatial and temporal patterns of land subsidence and sinkhole occurrence in the Konya Endorheic Basin, Turkey. *Geosciences,* 14(1), 5 https://www.mdpi.com/2076-3263/14/1/5#.

45. Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, 372, n71. https://doi.org/10.1136/bmj.n71

46. Saha, L., & Bauddh, K. (2021). Characteristics of mining spoiled and oil drilling sites and adverse impacts of these activities on the environment and human health. *In Phytorestoration of abandoned mining and oil drilling sites* (pp. 87-101). https://doi.org/10.1016/B978-0-12-821200-4.00020-0.

47. Saifulina, E., Janabayev, D., Kashkinbayev, Y., Shokabaeva, A., Ibrayeva, D., Aumalikova, M., ... & Bakhtin, M. (2023, March). Epidemiology of somatic diseases and risk factors in the population living in the zone of influence of uranium mining enterprises of Kazakhstan: a pilot study. *In Healthcare* (Vol. 11, No. 6, p. 804). https://www.mdpi.com/2227-9032/11/6/804#.

48. Sánchez, L. E., & Franks, D. M. (2022). An evolving agenda for environmental, health, and safety management in mining. *InRoutledge Handbook of the Extractive Industries and Sustainable Development* (pp. 329-348). https://doi.org/10.4324/9781003001317.

49. Solari, L., Montalti, R., Barra, A., Monserrat, O., Bianchini, S., & Crosetto, M. (2020). Multi-temporal satellite interferometry for fast-motion detection: An application to salt solution mining. *Remote Sensing*, 12(23), 3919 https://www.mdpi.com/2072-4292/12/23/3919#.

50. Son, H. J., Kang, S. H., Jung, J. P., & Kim, C. L. (2023). Long Term Trend of Uranium Production and Price.*Journal of Nuclear Fuel Cycle and Waste Technology* (JNFCWT),21(2), 295-301 https://db.koreascholar.com/Article/Detail/423391.

51. Sun, L., Wang, Z., Yang, C., Dai, Q., & Yao, Y. (2023, October). Application of Intelligent Automated Settlement Monitoring in Surface Subsidence of Salt Caverns Based on GNSS Technology. *In2023 IEEE 3rd International Conference on Data Science and Computer Application (ICDSCA)*(pp. 1551-1555). IEEE https://doi.org/10.1109/ICDSCA59871.2023.10392642.

52. Sydykov, Y., Sailaubay, Y., Maslov, K., & Zhanbossinova, A. (2025). Risks and environmental impacts of Kazakhstan's uranium production. *In BIO Web of Conferences* (Vol. 173, p. 03018). https://doi.org/10.1051/bioconf/202517303018.

53. Valluru, C. T., Rae, A., & Dekker, S. (2020). Behind subcontractor risk: A multiple case study analysis of mining and natural resources fatalities.*Safety*,6(3), 40 https://www.mdpi.com/2313-576X/6/3/40#.

54. Vasquez, C. N. (2021).Groundfall *Hazards Assessment Methodology to Minimize the Number of Fatal Accidents in Artisanal and Small-Scale Mining (ASM): A Case Study of Peruvian Mining*(Master's thesis, Colorado School of Mines)

https://www.proquest.com/openview/330b5c4069662e4504316ceb8549e109/1?pq-origsite=gscholar&cbl=18750&diss=y.

55. Wagner, M., & Mori, G. (2024). Solution Mining. *Research Institute*.

56. Wang, H., Wang, X., Wang, Y., Wang, D., Hu, K., Zhong, W., & Guo, Z. (2024). Influence of ammonium sulfate leaching agent on engineering properties of weathered crust elution-deposited rare earth ore. Acta Geotechnica, 19(4), 2041-2062 https://doi.org/10.1007/s11440-023-01999-x.

57. Wang, Y., Sun, Q., Zhou, J., &Lv, J. (2025). Research on Emergency Response to Pipeline Leakage Accidents in Port Petrochemical Enterprises. InE3S *Web of Conferences* (Vol. 656, p. 01013). https://doi.org/10.1051/e3sconf/202565601013.

58. Wang, Z., Chen, F., Li, H., Huang, G., & Yang, C. (2025). Development and experimental study of China's first pressurized cavern testing device for salt caverns: measurement, 118930 https://doi.org/10.1016/j.measurement.2025.118930.

59. Warhurst, A., & Noronha, M. L. (Eds.). (2024).Environmental policy in mining: Corporate strategy and planning. *Taylor & Francis*.

60. Willacy, C., Dooley, T. P., Moscardelli, L., & De Borst, K. (2025, June). The Imageability of Salt Inclusions and Caverns for Safe Hydrogen Storage. In86th EAGE Annual Conference & Exhibition (Vol. 2025, No. 1, pp. 1-5). *European Association of Geoscientists & Engineers*https://doi.org/10.3997/2214-4609.202510036.

61. Xue, T., Yang, C., Shi, X., Hongling, M., Li, Y., Ge, X., & Liu, X. (2024). The formation mechanism of irregular salt caverns during solution mining for natural gas storage. Energy Sources, Part A: *Recovery, Utilization, and Environmental Effects*,46(1), 8042-8058 https://doi.org/10.1080/15567036.2020.1764151.

62. Xu, J., Yan, C., Boota, M. W., Chen, X., Li, Z., Liu, W., & Yan, X. (2024). Research on automatic identification of coal mining subsidence area based on InSAR and time series classification. *Journal of Cleaner Production*,470, 143293 https://doi.org/10.1016/j.jclepro.2024.143293.

63. Yang, X., Krul, K., & Sims, D. (2022). Uncovering coal mining accident coverups: An alternative perspective on China's new safety narrative. *Safety science*, 148, 105637 https://doi.org/10.1016/j.ssci.2021.105637.

64. Ye, W., Wang, Y., Ding, J., Yao, X., & Wang, S. (2024). Influence of brine leakage on frozen wall development in offshore sand layer when active freezing: A numerical study. *Cold Regions Science and Technology*,217, 104043 https://doi.org/10.1016/j.coldregions.2023.104043.

65. Yi, W., Li, Q., Zhao, X., Liu, W., & Du, J. (2023). Feasibility assessment of solution mining and gas storage in salt caverns: a case study of the Sanshui salt mine. *Frontiers in Energy Research*,11, 1301765 https://doi.org/10.3389/fenrg.2023.1301765.

66. Yu, H., Liu, Y., Ma, H., Zhao, K., & Liu, J. (2022). Pillar safety in shallow salt caverns by using numerical simulations—Journal *of Energy Storage*,55, 105881 https://doi.org/10.1016/j.est.2022.105881.

67. Yu, J., He, H., Liu, Z., He, X., Zhou, F., Song, Z., & Yang, D. (2025). Analysis of Spatiotemporal Characteristics of Microseismic Monitoring Data in Deep Mining Based on ST-DBSCAN Clustering Algorithm.*Processes*,13(8), 2359 https://www.mdpi.com/2227-9717/13/8/2359#.

68. Yussupov, K., Mikhalovsky, S., Khalid, M., Rysbekov, K., Omarov, A., Azat, S., & Akzholova, A. (2025). Research of influence of various factors on repair-and-renewal operations in technological wells during uranium geotechnology in complex mining and geological conditions. *Mining of Mineral Deposits*,19(1) https://doi.org/10.33271/mining19.01.132.

69. Zeqiri, K., Hetemi, M., Uka, U., Ibishi, G., & Mijalkovski, S. (2022). Analysis of near-miss incidents (NMI) reporting in mining operations. *Mining of Mineral Deposits*,16(3), 25-30 http://mining.in.ua/2022vol16_3_4.html.

70. Zhang, G., Liu, Y., Wang, T., Zhang, H., Wang, Z., Zhao, C., & Chen, X. (2021). Pillar stability of salt caverns used for gas storage considering sedimentary rhythm of the interlayers. *Journal of Energy Storage*,43, 103229 https://doi.org/10.1016/j.est.2021.103229.

71. Zhang, G., Zhang, H., Liu, Y., Wang, T., & Wang, Z. (2023). Surrounding rock stability of horizontal cavern reconstructed for gas storage. *Journal of Energy Storage*,59, 106534 https://doi.org/10.1016/j.est.2022.106534.

72. Zhang, H., Zhang, G., Liu, K., Fu, X., Li, Y., & Liu, Y. (2025). Comparison of schemes for layered and continuous solution mining in bedded salt formations by horizontal interconnected wells. *International Journal of Mining Science and Technology*https://doi.org/10.1016/j.ijmst.2025.10.003.

73. Zhang, N., Liu, X., Zhang, Y., Gu, H., Yan, B., Jia, Q., & Gao, X. (2024). Investigating the mechanism of land subsidence due to water network integration at the Guangzhou Longgui Salt Mine and its impact on the adjacent subway.*Water*,16(12), 1723 httpshttps://www.mdpi.com/2073-4441/16/12/1723?utm_campaign=releaseissue_water&utm_medium=email&utm_source=releaseissue&utm_term=titlelink6#

74. Zhang, N., Li, J., Xu, W., Naumov, D., Zill, F., Chen, Y., & Nagel, T. (2026). Mind the sump: Solution mining-based reconstruction of sediment-filled regions for improved stability modeling of salt caverns. *Tunnelling and Underground Space Technology*,170, 107352 https://doi.org/10.1016/j.tust.2025.107352.

75. Zhang, T., & Yang, Y. L. (2024). Characteristics of mine goaf occurrence and treatment technologies in China: A comprehensive review. *Environmental Earth Sciences*,83(15), 441.https://doi.org/10.1007/s12665-024-11754-4

76. Zhang, Y., & Li, W. (2021, October). Inverse Simulation for Salt Cavern Wall Collapse during Cycling Loading: A Field Case Study. *InIOP Conference Series: Earth and Environmental Science* (Vol. 861, No. 3, p. 032066). 10.1088/1755-1315/861/3/032066.

77. Zhang, Z., & Dong, H. (2025). A Surface Subsidence Monitoring Method for Narrow and Elongated Mining Areas by Combining InSAR and the Improved Probability Integral Method.*Applied Sciences*,15(24), 13086 https://www.mdpi.com/2076-3417/15/24/13086#.

78. Zhao, A., Li, Y., Shi, X., Zhao, K., Hao, S., Gong, X., & Jiang, S. (2021, June). An inversion method of the surface subsidence of a salt mine solution mining. *InARMA US Rock Mechanics/Geomechanics Symposium(pp. ARMA-2021). ARMA* https://onepetro.org/ARMAUSRMS/proceedings-abstract/ARMA21/ARMA21/467930.

79. Zhao, A., Li, Y., Shi, X., Hao, S., Che, Z., Yang, K., ... & Ma, H. (2025). Mechanism of Anomalous "Internal Subsidence and Peripheral Uplift" in a Salt Mine goaf: A Multi-Source Validated Superposition of Poroelastic Uplift and Mining-Induced Subsidence. *Geomechanics for Energy and the Environment*, 100769 https://doi.org/10.1016/j.gete.2025.100769.

80. Zhao, J., Yang, X., Zhang, Z., Niu, Y., & Zhao, Z. (2023). Mine subsidence monitoring integrating DS-InSAR with UAV photogrammetry products: Case studies on Hebei and Inner Mongolia. *Remote Sensing*,15(20), 4998 https://www.mdpi.com/2072-4292/15/20/4998#.

81. Zhao, Y., Yan, Y., Liu, K., Zhao, X., Li, H., Cao, J., ... & Ma, K. (2024). Analysis of coal mine safety accident features in China, 2017–2022.*Geohazard Mechanics*,2(2), 108-120 https://doi.org/10.1016/j.ghm.2024.03.002.

82. Zhu, M., Yu, X., Tan, H., & Yuan, J. (2024). Integrated high-precision monitoring method for surface subsidence in mining areas using D-InSAR, SBAS, and UAV technologies. *Scientific Reports*,14(1), 12445https://doi.org/10.1038/s41598-024-63400-5.