

Review

Comprehensive Review on Integration of Geohazards in Mine Planning

Lawrence Madziwa¹ and Heike Wanke^{2,*} ¹ Department of Civil, Mining and Process Engineering, Namibia University of Science and Technology (NUST), Windhoek 9000, Namibia; lmadziwa@nust.na² Department of Applied Geosciences, German University of Technology in Oman (GUtech), Athaibah, Muscat 130, Oman

* Correspondence: heike.wanke@gutech.edu.om

Abstract

Geohazards are present at every stage of a mine's life cycle (initial exploration, site investigations, active operations, closure, reclamation, legacy management). This study has reviewed the literature covering mining and geohazards gathered from the Scopus bibliographic database. Quantitative metadata analysis was conducted on keyword co-occurrence within the 150 selected publications, and thematic clustering was mapped. In addition, five case studies were analysed to add further in-depth analysis. The publication volume shows a sharp uptrend starting around 2015, and 45% of the articles indicate a corresponding author from China. Publications more often cover geohazards in underground mines than open-pit/surface mining. AI methods are a rapidly evolving subject. Overall, the review reveals an imbalance in research attention across different stages of the mine life cycle. While only approximately 6% of the literature addresses exploration-stage geohazards, the case studies demonstrate that early identification is critical. In conclusion, technical capabilities for geohazard monitoring have advanced dramatically, especially with interferometric synthetic aperture radar (InSAR) deformation analysis, machine learning classification, and multi-sensor data fusion; however, the field suffers from systematic integration of geohazards across the mine life cycle.

Keywords: geohazards; mine planning; mining; risk assessment; geohazard monitoring; InSAR (Interferometric synthetic aperture radar)

1. Introduction

While mining activities may trigger geohazards [1], pre-existing natural geohazards equally form a risk to any mineral extraction project. Geohazards are present at every stage of a mine's life cycle, ranging from initial exploration and site investigations to active operations and extending into closure, reclamation, and long-term legacy management. Risks such as sinkholes, land subsidence, slope instability, fault reactivation, sudden water inrushes, and the movement of contaminants pose severe threats to worker safety, local communities, essential infrastructure, and the surrounding environment [2–5]. Their consequences span from localised operational disruptions [6] to catastrophic geotechnical events [7] with transboundary social and economic repercussions.

Over the past two decades, considerable advancements in technologies of earth observation, geophysical sensing, and data science techniques have reformed the field of geohazard detection and modelling (e.g., [8–11]). InSAR (interferometric synthetic aperture



Academic Editor: Tiago Miguel Ferreira

Received: 6 August 2026

Revised: 25 August 2026

Accepted: 31 August 2026

Published: 3 September 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

radar) technology and three-dimensional displacement recovery and inversion methods provide highly spatially resolved and continuous deformation fields at regional scale [12,13]. Conversely, machine learning algorithms allow hazard classification and anomaly detection to be undertaken automatically and based on large volumes of heterogeneous data [14–16]. Moreover, multimodal data fusion techniques integrate weakly connected multidimensional data, including underground mine measurements, for geohazard prediction [17]. All the aforementioned techniques together constitute a major advancement in the ability to characterise geohazards with high precision and frequency over the whole lifetime of a mining project.

Despite all the aforementioned technological advancements, the peer-reviewed literature reviewed in this work presents a pattern of systematic bias when it comes to the topic of geohazards and their treatment throughout the mining life cycle. Most research to date has focused on active underground and open-pit mines, as well as on the long-term risks associated with abandoned sites. However, less attention has been given to identifying geohazards during the exploration stage of greenfield projects or to how hazard assessments can systematically be integrated throughout a mine's entire life cycle, from initial exploration and design to eventual closure. This imbalance has real-world implications: proactively identifying and mitigating geohazards during exploration and feasibility studies can significantly lower costs, reduce legal liabilities, and protect host communities [18,19], and it can strengthen the overall risk management framework of mining projects throughout their life cycle.

This review aims to evaluate the current understanding of how geohazards can be dynamically and systematically integrated into mine planning. Specifically, it examines how geological hazards are identified, assessed, monitored, and managed within the decision-making processes at every stage of mining, such as exploration, design, production, and closure, to promote safer, more economically viable, and sustainable mineral development. The focus of this review is on natural geohazards and excludes technical hazards on geological material in the mining sector, e.g., tailing dam failures. The review is motivated by the following research questions:

- Which geohazards are typically considered at each stage of mine planning?
- How closely does the existing scientific literature align with the integration into practical mine planning?
- Do geohazards impact mine planning similarly across both large-scale surface and underground operations?
- How are geohazard risk assessments revised and mine-planning decisions updated when new information comes to light?

The review is organised into several parts: a methodology section (covering searches of the literature, metadata analysis, and case studies), a thematic review of the literature categorised by life cycle stage, a bibliometric metadata analysis, and an overview of diverse case studies from the USA, Egypt, Greece, Ukraine, and China. Finally, the study concludes by analysing key trends, highlighting persistent research gaps, and proposing practical recommendations to encourage better geohazard awareness throughout the entire mining project life cycle.

2. Methodology

2.1. Review Methodology

The strategy employed to search the literature followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework [20] to ensure transparency and reproducibility in identification, screening, and synthesis of the literature.

The literature was gathered from the Scopus bibliographic database with no restrictions on publication year. The search used the terms ‘geohazards’ and ‘mining’ (applying the Boolean expression ‘and’) and setting Scopus to search for these words in the article title, abstract, and keywords fields. The initial search returned 222 publications from 1997 to 2026. To ensure consistent interpretation of content, the search was limited to English-language publications. The researchers excluded grey literature, conference abstracts, unpublished reports, and theses from the main body of the literature, as this review focuses on the peer-reviewed evidence base. Only peer-reviewed journal articles, review articles, and book chapters have been included, resulting in 150 eligible records after applying these document-type filters.

Google Scholar was not part of the primary search strategy. A title-field search with the same terms returned only records already found in Scopus. An unrestricted full-text search produced about 34,900 results, which remained too many to manage and lacked the precision needed for systematic screening. Google Scholar is known for returning many duplicates and does not have a reliable bulk download tool. Systematic review strategies, e.g., [21], revealed that Web of Science lacks keyword functionality, and JSTOR database was excluded, as it also returns a lot of grey literature. We acknowledge that a few relevant studies outside the Scopus index might have been missed. However, given the global scope of the review and Scopus’s strong coverage in engineering and earth sciences, we believe this limitation is unlikely to significantly impact the findings.

We applied further eligibility criteria during full-text screening. Publications were included if they dealt with geohazards that were directly linked to, or heavily influenced by, mining or mineral resource activity. We excluded papers that discussed general geohazards in non-mining contexts or mining topics that did not have a significant geohazard component, such as mineral processing or occupational safety unrelated to geological instability. Each selected paper was assigned to one of eight thematic categories based on its stated primary contribution. Life cycle stage (e.g., exploration, post-mining/legacy) took precedence where a paper’s main focus was a specific stage; papers whose primary contribution was methodological (e.g., a machine learning classifier or InSAR processing technique demonstrated across mixed settings) were instead coded under ‘machine learning and AI’ or ‘InSAR and remote sensing’, respectively, even where an underground or open-pit setting was used as the demonstration case. We acknowledge this single-category assignment is not fully mutually exclusive and may lose information relative to independent multidimensional coding by life cycle stage, mining type, hazard type, and method; this is noted as a limitation in Section 4.5.

We extracted bibliometric data, including publication year, the country of the corresponding author’s affiliation, and author-assigned keywords, for quantitative analysis. We conducted co-word analysis on author keywords using Python 3 coding to identify thematic clusters and conceptual connections within the body of work.

2.2. Quantitative Metadata Analysis

To provide context for the thematic synthesis and uncover structural patterns within the study sample that a narrative review might overlook, a quantitative metadata analysis was conducted on all 150 selected publications. This analysis looks at four key dimensions: the timeline of publication trends, the thematic makeup of different research categories, the geographical distribution of study sites and author affiliations, and the conceptual links between recurring keywords identified through co-word analysis. Taken together, these dimensions build a bibliometric framework that helps interpret where research in mine planning and geohazards has focused, what has been overlooked, and where the field is currently heading.

2.3. Keyword Co-Occurrence and Thematic Clustering

To uncover the underlying thematic structure of the body of the literature and assess how closely key research topics are linked, we performed a co-word analysis on the author-assigned keywords from all 150 publications. Co-word analysis is a standard content analysis method based on the idea that when two keywords appear together in the same paper, they share a significant intellectual or methodological connection [22]. This approach is frequently used in bibliometric research to map out emerging fields, pinpoint thematic clusters, and track how research fronts evolve over time.

The following keyword standardisation protocol was applied as a preprocessing step for the author-assigned keywords analysis:

- (1) Case normalisation: All keywords converted to lowercase.
- (2) Stemming: Plural forms converted to singular (e.g., 'hazards' to 'hazard').
- (3) Synonym merging:
 - 'synthetic aperture radar,' 'sar,' 'insar,' 'interferometric synthetic aperture radar,' 'interferometry' to 'insar';
 - machine learning,' 'deep learning,' 'artificial intelligence,' 'ai' to 'machine learning';
 - 'subsidence,' 'ground deformation,' 'land subsidence' to 'subsidence' (context-dependent);
 - 'open pit,' 'opencast,' 'surface mining' to 'surface mining';
 - 'underground,' 'subsurface' to 'underground mining'.
- (4) Spelling standardisation: UK/US variations standardised.
- (5) Abbreviation expansion: Abbreviated terms expanded where unambiguous.
- (6) Stop-word removal: Generic terms without analytical value removed.

All keyword frequencies, co-occurrence matrices, and network analyses were computed using the standardised term set.

The strength of the relationship between keyword pairs was measured using Salton's cosine coefficient [23], a normalised similarity metric that is calculated as follows:

$$S_{(i,j)} = \frac{C_{(i,j)}}{\sqrt{[C_{(i)} \times C_{(j)}]}} \quad (1)$$

In this formula, $C_{(i,j)}$ represents the number of documents where keywords i and j co-occur, while $C_{(i)}$ and $C_{(j)}$ represent the total frequency of each individual keyword. By using Salton's cosine, we account for the natural bias toward highly frequent terms that often skews raw co-occurrence counts. This results in a normalised score ranging from 0 (no significant co-occurrence) to 1 (perfect co-occurrence, where the terms always appear together). Generally, a coefficient higher than 0.5 points to a strong thematic link, while values exceeding 0.7 suggest the two terms are almost exclusively coupled within the dataset.

2.4. Case Study Analysis

While the thematic and bibliometric analyses mentioned above map out the broad landscape of geohazard research in mining, they tend to operate at a level of abstraction. This can sometimes mask the practical operational realities, specific methodological decisions, and the distinctions of knowledge transfer found in individual site investigations. To bridge this gap, the case study analysis offers an overview through an in-depth examination of five studies pulled directly from the reviewed literature.

The five cases were selected from the 150 included studies using five explicit criteria, chosen to maximise diversity across the sample:

- Mine type and commodity (coal, hard-rock gold, evaporite/salt);
- Dominant hazard mechanism (subsidence, dissolution collapse, slope instability, spontaneous combustion);
- Mine life cycle stage emphasised in the source study (operational, post-closure, or spanning both);
- Geographic/regional representation, including at least one African case given the under-representation identified in Section 3.2.3;
- Availability of a documented, quantitative monitoring or risk analysis method suitable for cross-case comparison.

The five selected cases were Amyntaio, Solotvyno, Sukari, Wuda, and Bald Mountain. These were the studies within the reviewed sample that most clearly satisfied all five criteria simultaneously. Subsequent comparison of the cases along five common life cycle dimensions (pre-operational baseline, operational monitoring, community/off-site impact, closure planning, and transferability) provides the systematic analytical framework requested. Collectively, these cases illustrate the wide range of real-world challenges and the varying ways they are addressed in the scientific literature.

The five cases include: (i) the Amyntaio open-pit lignite mine in Greece, which showcases the complex multi-hazard nature of large-scale surface mining and the far-reaching impacts of operational dewatering [7,24]; (ii) the Solotvyno salt mine in Ukraine, which serves as a stark warning about the risks of poor post-closure planning and the institutional neglect of legacy geohazards [25]; (iii) the Sukari gold mine in Egypt, which highlights how satellite-based monitoring can be both effective and scientifically valuable in data-scarce, hard-rock mining environments in Africa [26]; (iv) the Wuda coalfield in Inner Mongolia, China [27]; and (v) the Bald Mountain mine in Nevada, USA, which brings attention to the often-overlooked risk of underground coal-fire ignition and demonstrates how structured risk analysis frameworks can be applied to hazards that do not involve physical deformation [28]. A structured overview of these five cases is provided in Table 1.

Table 1. Overview of the five case studies selected for in-depth analysis.

Case Study	Mining Context	Life Cycle Stage	Methods Applied	Key Contributions
Amyntaio open-pit mine, Greece [7,24]	Open-pit lignite; dewatering-induced subsidence and slope reactivation	Operational to legacy	GIS (geographic information system) susceptibility mapping; InSAR; geomechanical modelling	Cross-boundary subsidence; community risk zonation; multi-hazard integration
Solotvyno salt mine, Ukraine [25,29]	Underground salt extraction; post-closure flooding and dissolution collapse	Post-mining to legacy	Multi-temporal InSAR (1992–2021); 30-year SAR time series; risk mapping	Escalating post-closure hazard; institutional failure; perpetual monitoring imperative
Sukari gold mine, Egypt [26]	Large open-pit hard-rock gold mine in arid crystalline terrain	Operational	Sentinel-1 InSAR slope monitoring; satellite deformation mapping	Only substantive African hard-rock case; demonstrates monitoring feasibility in data-scarce settings
Wuda coalfield, China [27]	Underground coal extraction with spontaneous combustion geohazard	Operational	Bow-tie risk analysis; hybrid data; thermal remote sensing	Structured anticipatory risk framework; non-deformation hazard type; transferable risk logic
Bald Mountain mine, Nevada, USA [28]	Large open-pit gold mine slope instability in arid mountainous terrain	Operational	Sentinel-1 InSAR back-analysis of pit wall failures	Real-world validation of InSAR for early warning and operational decision-making in a major US gold mine

3. Results

3.1. Results of the Analysis of the Literature

The 150-paper collection addresses geohazards throughout the mining life cycle but with strong prominence on underground and surface workings, post-mining, and the use of remote sensing methods. Fewer studies explicitly address greenfield exploration geohazards or systematically integrate geohazard considerations with the planning and design of mining projects. The following sections collate the literature by topic to illustrate patterns and trends in the evidence. Section 3.1.10 provides an overview of the gaps and opportunities identified in the review.

3.1.1. Exploration-Stage Geohazards

Geohazards during the exploration stage were a minor theme in the literature reviewed, appearing in approximately 6% of the papers and often as an epilogue to studies focused on geoscience or geotechnical aspects of mining. A possible explanation for this low emphasis is that exploration-stage geohazards present fewer immediate operational or economic costs to mining companies than geohazards at later life cycle stages and are therefore less of a priority for practical research.

Mining industry examples show that records about an area's exploration history and early investigations can yield valuable information about geohazards. Shot hole and drilling data from seismic exploration can identify unstable ground or unusual rock conditions before major development is underway [30]. Rock mass classification studies in porphyry copper systems identify ground strengths that can inform initial design choices for pits and underground excavations [31]. Regional geology summaries can also inform exploration-stage geohazard assessments, such as studies of Cenozoic detritus in the Pilbara region of Western Australia, which recognised the extensive cover of weathered sediment and its implications for slope stability and groundwater flows [18]. Similarly, hazards associated with karst, evaporite dissolution, and legacy workings were a frequent concern during exploration, especially with regards to drilling and site preparation safety. Studies of gypsum and halite karst highlighted the risks of ground collapse and solution subsidence that could affect exploration activities [32–34]. Analysis of paleo-collapse structures and their effects on flow paths and contamination risks are also relevant to exploration geohazard assessments, as are bearing-capacity issues over abandoned workings, to which brownfield and infill mining projects are particularly liable [35,36].

Studies of remote sensing applications to mining industry geohazards focus predominantly on identifying ground deformation features or displacement fields amenable to operational or post-mining management. These include high-resolution InSAR and 3D displacement retrievals that can identify pre-existing ground deformation, groundwater-related consolidation of tailings storage facilities, and localised subsidence features that should be avoided during early project development and infrastructure placement [12,13,37]. Few papers treat greenfield exploration geohazards as a distinct category or set of concerns. Most relevant studies examine geohazards as a subset of operational issues or discuss early hazard recognition in the context of due diligence or feasibility assessments rather than in terms of exploration-specific methodologies. An opportunity exists to develop systematic approaches to exploration- and field-development-stage geohazard management, which would leverage existing databases, targeted geophysical surveys, and satellite-based screening methods to reduce the risks associated with project initiation and early ground preparations.

3.1.2. Underground Mining Geohazards

By far the largest class of papers in the database of the literature (approximately 25%) are those that focus on underground mining, representing a broad range of geotechnical issues associated primarily with longwall and room-and-pillar mining, with particular emphasis on subsidence, floor heave, rockfall, fault reactivation, goaf delineation, and water ingress. Early works on underground mining geohazards examined regional patterns of ground deformation associated with coal mining activity in Colombia and how these related to social costs to local populations and infrastructure, depending on the longwall mining method used [6]. More recently, stress–floor heave interactions in deep thick coal seams have been subject to numerical and geophysical modelling, with a view to improving floor strength estimates for pillar design and longwall advance schedules [38]. In general, the relationship between underground mining activities and ground surface deformation, including the potential for rockslides and rock avalanches triggered by undercutting, has been increasingly recognised as a multi-hazard interaction requiring integrated management [39].

Engineering responses to underground mining geohazards were a frequent topic across the selected literature, with a focus on roadway backfilling and support, goaf filling, and other means to reduce rockfall risk and surface deformation [40,41]. Detection and assessment of underground goaf were a recurring requirement for water hazard management, addressed using borehole methods, in-mine time-domain electromagnetic methods for aquifer detection, and surface deformation proxies [42]. Another common approach to managing underground mining geohazards was the deployment of micro-seismic arrays for early-warning detection of rock bursts or seismic rupture events. These systems increasingly relied on automated phase picking using convolutional neural network (CNN)–Kalman automaton hybrids and similar approaches to improve the accuracy of event location estimates for triggering activities in complex underground environments [43]. However, as several authors noted, such methods typically responded to known rockfall triggers, rather than attempting to identify new ones, and fitted within a broader program of micro-seismic–visual model fusion for enhanced ground behaviour understanding rather than constituting an independent system for hazard recognition [17].

3.1.3. Surface and Open-Pit Mining Geohazards

Open-pit mining was much less common as a focus for geohazard research in the literature than underground mining but attracted considerable attention whenever it was undertaken, with particular focus on slope stability, spoil and waste dump performance, near-surface ground deformation, and sinkholes. Spatial analysis of risk factors and their impact on open-pit coal mines in Greece and Turkey provided valuable inputs for prioritizing monitoring and engineering activities and informed local authorities about the areas of highest risk to nearby infrastructure [44]. The large open-pit lignite mine at Amyntaio in West Macedonia became infamous for its extensive subsidence hazard footprint, which extended beyond the mine's boundaries into populated areas, threatening residential buildings and infrastructure [24].

The challenge of surface mining geohazard management is mostly solved by the opportunities for satellite-based remote sensing, which can penetrate to the ground surface to measure deformation in pits, waste dumps, tailings storage facilities, and related infrastructure with relative ease. Multiple studies used Sentinel-1 and other SAR platforms to study slope stability, mine subsidence, and tailings dam integrity in open-pit settings [45,46]. Similar approaches have been taken to coastal- and shore-based mining, where SAR and airborne photogrammetry can be used to estimate the impact of black sand mining on coastal erosion and the built environment [47]. Sinkholes that form at or near open-pit min-

ing works are a particular concern in karst regions such as Malaysia, where they frequently occur at the intersection of spoil, waste, and natural sediments [48].

3.1.4. Operational Monitoring, Decision Support, and Digital Tools

Geohazard management during the operational phase was the most intensively studied topic across the reviewed sources, reflecting ongoing efforts to collate and apply information to understand ground behaviour around mines. Space- and ground-based (GB) radar, including GBInSAR, contributed to a wealth of publications on operational ground deformation monitoring, much of it focused on using deformation time series to inform trigger-action response systems that could be applied to operational decision-making [12,49,50]. Algorithms that retrieved 3D deformation fields using TDFPI (three-dimensional and full-parameter inversion) approaches and similar three-dimensional full-parameter inversions, plus multi-track InSAR filtering, contributed to improved temporal resolution and accuracy in active mining area deformation estimation [50,51].

Engineering responses to geohazards during operations were a recurring topic, with studies focusing on slope design recommendations, adaptive benching and dewatering strategies, and drainage zoning as ways to respond to observed ground deformation and reduce the likelihood and impact of geohazard events [41,52]. Digital approaches to operational geohazard management saw an increased application of smartphone apps for field data gathering, Internet of Things-based environmental monitoring systems, and integrated decision-making frameworks to support operational personnel in making rapid decisions about geohazards based on monitored ground deformations [53].

Operational-phase hazard monitoring and management systems were largely developed in direct response to observed ground deformation patterns, often limited to localised or even mine-specific decision-making frameworks. The literature rarely addressed the value of collating and applying field survey and exploration data to operational-phase hazard management, with few mentions of systematic approaches to linking operational and post-mining practices despite the potential benefits to both.

3.1.5. Post-Mining, Legacy, and Abandoned-Mine Geohazards

The impacts of post-mining activities constituted another common focus for geohazard research, at approximately 15% of the body of the literature. Abandoned underground workings created geohazards that often affected town planning, infrastructure, and local hazard management for years after a mine's closure. Studies from the UK and Central Europe highlighted the range of mechanisms that contributed to floor heave, pillar failure, and flooding risks in formerly worked coal fields, as well as policy responses to the social and economic effects of mine subsidence [2,4,54].

Long-term monitoring of ground deformation in post-mining settings using InSAR revealed the extent of ground deformation hazards around salt mines, linked to dissolution processes and flooding of abandoned workings and presenting with complex temporal patterns, including long-term acceleration [25,55]. Institutional responses to post-mining geohazards included the development of subsidence hazard maps and their integration into financial and planning support systems for affected communities, as well as the use of mining-related geology in local authority planning and development control [56,57]. At the same time, many post-mining areas, particularly in low-income countries, were without comprehensive field or monitoring programs to evaluate ground stability or support the development of engineering responses to geohazards.

3.1.6. Reclamation and Environmental Restoration

The issue of reclamation and environmental restoration cuts across multiple aspects of mining industry geohazard management but appeared as a specific topic in only a

handful of papers. Engineering responses to geohazards during reclamation included the design of drainage and excavation-cutting stability schemes for alluvial tin mining, while studies on post-mining subsidence prioritised tailings and waste facilities for reclamation activities based on risk assessment using machine learning [58]. An emerging approach to post-mining geohazard management and reclamation was rooted in geo-heritage principles and focused on the development of tourist attractions and hazard reduction in a manner that considered the region's unique geological features and conservation needs [59]. Overall, reclamation and environmental restoration were rarely the focus of geohazard research, even as they were frequent contextual factors in other domains of the literature. Opportunities for additional research and innovation could be found in developing generalised approaches to restoring large-scale surface and subsidence hazards based on operational-phase monitoring data.

3.1.7. Machine Learning, Data Mining, and Artificial Intelligence Applications

The application of machine learning and other AI methods to mining industry geohazards is a rapidly evolving subject but is represented in only approximately 9% of the literature reviewed. Random forest classification of advanced differential (AD) InSAR time-series data was used to minimise the need for manual interpretation and prioritise ground deformation features for follow-up analysis and could be used for broad-scale screening without knowledge of deformation sources [14]. Unsupervised learning was used to classify reports on geohazards of different geological origins and contributed to improved micro-seismic phase picking and automated labelling of seismic events in underground mining settings [15,43]. Multimodal approaches to geohazard recognition and forecasting used combinations of geophysical, remote sensing, and field data to improve accuracy in operational underground settings [17].

Despite the potential advantages of these approaches, the papers in the study sample suggested that the practical implementation of AI-based geohazard recognition and response systems in the mining industry was still confined to prototype or single-case applications. Some of the main barriers to the adoption of AI methods for mining industry geohazards included the limited availability of standardised training data, the challenge of adapting algorithms to different settings and hazard recognition tasks, the potential difficulty in auditing decisions made by complex models, and the need to integrate such systems with operational planning and decision-making frameworks. The literature stressed the need to develop standardised open data sets, auditing and validation procedures, and human-centred systems that retained the ability to apply expert judgement to individual hazard recognition tasks [17,43].

3.1.8. InSAR, Remote Sensing, and Other General Methodological Advances

General topics related to InSAR and remote sensing accounted for the largest category of papers in the dataset of studies (26%), reflecting the growing use of both fields in mining industry geohazard research across all stages of the mining life cycle. The literature included a wealth of methodological contributions, ranging from end-to-end displacement field retrieval flows (including SPIKE three-dimensional retrieval software and adjacent track temporal filtering approaches [50]) and full parameter inversions [51] to the use of Kalman filters in three-dimensional displacement field estimation and related time-series analysis [13]. Research on machine learning-assisted hazard recognition also contributed to the expansion of automated classification methods and cloud-based processing flows, including the use of open news archives and similar resources to enable semantic processing of geohazard-related information [14,60].

Multi-sensor flows that combined information from different SAR, LiDAR (light detection and ranging), terrestrial scanning, and field approaches were a reasonable direction in remote sensing field research, aimed at overcoming the limitations of individual sensor platforms and approximating the accuracy of combined field and satellite measurements [61,62]. Finally, national-level interferometric monitoring programs generated extensive deformation time series that enabled the study of temporal patterns of ground deformation and the identification of anomalous features, supporting local land-use planning and development control initiatives at national levels [55,63].

3.1.9. Cross-Sector Themes: Pipelines, Karst, Urban Geology, and Policy

A small number of papers addressed geohazard research topics that went beyond a mine itself but had direct relevance to the wider mining infrastructure. These included pipeline geohazard management, karst hazard recognition, and urban geoscience approaches, all of which sometimes intersected with mining industry geohazards and provided potential approaches and insights.

Pipeline geohazard studies were particularly relevant to mining industry challenges in terms of their focus on ground deformation associated with linear development and its impact on structural integrity. Quantitative risk assessment approaches used in pipeline geohazard management were directly applicable to mining industry problems, particularly those related to linear infrastructure such as access roads, transportation routes, and power line installations [64,65].

Urban geoscience studies provided a perspective on addressing geohazards in populated areas with complex socio-technical systems that often had only limited resources to address the challenges. The literature emphasised the role of subsidence hazard and karst risk mapping in urban planning, as well as the use of mining-related geology to inform local authority planning and development control in post-mining settings [57,66]. Relatedly, geo-heritage studies and the literature on geological surveys and public policy suggested that geological survey organisations had a unique role to play in urban hazard management by contributing to the development of governance systems, policies, and procedures that supported proactive hazard recognition and management initiatives [56,59].

3.1.10. Synthesis: Patterns, Dominant Advances, and Persistent Gaps

An analysis of the 150-paper research literature reveals three primary trends. First, remote sensing and InSAR serve as the technical foundation for modern geohazard observation, driving significant breakthroughs in three-dimensional retrieval, temporal data fusion, inversion modelling, and automated classification. Second, research is most heavily concentrated on active underground mining operations, which has led to the development of practical monitoring systems and site-specific mitigation strategies. Third, while machine learning and multimodal sensor fusion are quickly becoming essential for pattern recognition and early warning, they are still mostly stuck in the research phase and have yet to be standardised for widespread use in high-stakes operational environments.

In terms of geography, East Asia, and China in particular, leads the current publication output. This is largely due to the massive scale of underground coal mining in the country and a large, highly active research community focused on the overlap of remote sensing and geotechnical engineering. European research also remains strong, particularly regarding post-mining and legacy geohazards. However, Africa, South America, and Oceania are noticeably under-represented in the peer-reviewed literature, even though extractive industries play a massive role in those regions. This geographic gap has real-world implications: mining projects in these under-represented areas often lack access to locally

calibrated benchmarks, geological baselines, or mitigation case studies tailored to their specific contexts.

The literature highlights several critical gaps in both research and practice:

- The need for formalised geohazard protocols during the exploration stage that combine satellite pre-screening, legacy data mining, and targeted geophysics for greenfield assessments.
- The development of life cycle integration frameworks that carry hazard intelligence from exploration through to design, operations, and closure rather than treating these phases as isolated events.
- A requirement for standardised, transferable machine learning models, open-access benchmark datasets, and cross-site validation protocols to move technology from the lab to the field.
- Stronger links between real-time deformation monitoring and the design criteria used for mine closure and long-term risk management.
- A push for more applied research and monitoring deployment in regions currently lacking academic coverage, specifically Sub-Saharan Africa, Central Asia, and Latin America.

3.2. Results of the Quantitative Metadata Analysis

3.2.1. Temporal Distribution of Publications

Figure 1 illustrates the annual and cumulative distribution of the research articles reviewed here. The data shows a sharp uptrend in publication volume starting around 2015, with the highest levels of productivity occurring after 2018. This upward trend aligns with broader developments in geohazard and remote sensing research, fuelled by several key factors: the improved availability and resolution of satellite monitoring, particularly following the launch of the European Space Agency’s Sentinel-1 constellation (2014 and 2016) which made high-quality InSAR data accessible to researchers worldwide; increasing pressure from international regulators and corporations for mining companies to monitor and report surface deformation; and a growing global concern over the long-term hazards left behind by abandoned mines in densely populated areas of Europe and Asia. The cumulative curve shows that over 60% of the literature was published in the last ten years, highlighting both how new this field is and how rapidly it is evolving.

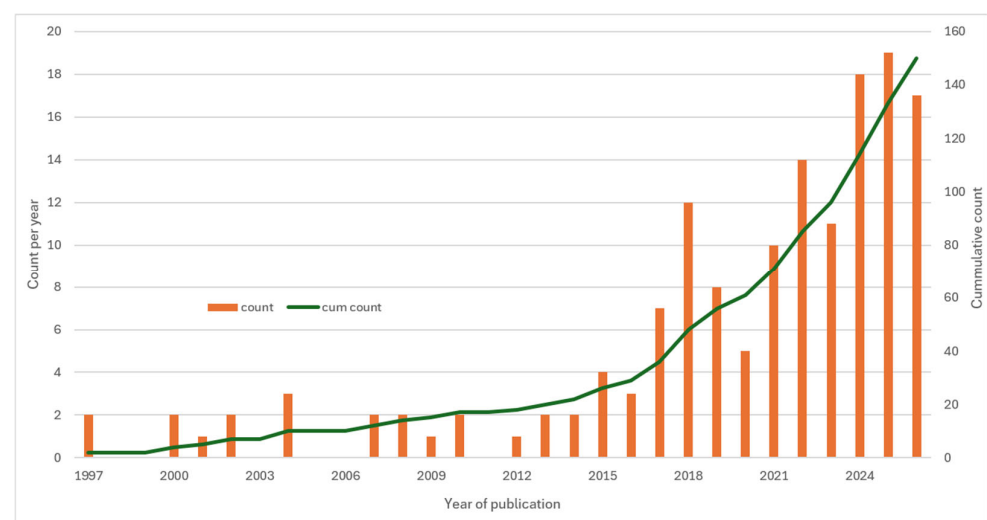


Figure 1. Annual count and cumulative distribution of research articles included in this review, by year of publication.

Before 2010, most research focused on documenting subsidence in established coal mining areas across Europe and China, typically relying on traditional methods like conventional surveying, GPS displacement tracking, and levelling (e.g., [67,68]). Around 2012, the methodological landscape began to shift as spaceborne radar remote sensing (InSAR) started to supplement and eventually replace many field-based techniques. This transition offered much broader spatial coverage and better temporal resolution while significantly reducing the need for manual fieldwork [69–72]. The sharp increase in research seen after 2018 is driven by two main factors: the rapid rise of machine learning in geohazard monitoring and prediction [73,74] and the maturity of cloud-computing platforms like Google Earth Engine, which has made large-scale time-series InSAR analysis much more accessible by lowering computational hurdles [75–77].

3.2.2. Thematic Distribution by Research Category

Each of the 150 reviewed papers was sorted into one of eight thematic categories based on its main research focus (Table 2; Figure 2). The two biggest categories are InSAR and remote sensing ($n = 39$; 26.0%) and underground mining ($n = 38$; 25.3%); together, they make up more than half of the entire collection. This overlap is no accident; it highlights the natural connection between radar satellite technology and the study of how subsurface extraction affects the ground. Many InSAR-focused studies look specifically at ground deformation caused by underground coal mining, and their technical breakthroughs—temporal fusion, three-dimensional inversion, and automated change detection—have direct applications for monitoring mining-related geohazards in general.

Table 2. Distribution of reviewed publications by thematic research category.

Category	Number of Publications	%	Top Countries (Based on Affiliation of Corresponding Author)	Key Themes
Underground mining	38	25.3	China, UK, Greece, Colombia	Subsidence, goaf, floor failure, fault reactivation, deep coal
Open-pit/surface mining	11	7.3	Greece, Egypt, Malaysia	Slope stability, sinkholes, surface deformation
Post-mining/legacy	22	14.7	UK, Poland, Czech Republic, Ukraine	Long-term subsidence, abandoned mines, urban impacts
Exploration geohazards	9	6.0	China, UK, Canada, Australia	Drilling risks, karst, site investigation
Reclamation and waste mgmt.	5	3.3	Poland, Australia	Waste stabilisation, environmental recovery
Machine learning and AI	13	8.7	China, Italy	Predictive modelling, classification, micro-seismic
InSAR and remote sensing	39	26.0	China (dominant)	InSAR monitoring, deformation mapping, broad applications
Balance/other	13	8.7	Various	Pipelines, karst, urban planning, multi-hazard, reviews

Post-mining and legacy impacts form the third-largest category ($n = 22$; 14.7%), reflecting a steady global interest in the geohazard risks left behind after mines are abandoned, as well as the legal and policy responsibilities governments face in former coal-producing regions. Although it is still a relatively young subfield, machine learning and AI have already emerged as a distinct category, making up 8.7% of the studies ($n = 13$). This indicates an accelerating shift toward using data-driven predictive and classification tools within geohazard science. The remaining four categories make up the rest of the research:

open-pit and surface mining (7.3%), exploration geohazards (6.0%), reclamation and waste management (3.3%), and a miscellaneous category covering reviews, pipeline geohazards, and multi-hazard studies (8.7%). This distribution shows that while the literature touches on the entire mining lifecycle, research is heavily concentrated on active operational stages and their immediate consequences, leaving less attention to the geohazards associated with the exploration and closure phases.

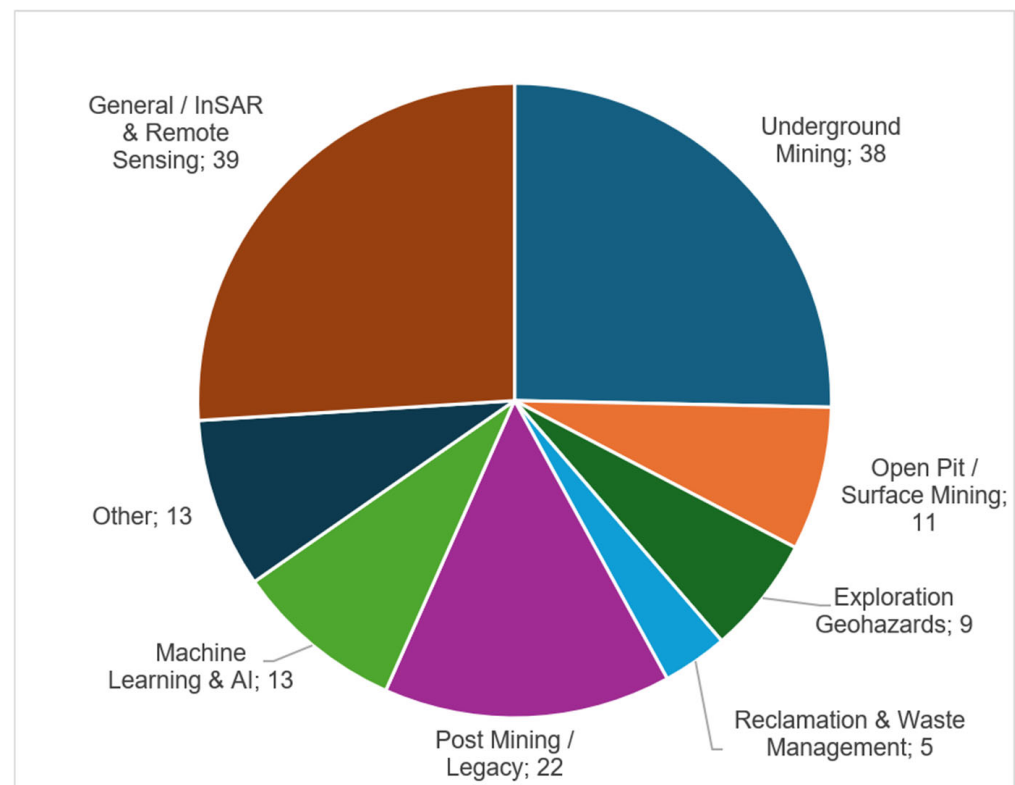


Figure 2. Proportional distribution of publications by thematic research category.

3.2.3. Geographical Distribution of Research

The geographical distribution of reviewed studies, presented in Figure 3 and summarised in Tables 3 and 4, shows that research activity is heavily concentrated in just a few countries. Publications with corresponding authors from China alone contributed 68 publications accounting for 45.3% of the total review sample, an amount that surpasses the combined output of all other represented countries except the United Kingdom and Poland. The physical location of the mining operation or study area was recorded when explicitly stated in the paper. This indicator reflects where geohazards are being studied and is presented in Table 4. The difference between author affiliation (45.3% Chinese authors) and study location (34.7% of studies in China) suggests that Chinese researchers also contribute to studies conducted outside China, particularly through international collaborations. The concentration of Chinese authorship (45.3%) is higher than the concentration of studies located in China (34.7%), indicating that Chinese institutions are involved in international research beyond their domestic mining operations. Both metrics confirm the dominance of Chinese research output, though the magnitude differs.

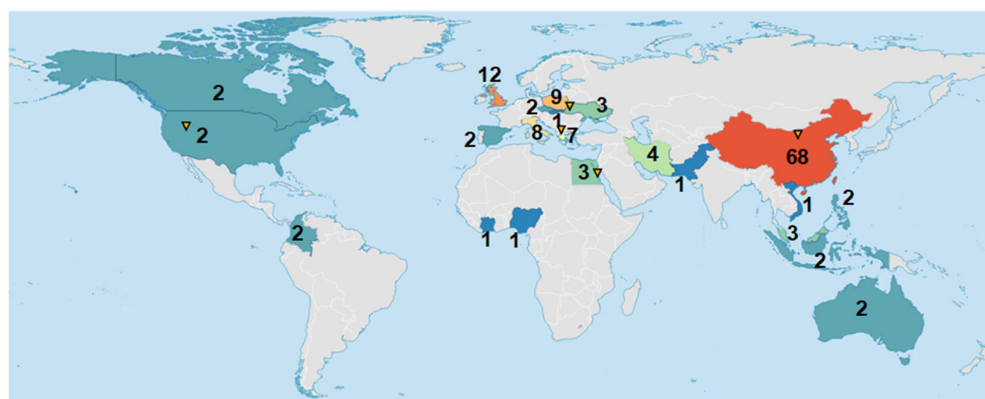


Figure 3. Geographical distribution of reviewed studies on mining-related geohazards with count of studies per country (numbers in the map) based on the corresponding author affiliation (details in Table 3). The locations of the 5 case study mines (Table 1) are indicated by small orange triangles.

Table 3. Distribution of reviewed publications by country of corresponding author affiliation (n = 150).

Rank	Country	Number of Publications	%	Main Research Focus
1	China	68	45.3	Underground mining subsidence, InSAR deformation monitoring, deep coal mines, micro-seismic, goaf
2	United Kingdom	12	8.0	Coal mining subsidence, abandoned mines, karst geohazards, legacy mine impacts
3	Poland	9	6.0	Lignite mines, national geohazard inventories, post-mining subsidence
4	Italy	8	5.3	InSAR classification, Rome geohazards, landslide inventories
5	Greece	7	4.7	Amyntaio coal mine, open-pit slope stability and dewatering subsidence
6	Iran	4	2.7	Coal mines, travertine geo-heritage
7	Egypt	3	2.0	Sukari gold mine stability monitoring
	Malaysia			Sinkholes in Kinta Valley
	Ukraine			Solotvyno salt mine deformation
10	Czech Republic	2	1.3	Subsidence mapping for urban planning
	Colombia			Mining subsidence monitoring
	Canada			Pipeline geohazards and oil sands exploration
	Philippines			Environmental impacts of black sand mining
	Australia			Pilbara Cenozoic detrital geohazards
	Spain			Evaporite dissolution and subsidence
	Indonesia			Contaminated mining regions, remote sensing monitoring
	United States			Shale exploration, California Alquist–Priolo fault zoning
18	Others	1	3.5	Vietnam, Ivory Coast, Nigeria, Pakistan, Slovakia, with one paper each

Table 4. Distribution by location of the study site.

Rank	Country	Number of Publications	% of Sample
1	China	52	34.7
2	Greece	7	4.7
3	United Kingdom	6	4.0
4	Poland	5	3.3
5	USA	4	2.7
...	Other	76	50.6

This dominance stems from a combination of several key factors. First, China is the world's leading producer and consumer of coal, making it uniquely vulnerable to large-scale land subsidence caused by underground mining. Second, the country has channelled massive investment into remote sensing infrastructure, including its own networks of commercial SAR satellites. Finally, there is the sheer scale and output of Chinese universities and government agencies working at the intersection of geotechnical engineering, Earth observation, and data science. Consequently, Chinese research tends to focus heavily on the mechanics of deep coal mine subsidence, goaf management, mapping surface deformation via multi-temporal InSAR, and, more recently, the use of machine learning for monitoring and prediction.

The United Kingdom ($n = 12$; 8.0%) and Poland ($n = 9$; 6.0%) follow as the next most active contributors in terms of corresponding author affiliation. Both nations deal with the long-term legacies of intensive historical coal mining and the resulting need to manage post-mining geohazards. UK-based research has focused largely on subsidence in abandoned mines, characterising karst geohazards, and studying how residual ground movement affects urban planning in former coalfield areas, particularly in South Wales and the East Midlands. Similarly, Polish studies emphasise ground instability following mining and have been instrumental in creating national geohazard inventories through government geological survey programs. Italy ($n = 8$; 5.3%) has driven significant methodological progress in InSAR-based classification and urban mapping, notably through monitoring projects in the Rome metropolitan area. Greece ($n = 7$; 4.7%) stands out due to detailed studies of the Amyntaio lignite open-pit mine, which serves as a primary case study for slope reactivation and subsidence caused by dewatering. The remaining 17 countries contributed between one and four papers each, making up about 25% of the total collection.

Looking at the geographic spread, there is a conspicuous absence of research authored in Africa. Despite hosting some of the world's fastest growing and most significant mineral extraction sites, the continent contributes only five publications to the dataset of studies, led by Egypt ($n = 3$), followed by Nigeria ($n = 1$) and Ivory Coast ($n = 1$). Sub-Saharan nations, including South Africa, Zimbabwe, Botswana, Namibia, the Democratic Republic of Congo, Zambia, and Tanzania, are major hubs for gold, diamond, copper, uranium, and rare-earth mining. Yet, the geohazards associated with these activities are almost entirely missing from the peer-reviewed literature. This gap represents more than just a lack of data; it means operational risks may be going unassessed. This creates a vital opportunity for research investment that could address local safety and regulatory requirements while helping to diversify the global evidence base within the geohazard science community.

3.3. Results of Keyword Co-Occurrence and Thematic Clustering

Table 5 presents the 15 most frequently co-occurring keyword pairs. The co-occurrence analysis of keywords from 150 selected publications reveals a highly specialised and coherent research domain focused on mining-induced geohazards, particularly subsidence

monitoring. The dominant thematic cluster is formed by the strong interconnection between geohazards, subsidence, mining, and synthetic aperture radar (SAR)/interferometric synthetic aperture radar (InSAR) technologies. Notably, ‘synthetic aperture radar’ appears in eight of the top fifteen co-occurring pairs, demonstrating that InSAR-based deformation monitoring has become the primary methodological approach in this field.

The strongest normalised association (Salton’s cosine = 0.6436) exists between the terms ‘coal’ and ‘coal mines’, indicating that these two terms are used in a highly overlapping way within the sample of the literature. From the absolute publication counts and the country-level commodity focus reported in Section 3.2.3, particularly the concentration of Chinese coal mining studies, this pattern is consistent with coal mining environments being the dominant setting for published geohazard research despite the global shift toward diverse commodities such as gold, copper, and critical minerals. Of the 150 papers reviewed, 47 (31.3%) explicitly addressed coal mining compared to 12 (8.0%) addressing gold, eight (5.3%) addressing copper, and five (3.3%) addressing critical minerals. This absolute distribution, combined with the network analysis, supports the conclusion that coal research dominates the literature.

Table 5. Top 15 co-occurring keyword pairs, ranked by absolute co-occurrence frequency.

Rank	Keyword 1	Keyword 2	Co-Occurrence Frequency	Salton’s Cosine Normalised Association Strength
1	Geohazards	Hazards	23	0.4242
2	Subsidence	Synthetic aperture radar	22	0.3826
3	Interferometric synthetic aperture radars	Synthetic aperture radar	21	0.5678
4	Deformation	Synthetic aperture radar	20	0.4683
5	Interferometry	Synthetic aperture radar	18	0.4971
6	Mining	Subsidence	16	0.2859
7	Geohazards	Mining	16	0.2811
8	Hazards	Mining	14	0.2722
9	Geohazards	Subsidence	14	0.2373
10	Hazards	Synthetic aperture radar	13	0.2460
11	Coal	Coal mines	13	0.6436
12	Data mining	Geohazards	12	0.2928
13	Hazards	Risk assessment	12	0.3655
14	Mining	Synthetic aperture radar	12	0.2163
15	Remote sensing	Synthetic aperture radar	11	0.2857

Overall, the literature exhibits a clear methodological orientation toward advanced remote sensing techniques (particularly InSAR) for the detection, monitoring, and risk assessment of mining-related ground deformation and associated geohazards. While these tools have produced valuable insights, their predominant application within coal mining contexts underscores the need for broader, multi-commodity research to support more inclusive and transferable geohazard management frameworks.

Figure 4 illustrates the co-word network derived from the keyword co-occurrence matrix. Through community detection analysis, three distinct thematic clusters emerge. The largest and most central cluster centres on subsidence, InSAR, synthetic aperture radar, deformation, and monitoring. This represents the field’s dominant methodological

approach: using satellite remote sensing to detect and measure mining-induced ground deformation. A second cluster links geohazards, hazards, and risk assessment, reflecting a broader perspective focused on hazard management. The third, more applied cluster connects mining, coal mines, underground mining, and opencast mines, highlighting the specific extractive industry context where these geohazards occur.

Taken together, the co-word analysis shows that the literature is organised around three primary axes: (1) characterising and monitoring ground deformation via advanced InSAR techniques, (2) framing these phenomena within the concept of geohazards, and (3) studying their occurrence within specific mining environments, particularly coal mines. These overlapping themes define the current research frontiers in the field of mining geohazards.

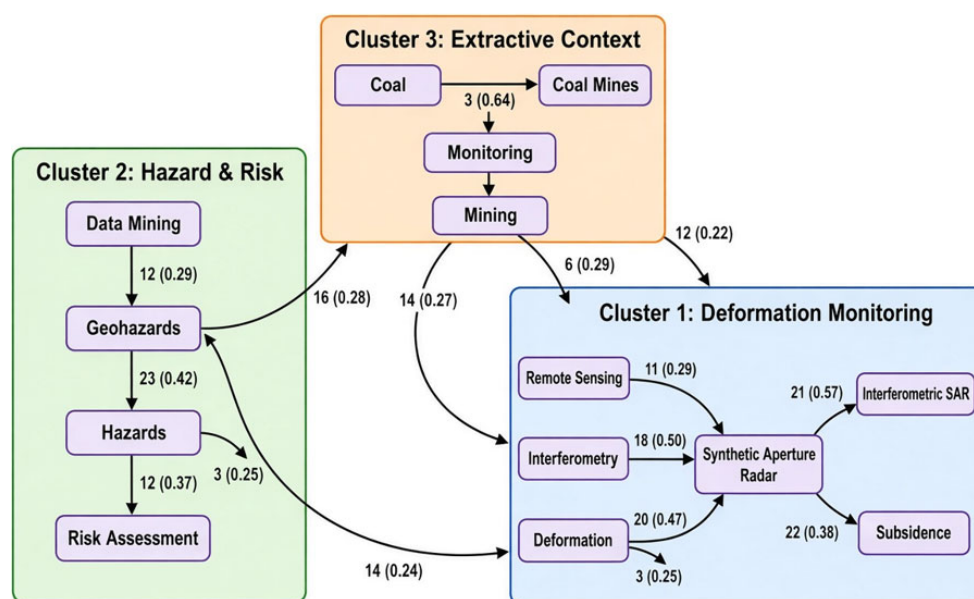


Figure 4. Keyword co-occurrence network diagram derived from author-assigned keywords of all reviewed publications. Node size is proportional to keyword degree centrality (number of co-occurring partners). Edge weight reflects co-occurrence frequency. Colour coding identifies three primary thematic clusters identified by community detection analysis.

3.4. Results of the Case Study Analysis

3.4.1. Amyntaio Open-Pit Lignite Mine, West Macedonia, Greece

Operated by the Public Power Corporation of Greece in West Macedonia, the Amyntaio mine extracts lignite from Pliocene lacustrine sediments interbedded with clay and peat layers. Since the 1970s, continuous large-scale dewatering has been required to maintain slope stability, creating a high-risk geohazard environment where interbedded clay and lignite layers (low shear strength, high compressibility) are vulnerable to consolidation-driven subsidence and gravitational failures [24]. Located approximately 2 km from the town of Amyntaio, surface deformation directly impacts residential buildings, infrastructure, and transport networks.

Loupasakis et al. [24] demonstrated that dewatering-induced consolidation of compressible layers drives surface settlement exceeding 1.5 m near the pit, with measurable deformation extending 3–4 km into surrounding agricultural plains. Building on this, Tzampoglou et al. [44] developed a GIS-based multi-hazard susceptibility framework integrating subsidence, slope instability, seismic triggers, and hydrological hazards into spatial risk maps. Later research using InSAR, inclinometers, and GPS documented slope reactivation along the pit edge, confirming that displacement often precedes bench-scale instability and that early-warning systems are feasible [7].

Key insight: Dewatering at Amyntaio created a geohazard footprint that stretched far beyond the mine's legal boundaries, impacting communities and infrastructure that the operator does not directly control. This highlights the limitations of hazard assessments that only look at the immediate mine site and emphasises the need for regional-scale impact assessments as a standard part of planning for large open-pit mines.

3.4.2. Sotvyno Salt Mine, Zakarpattia Oblast, Ukraine

Located in Ukraine's Zakarpattia Oblast, the Sotvyno salt mine operated from the 19th century until closure, targeting Miocene halite deposits with gypsum and anhydrite at depths of approximately 300 m. Because halite is highly soluble, groundwater rebound following the cessation of dewatering dissolved remaining salt pillars, expanding voids and triggering progressive, accelerating surface deformation that now threatens the town of several thousand people situated directly above the workings [25].

Dobos et al. [25] utilised multi-temporal InSAR data from ERS-1/2, Envisat, and Sentinel-1 satellites (1992–2021) to reconstruct deformation history with millimetre precision. Cumulative line-of-sight displacement exceeded 200 mm over 30 years, with deformation rates accelerating significantly after 2010 as dissolution-driven collapse intensified.

Key insight: The Sotvyno case proves that the liability associated with an evaporite mine does not end when the mine closes; in fact, it intensifies. Deformation rates were actually higher in the decade following closure than they were during active mining, driven by the groundwater-induced dissolution of residual pillars. This highlights a vital need for closure plans in evaporite and soluble-rock mines to include permanent monitoring obligations and fully funded remediation plans rather than simply stopping the dewatering process.

3.4.3. Sukari Gold Mine, Eastern Desert, Egypt

Located in Egypt's Eastern Desert, approximately 700 km south of Cairo, Sukari is Africa's largest gold producer, exploiting a Precambrian shear-zone-hosted deposit within the Arabian–Nubian Shield. Extraction combines large-scale open-pit mining with underground sublevel caving, creating a complex three-dimensional geomechanical environment. Open-pit slopes in fractured crystalline rock are susceptible to large-scale planar, wedge, and toppling failures along faults and shear zones, while underground caving-induced subsidence can compromise pit floor and lower wall stability.

Research demonstrates the effectiveness of satellite-based InSAR monitoring at Sukari. Mohamadi [26] employed persistent scatterer interferometry (PSI) using Sentinel-1 data to identify potential geohazards across the entire mining site. Displacement maps pinpointed accelerating movement on pit walls aligned with known structural weaknesses, confirming that satellite monitoring provides a reliable independent check on traditional geotechnical methods. The 6–12 day repeat cycle of Sentinel-1 enables detection of early slope instability signs weeks to months before failure, making InSAR a practical tool for operational trigger-action protocols.

Key insight: Out of 150 studies reviewed, Sukari is one of only three African mining sites mentioned. The success of InSAR at this site directly challenges the idea that satellite monitoring is unworkable in Africa due to technical limits or data shortages. The hurdles appear to be institutional and financial rather than technical; closing this gap is one of the most practical opportunities identified in this review.

3.4.4. Wuda Coalfield, Inner Mongolia, China

The Wuda coalfield is a Carboniferous–Permian basin where longwall extraction has created a well-documented history of natural and mining-induced underground coal fires from spontaneous ignitions occurring when residual coal in mined-out areas catches fire due

to oxygen ingress through subsidence cracks, ventilation systems, or surface outcrops [27]. These fires create cascading geohazards: combustion hollows subsurface voids accelerating collapse and subsidence; toxic gas release (CO, CO₂, H₂S) poses immediate risks to workers and communities; and heat weakens shaft linings and surface infrastructure.

Song et al. [27] applied a bow-tie risk analysis framework to Wuda's coal-fire hazards; this is an uncommon example of formal quantitative risk assessment for underground mining geohazards. The method models causal pathways (fault tree: oxygen ingress, spontaneous heating, frictional sparks, proximity to known fire zones) and consequences (consequence tree: accelerated subsidence, toxic gas leaks, infrastructure damage, community evacuation) with barrier controls on both sides. Thermal remote sensing provided continuous mapping of subsurface fire extent, complementing borehole gas monitoring to pinpoint zones requiring sealing, enhanced monitoring, or emergency evacuation.

Key insight: The Wuda application shows that structured risk analysis tools that are common in the petrochemical and process safety industries can be successfully adapted for underground mining. Unlike deformation monitoring, which is mostly reactive, the bow-tie framework forces a look at causal pathways and prevention barriers before a disaster strikes. This makes it a perfect fit for the proactive, life cycle approach reinforced in this review.

3.4.5. Bald Mountain Mine, Nevada, USA

Operated by Kinross Gold Corporation in Nevada's Basin and Range Province, Bald Mountain is a large-scale open-pit gold mine targeting disseminated mineralisation in faulted Paleozoic rocks. With pit depths exceeding 300 m, steep topography, fractured rock, and shifting hydrogeological conditions create significant slope stability challenges common to Western US open-pit gold mines.

Bourgeois et al. [28] performed InSAR back-analysis on two major slope failures: the December 2014 east wall failure at Top Pit and the January 2023 north wall failure at Saga Pit. Using Sentinel-1 descending orbit data, they identified measurable displacement acceleration weeks to months before instability became visually apparent. Satellite findings validated with ground-based tools helped refine trigger–action response thresholds.

Key insight: Bald Mountain serves as a prime example of InSAR moving beyond a mere research tool to become a practical early-warning system. In a major Western open-pit mine, it provides the kind of actionable intelligence needed for real-time slope management and proactive operational planning.

3.4.6. Lessons for Life Cycle Geohazard Integration

Taken together, these five case studies reveal a consistent pattern of structural challenges when trying to integrate geohazard science into practical mine planning. Table 6 provides a structured comparison of these five sites across the five life cycle dimensions examined in this review.

First, a recurring issue across all five cases is the general absence of pre-operational geohazard baselines. As Table 6 shows, none of the five sites had a satellite-based surface deformation baseline formally established during the exploration or pre-feasibility stage. Bald Mountain and Wuda are best described as partial cases: pre-existing SAR archives and regional coal-fire mapping data existed for these areas respectively, but in neither case were these data systematically incorporated into pre-extraction design decisions.

In the Amyntaio and Solotvyno cases, this oversight meant it was impossible to clearly distinguish mining-induced deformation from natural geological shifts or other human activities. A practical and inexpensive fix is to use archived satellite data that predates mine

construction to start InSAR monitoring; this should be a standard part of environmental and geohazard baseline programs during the exploration phase.

Table 6. Cross-case comparison of geohazard life cycle integration across the five selected case studies (compiled from [7,24–29,44]). Colour coding is based on the level of geohazard consideration; red for absent and inadequate; green for strong.

Life Cycle Dimension	Amyntaio (Greece)	Solotvyno (Ukraine)	Bald Mountain (USA)	Sukari (Egypt)	Wuda (China)
	Partial	Absent	Partial	Absent	Partial
Pre-operational geohazard baseline	No InSAR baseline prior to operations; hydrogeological risk under-characterised at design stage	Salt dissolution and groundwater rebound risks not formally assessed before closure	Pre-failure baseline; InSAR applied reactively	Satellite monitoring initiated during operations; no pre-development deformation baseline documented	Coal-fire zones regionally mapped but not formally integrated into pre-extraction design decisions
	Strong	Weak	Strong	Moderate	Moderate
Operational monitoring system	Multi-method system (InSAR, GPS, inclinometers); trigger-action thresholds defined and documented	During operations; InSAR monitoring applied retrospectively after closure and flooding had commenced	Sentinel-1 InSAR successfully used for real-time early warning and operational decision-making	Satellite-based slope monitoring demonstrated; integration with operational decisions not fully described	Bow-tie risk framework applied; thermal remote sensing used; no real-time automated alert system
	Explicit	Inadequate	Limited	Limited	Partial
Community and off-site impact management	Subsidence crossed residential boundary; community risk mapping and impact compensation documented	Solotvyno town directly endangered; no funded community protection post-closure	Remote location reduces community exposure	Remote desert location reduces community exposure; wadi flooding and dust risks not addressed	Coal fire affects surface stability and air quality; off-site community health impacts not quantified
	Emerging	Absent	Ongoing operations	Ongoing operations	Unresolved
Closure and post-closure planning	Long-term monitoring planned; land-use restrictions applied, but full closure plan not published	Mine closed without remediation funding; hazard accelerated dramatically after cessation of dewatering	Closure planning not yet documented	Closure planning not yet documented in the reviewed literature	Coal fires represent an open-ended closure challenge with no permanent extinguishment strategy
	High	High	High	Very high	Moderate
Transferability to African/Global South mining contexts	Multi-hazard open-pit GIS framework applicable to African open-pit and pit-expansion contexts	Legacy hazard management lessons critical for post-colonial abandoned mines across Sub-Saharan Africa	Practical InSAR early-warning methods transferable to arid open-pit operations	Directly demonstrates satellite monitoring applicability in data-scarce African crystalline environments	Bow-tie framework fully transferable; coal-fire hazard specific to coal-bearing geological settings

Second, the case of Solotvyno provides a stark warning about the dangers of poor closure planning, a problem that is visible to varying degrees at all five sites. While Bald Mountain excels at real-time monitoring, it still follows the common industry trend of pushing detailed closure geohazard planning to the last minute. Geohazard risks do not disappear once extraction stops; in fact, they often escalate during the post-closure phase as dewatering ends, voids interact with groundwater, and the structural support of active infrastructure is removed. Consequently, closure plans must treat long-term geohazard management as a serious, fully funded obligation rather than a leftover liability to be dealt with only when necessary.

Third, these five cases collectively highlight the importance of using a variety of methods. Amyntaio and Bald Mountain show how InSAR is becoming a mature tool for managing deformation in open-pit mines, while Sukari demonstrates that this technology works effectively even in African environments. Solotvyno serves as a reminder of the long-term risks associated with soluble-rock mines, and Wuda expands the scope beyond simple deformation to include combustion and other complex hazards managed

through frameworks like bow-tie analysis. There is no ‘silver bullet’ solution; true life cycle integration requires a diverse toolkit that blends satellite remote sensing, ground-based instruments, structured risk analysis, and robust governance.

Finally, the Sukari case demonstrates that high-quality satellite monitoring is technically feasible and beneficial in an African, Global South mining context. Bald Mountain, while located in Nevada, USA, rather than the Global South, shows that the same InSAR-based methodology is transferable across arid, large-scale open-pit settings more broadly. Taken together, the two cases suggest, as a hypothesis warranting further comparative evidence, that barriers to wider adoption in under-represented regions are more likely institutional and regulatory than purely technical, particularly the absence of mandatory pre-operational deformation baselines and continuous monitoring requirements. Closing this governance gap is one of the most effective pathways to improved life cycle geohazard management.

4. Critical Evaluation and Synthesis

4.1. Geohazards Across the Mine Life Cycle

This review reveals imbalances in research attention across different stages of the mine life cycle. While approximately 6% of the literature addresses exploration-stage geohazards, the five case studies demonstrate that early identification is critical. The Bald Mountain and Sukari cases show that establishing satellite-based deformation baselines before operations begin enables detection of mining-induced changes versus natural ground movement [26,28]. Yet, as the Solotvyno case starkly illustrates, with escalating post-closure collapse following 30 years of monitoring [25], the absence of pre-mining baseline data makes distinguishing anthropogenic from natural deformation nearly impossible.

The Amyntaio open-pit mine provides the clearest example of dewatering-induced multi-hazard interaction. Loupasakis et al. [24] demonstrated that dewatering consolidation caused surface settlement exceeding 1.5 m, with deformation extending 3–4 km beyond legal boundaries, affecting residential areas and infrastructure. This case exemplifies how surface mining geohazards can have transboundary impacts, a finding reinforced by Tzampoglou et al. [44], who developed GIS-based multi-hazard susceptibility frameworks that integrated subsidence, slope instability, seismic triggers, and hydrological hazards. The InSAR-based slope monitoring at Bald Mountain [28] shows that displacement acceleration precedes bench-scale instability by weeks to months, a critical early-warning capability that should be standard in operational planning.

As a critical insight from Porter et al. [78], geohazard processes typically exhibit magnitude–frequency relationships where larger events occur less frequently than smaller events, yet the smallest event that can lead to a credible loss scenario often dominates risk, particularly along transportation corridors. This has profound implications for monitoring design: systems must be sensitive enough to detect small, frequent events while maintaining capability to characterise rare, catastrophic scenarios. The remote sensing technologies reviewed in Zhang et al. [79] demonstrate that achieving this balance requires multi-platform integration, as individual monitoring methods have inherent limitations. For example, InSAR can detect millimetre-scale deformation across wide areas but suffers from decorrelation in regions with dense vegetation or excessive deformation gradients, while UAV photogrammetry provides high-resolution local data but has limited temporal coverage [79].

4.2. Alignment Between the Literature and Practice

The review identifies three key misalignments. First, there is a life cycle integration gap: research concentrates heavily on active underground mining (about 25% of

papers) and post-mining phases (about 15%), while exploration and reclamation remain under-represented. This means critical decisions during project initiation lack systematic geohazard intelligence. Porter et al. [78] reinforce this concern, noting that as projects advance from exploration to construction, the number of personnel onsite increases and seasonal duration of site activities expands, increasing exposure time to geohazards. Yet risk matrices, the primary tools used for corporate risk assessment, are typically only intended for screening-level assessments and often fail to capture the spatial and temporal probability components essential for accurate geohazard risk characterisation [78].

Second, a geographic bias exists: China contributes 45% of studies, while Africa, known for hosting major gold, diamond, and copper reserves and extraction, contributes only five publications. The Sukari gold mine case [26] indicates that satellite monitoring works effectively in African hard-rock environments, suggesting this gap reflects research investment rather than technical barriers. Porter et al. [78] emphasise that geohazards can impact resource development at all project stages, and the variability in spatial and temporal probabilities for people and infrastructure exposed to geohazards can have a large influence on risk exposure, a factor that requires context-specific assessment that may not transfer well across geographic regions.

Third, a commodity bias persists: coal mining dominates the literature (strongest normalised association: coal–coal mines at Salton’s cosine = 0.6436), limiting generalizability to gold, copper, and critical mineral extraction. This is particularly concerning given that non-coal mining areas, such as metal and rare-earth mines, often exhibit significant lithological heterogeneity and more complex structural controls [79]. The Wuda coalfield case [27] offers a proactive counterpoint: applying bow-tie analysis, common in petrochemical safety, to underground coal-fire hazards demonstrates how structured risk frameworks can identify causal pathways and prevention barriers before disasters occur. This contrasts with the predominantly reactive deformation monitoring approaches that dominate the literature.

4.3. Surface Versus Underground Operations

The case studies reveal distinct operational challenges. Surface mining (Amyntaio, Bald Mountain, Sukari) faces slope instability, dewatering-induced subsidence, and community cross-boundary impacts. Underground operations (Solotvyno, Wuda) experience flooding, dissolution collapse, and combustion hazards [25,27]. However, both share the need for InSAR-based monitoring and early-warning systems. The Solotvyno 30-year time-series analysis demonstrates that post-closure hazards can accelerate over decades [25], challenging the assumption that closure ends geohazard risk.

Zhang et al. [79] provide a comprehensive framework for understanding these differential monitoring requirements. Their analysis shows that surface subsidence monitoring requires vertical displacement precision of $\pm 1\text{--}5$ mm and horizontal displacement of $\pm 1\text{--}2$ mm, with core detection indicators including subsidence magnitude, rate, and horizontal displacement. In contrast, ground fissure monitoring requires width detection ≥ 0.1 mm and length error $\leq 1\%$, achieved through UAV photogrammetry and LiDAR. For landslides, monitoring demands displacement precision ≥ 1 mm and strain ≥ 10 $\mu\epsilon$, while collapses require displacement ≥ 0.5 mm and vibration frequency detection of 1–100 Hz [79]. This tiered precision framework highlights why a one-size-fits-all monitoring approach is inadequate.

Porter et al. [78] add another critical dimension: the risk formulation for geohazards must incorporate hazard probability ($P(H)$), spatial probability ($P(S:H)$), temporal probability ($P(T:S)$), vulnerability (V), and consequence value (E). Their example of rockfall risk along a transportation corridor demonstrates that expected annual fatalities (approximately 5.6×10^{-4}) are often far below the thresholds that trigger action in corporate risk

matrices yet, cumulatively, may represent unacceptable risk. This mathematical reality challenges the practice of using simple risk matrices for operational decisions without understanding how spatial and temporal probabilities combine with vulnerability to produce risk estimates.

4.4. Revising Risk Assessments

InSAR time-series analysis enables continuous risk assessment refinement. The Bald Mountain back-analysis [28] demonstrates how satellite data can refine trigger–action response thresholds. National monitoring programs, such as Poland’s interferometric system [55], support local planning by identifying anomalous deformation features. However, as Liang et al. [17] note, multimodal approaches remain at the prototype stage, with limited integration into operational decision-making. Zhang et al. [79] identify four critical bottlenecks in current monitoring systems, including single-data dimensionality, limited environmental adaptability, deployment and stability challenges, and anti-interference limitations. The Amyntaio case’s cross-boundary subsidence [7,24] underscores that risk assessments must extend beyond mine leases, a lesson still inadequately integrated into regulatory frameworks. Porter et al. [78] reinforce this, noting that while individual geohazards may be statistically independent, they often share common triggering events (e.g., rainfall, seismic activity), meaning multiple hazards can occur simultaneously. This interdependence complicates risk summation: the financial impact of business interruption per unit of time is not linear [80], and multiple system components operating in series can pose high risk even when individual component risks are relatively low. They note that guidance is often missing on how to combine risk from different event magnitudes or evaluate system-level risk using standard matrices.

4.5. Limitations of This Review

This review is limited to the English-language, peer-reviewed literature from Scopus, excluding grey literature and industry reports, and thus, some additional insight might have been missed, but for quality assurance these exclusions were necessary; nevertheless, the selected papers represent the topic at a global scale (see world map, Figure 3). The exclusion of grey literature and industry reports may particularly affect the results regarding transfer of geohazard information between mining stages, as this practical life-of-mine integration is likely to be documented in technical and regulatory reports rather than exclusively in journal articles.

In addition, this study relies on single-category assignment, which is acknowledged as a limitation given that the categories are not fully mutually exclusive; however, independent multidimensional coding was not practically feasible.

The strong regional bias in existing research limits generalizability, and the rapid pace of technological change complicates cross-study comparisons. Similarly, risk matrix guidance documents are often brief and cryptic [78], and the calibration of geohazard event frequency estimates is usually done through records of events that have occurred—but geohazard events that do not reach, or come close to reaching, elements at risk are often not observed and are under-reported, introducing systematic uncertainty. However, such ‘near misses’ would contribute to scale and better-quality training samples, particularly for deep learning and machine learning applications.

5. Conclusions and Recommendations

5.1. Conclusions

This review of 150 publications demonstrates that technical capabilities for geohazard monitoring have advanced dramatically especially with InSAR deformation analysis,

machine learning classification, and multi-sensor data fusion. However, a pronounced imbalance in research attention across the mine life cycle exists. The five case studies, compared using the explicit cross-stage indicators in Table 6 (pre-operational baseline, operational monitoring, community impact management, closure planning, and cross-regional transferability), further suggest that individual studies rarely transfer geohazard intelligence across more than one or two adjacent life cycle stages. We note this pattern is illustrated by five purposively selected cases rather than quantified across the full sample of 150 studies and should be read as a hypothesis supported by targeted evidence rather than a fully quantified property of the literature.

Three overarching conclusions emerge:

First, exploration-stage geohazards are critically under-researched (about 6% of the literature), yet the case studies demonstrate that establishing pre-mining baselines is essential for distinguishing anthropogenic from natural deformation. Without early hazard identification, operations default to reactive management, with spiked costs and regulatory risks. The smallest credible event often dominates risk [78], making early characterisation particularly valuable because it allows proactive design of mitigation measures rather than emergency responses.

Second, the geographic and commodity concentration of research focuses on China and predominantly on coal, which severely limits the transferability of findings to other regions and mining types. The near absence of African research represents both a knowledge gap and an opportunity for targeted investment. Monitoring requirements vary significantly across hazard types and geological setting [79], suggesting that local calibration is essential and monitoring hierarchy must be adapted to site-specific conditions, including vegetation cover, climate, and deformation characteristics. Geohazard risk is not static [78] and may increase in response to time (e.g., progressive failure), construction activities, forest fires, climate change, and other factors. This dynamic nature means that geographic transferability is further complicated by evolving conditions, particular during the post-closure stage [25].

Third, while InSAR has matured from research tool to operational monitoring system, integration with closure planning, decision-making frameworks, and community risk management remains weak. Post-closure hazards can escalate catastrophically when long-term monitoring and institutional responsibility are absent. Establishing multi-scale dynamic monitoring systems and digital visualisation platforms as critical safeguards can ensure lifecycle safety management [79]. Transitioning monitoring from mere deformation identification to proactive risk prediction through deep integration of observational data with mechanical and hydrological evolution models is necessary, particularly as projects develop, and land use changes, and in response to extreme climatic events, which are likely to have different recurrence intervals compared to the time of the initial mine planning (considering a typical mine life of at least 20 years). Connecting monitoring data, triggering conditions, and spatial and temporal probability estimates to a 'live' system can allow risk to be more readily updated, accurately portrayed, and fed into an enhanced early-warning system.

5.2. Recommendations

The following overarching recommendations are revealed from this review:

- Develop exploration-stage protocols combining satellite pre-screening, legacy data mining, and targeted geophysics for greenfield assessments, incorporating the risk formulation framework (P(H), P(S:H), P(T:S), V, E) to enable quantitative risk estimation from the earliest project phases;

- Prioritise research in under-represented regions, particularly Sub-Saharan Africa and Latin America, to develop locally calibrated benchmarks and case studies, accounting for variations in vegetation cover, climate, and geological conditions that affect monitoring technology performance;
- Create standardised, open-access benchmark datasets for machine learning models to move from prototypes to operational systems and enable robust comparison of algorithm performance across different mining environments;
- Expand research beyond coal to gold, copper, critical minerals, and other commodities, particularly examining how different rock mass properties, mining methods, and processing techniques influence geohazard evolution and monitoring requirements.

The following practical recommendations are revealed from this review:

- Establish pre-mining satellite deformation baselines as standard practice during exploration and feasibility phases;
- Establish a life-of-mine geohazard management approach that transfers and updates geohazard knowledge from exploration to closure through a continuously maintained geohazard register, avoiding the fragmentation that results from treating project phases separately;
- Develop regulatory frameworks requiring mine-leasehold expansion risk assessments, recognizing that geohazards (as at Amyntaio) extend beyond legal boundaries;
- Mandate post-closure monitoring with clear institutional responsibility, as demonstrated by Poland's national interferometric program [55] and the Geological Survey of Brazil's policy support [56].

The following recommendations regarding technology development are revealed from this review:

- Accelerate AI-based geohazard recognition through industry–academic partnerships, focusing on validation procedures and human-centred decision support;
- Strengthen links between real-time deformation monitoring and closure design criteria to ensure long-term risk management is built into operational planning.

5.3. Final Remarks

The manuscript's central finding shows that technical capability now exceeds systematic integration and points to a clear path forward. Mining geohazards will not be eliminated by better sensors alone. Instead, the industry and research community must commit to proactive, life cycle approaches that embed hazard intelligence from first exploration drill to final reclamation. The five case studies collectively demonstrate that when integrated, geohazard science works. The challenge lies in making integration the norm rather than the exception.

Author Contributions: Conceptualisation, H.W.; methodology, L.M. and H.W.; formal analysis, L.M.; writing—original draft, L.M.; writing—review and editing, L.M. and H.W.; supervision, H.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: During the preparation of this manuscript, the authors used Claude Sonnet 3 for the purposes of improving language and grammar. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Li, M.; Zhang, Y.; Zhang, J.; Wen, Z.; Huang, J.; Li, H. Monitoring and prediction of subsidence in mining areas of Liaoyuan Northern New District based on InSAR technology. *GeoHazards* **2026**, *7*, 17. [\[CrossRef\]](#)
- Culshaw, M.G.; McCann, D.M.; Donnelly, L.J. Impacts of abandoned mine workings on aspects of urban development. *Min. Technol.* **2000**, *109*, 132–139. [\[CrossRef\]](#)
- Donnelly, L. Geological investigations at a high altitude, remote coal mine on the Northwest Pakistan and Afghanistan frontier, Karakoram Himalaya. *Int. J. Coal Geol.* **2004**, *60*, 117–150. [\[CrossRef\]](#)
- Marschalko, M.; Yilmaz, I.; Bednárík, M.; Kubečka, K.; Bouchal, T.; Závada, J. Subsidence map of underground mining influence for urban planning: An example from the Czech Republic. *Q. J. Eng. Geol. Hydrogeol.* **2012**, *45*, 231–241. [\[CrossRef\]](#)
- Zhu, Z.; Fang, S.; Cao, H.; Zou, Q.; Li, K.; Li, C. Deformation laws of coal mining-affected slopes in loess gully area. *GeoHazards* **2026**, *7*, 89. [\[CrossRef\]](#)
- Donnelly, L.; De La Cruz, H.; Asmar, I.; Zapata, O.; Perez, J.D. The monitoring and prediction of mining subsidence in the Amaga, Angelopolis, Venecia and Bolombolo regions, Antioquia, Colombia. *Eng. Geol.* **2001**, *59*, 103–114. [\[CrossRef\]](#)
- Loupasakis, C. Contradictive mining-induced geocatastrophic events at open pit coal mines: The case of Amintaio coal mine, West Macedonia, Greece. *Arab. J. Geosci.* **2020**, *13*, 582. [\[CrossRef\]](#)
- Melo, C.M.; Kobiyama, M.; Michel, G.P.; de Brito, M.M. The relevance of geotechnical-unit characterization for landslide-susceptibility mapping with SHALSTAB. *GeoHazards* **2021**, *2*, 383–397. [\[CrossRef\]](#)
- Guan, Y.; Yu, L.; Hao, S.; Li, L.; Zhang, X.; Hao, M. Slope failure and landslide detection in Huangdao District of Qingdao City based on an improved Faster R-CNN model. *GeoHazards* **2023**, *4*, 302–315. [\[CrossRef\]](#)
- Sen, A.A.A.; Aljohani, F.H.; Bahbouh, N.M.; Ben Mnaouer, A.; Tayan, O.; Alkhodre, A.B. A Context-Aware Flood Warning Framework Integrating Ensemble Learning and LLMs. *GeoHazards* **2026**, *7*, 35. [\[CrossRef\]](#)
- Potoczny, K.; Goda, K.; Sadrekarimi, A. Machine Learning Analysis of Landslide Susceptibility in the Western Québec Seismic Zone of Canada. *GeoHazards* **2026**, *7*, 36. [\[CrossRef\]](#)
- Yang, Z.; Li, Z.; Zhu, J.; Wang, Y.; Wu, L. Use of SAR/InSAR in Mining Deformation Monitoring, Parameter Inversion, and Forward Predictions: A Review. *IEEE Geosci. Remote Sens. Mag.* **2020**, *8*, 71–90. [\[CrossRef\]](#)
- Yang, Z.; Xu, B.; Li, Z.; Wu, L.; Zhu, J. Prediction of Mining-Induced Kinematic 3-D Displacements from InSAR Using a Weibull Model and a Kalman Filter. *IEEE Trans. Geosci. Remote Sens.* **2022**, *60*, 4500912. [\[CrossRef\]](#)
- Festa, D.; Casagli, N.; Casu, F.; Confuorto, P.; De Luca, C.; Del Soldato, M.; Lanari, R.; Manunta, M.; Manzo, M.; Raspini, F. Automated Classification of A-DInSAR-Based Ground Deformation by Using Random Forest. *GISci. Remote Sens.* **2022**, *59*, 1749–1766. [\[CrossRef\]](#)
- Li, W.; Wu, L.; Xu, X.; Xie, Z.; Qiu, Q.; Liu, H.; Huang, Z.; Chen, J. Deep Learning and Network Analysis: Classifying and Visualizing Geologic Hazard Reports. *J. Earth Sci.* **2024**, *35*, 1289–1303. [\[CrossRef\]](#)
- Trinidad, M.; Momayez, M. Machine Learning in Slope Stability: A Review with Implications for Landslide Hazard Assessment. *GeoHazards* **2025**, *6*, 67. [\[CrossRef\]](#)
- Liang, R.; Zhang, C.; Huang, C.; Li, B.; Saydam, S.; Canbulat, I.; Munsamy, L. Multimodal Data Fusion for Geo-Hazard Prediction in Underground Mining Operation. *Comput. Ind. Eng.* **2024**, *193*, 110268. [\[CrossRef\]](#)
- Baxter, H. Pilbara Cenozoic Detrital Sequences and Associated Geohazards. *Aust. Geomech.* **2013**, *48*, 39–48.
- Griffin, M.S.; Keaton, J.R. Geotechnical considerations for mining in an era of uncertainty and change. In *Geotechnical Engineering for Infrastructure and Development*; ICE Publishing Limited: London, UK, 2015; pp. 2535–2540. [\[CrossRef\]](#)
- 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.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [\[CrossRef\]](#) [\[PubMed\]](#)
- Zakharovskiy, V.; Németh, K. Systematic literature review of the natural environment of the Coromandel Peninsula, New Zealand, from a conservation perspective. *Conservation* **2021**, *1*, 270–284. [\[CrossRef\]](#)
- Callon, M.; Courtial, J.-P.; Turner, W.A.; Bauin, S. From translations to problematic networks: An introduction to co-word analysis. *Soc. Sci. Inf.* **1983**, *22*, 191–235. [\[CrossRef\]](#)
- Salton, G.; McGill, M.J. *Introduction to Modern Information Retrieval*; McGraw-Hill: New York, NY, USA, 1983.
- Loupasakis, C.; Angelitsa, V.; Rozos, D.; Spanou, N. Mining geohazards: Land subsidence caused by the dewatering of opencast coal mines. The case study of the Amyntaio coal mine, Florina, Greece. *Nat. Hazards* **2014**, *70*, 675–691. [\[CrossRef\]](#)
- Dobos, E.; Kovács, I.P.; Kovács, D.M.; Ronczyk, L.; Szűcs, P.; Perger, L.; Mikita, V. Surface deformation monitoring and risk mapping in the surroundings of the Solotvyno Salt Mine (Ukraine) between 1992 and 2021. *Sustainability* **2022**, *14*, 7531. [\[CrossRef\]](#)
- Mohamadi, B. Utilizing InSAR for surface stability monitoring in mining sites: A case study of Sukari Gold Mine in Egypt. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2024**, *XLVIII-1*, 523–528. [\[CrossRef\]](#)

27. Song, Z.; Yu, Z.; Zhao, J.; Li, M.; Deng, J. Bow-tie analysis of underground coal-fire hazards and mining activities using hybrid data: A case study of Wuda Coalfield in Inner Mongolia, China. In *Bow Ties in Process Safety and Environmental Management*; Wiley: Hoboken, NJ, USA, 2021. [\[CrossRef\]](#)
28. Bourgeois, J.; Warren, S.; Sbaji, S.; Salzer, J.; Meda, A.; Lasich, T. Applications of InSAR for early indication of mine slope instability: Back analysis of satellite displacement data. In *Proceedings of the Slope Stability 2024*, Belo Horizonte, Brazil, 14–19 April 2024.
29. Pukanská, K.; Bartoš, K.; Bakoň, M.; Papčo, J.; Kubica, L.; Barlák, J.; Rovňák, M.; Kseňák, L.; Zelenakova, M.; Savchyn, I.; et al. Multi-sensor and multi-temporal approach in monitoring of deformation zone with permanent monitoring solution and management of environmental changes: A case study of Solotvyno Salt Mine, Ukraine. *Front. Earth Sci.* **2023**, *11*, 1167672. [\[CrossRef\]](#)
30. Smith, I.R. Data mining seismic shothole drillers' log records: Regional baseline geoscience information in support of pipeline proposal design, assessment, and development. In *Proceedings of the 7th International Pipeline Conference*, Calgary, AB, Canada, 29 September–3 October 2008; Volume 4, pp. 299–303. [\[CrossRef\]](#)
31. Perez Rodriguez, M.S.; Garcia-Aristizabal, E.F.; Vega-Posada, C.A.; Montoya-Dominguez, J.; Noriega, P.; Alfonso, J.; Cajicáca, L. Comparative study among rock mass classification systems in a porphyry deposit. *Bol. Cienc. Tierra* **2018**, *43*, 34–44. [\[CrossRef\]](#)
32. Cooper, A. Halite karst geohazards (natural and man-made) in the United Kingdom. *Environ. Geol.* **2002**, *42*, 505–512. [\[CrossRef\]](#)
33. Cooper, A.H. Did the Earth move for you? Buying a house? Every house-buyer in the UK could benefit from a new geological hazard service from the British Geological Survey. *Planet Earth* **2007**, 24–25.
34. Yaoru, L. Gypsum karst geohazards in China. In *The Engineering Geology and Hydrology of Karst Terrains*; CRC Press: Boca Raton, FL, USA, 2020; pp. 117–126. [\[CrossRef\]](#)
35. Zhou, W.F. Paleocollapse structure as a passageway for groundwater flow and contaminant transport. *Environ. Geol.* **1997**, *32*, 251–257. [\[CrossRef\]](#)
36. Waltham, A.C.; Swift, G.M. Bearing capacity of rock over mined cavities in Nottingham. *Eng. Geol.* **2004**, *75*, 15–31. [\[CrossRef\]](#)
37. Cigna, F.; Tapete, D. Present-day land subsidence rates, surface faulting hazard and risk in Mexico City with 2014–2020 Sentinel-1 IW InSAR. *Remote Sens. Environ.* **2021**, *253*, 112161. [\[CrossRef\]](#)
38. Liu, C.; Zhang, P.; Shang, J.; Yao, D.; Wu, R.; Ou, Y.; Tian, Y. Comprehensive research on the failure evolution of the floor in upper mining of deep and thick coal seam. *J. Appl. Geophys.* **2022**, *206*, 104774. [\[CrossRef\]](#)
39. Bai, Y.; Yin, Y.; Hongjie, D.; Gong, L.; Xiong, X.; Wei, X.; Gao, Y.; Tie, Y.; Li, Q.; Zhu, S.; et al. Mechanism and movement process of the “2.8” rock avalanche in Junlian County, Southwest China. *Landslides* **2026**, *23*, 1275–1289. [\[CrossRef\]](#)
40. Hallman, D.S. Foamed backfilling for combatting mine fires. *Environ. Geotech.* **2022**, *9*, 310–317. [\[CrossRef\]](#)
41. Zhou, N.; Li, M.; Zhang, J.; Gao, R. Roadway backfill method to prevent geohazards induced by room and pillar mining: A case study in Changxing Coal Mine, China. *Nat. Hazards Earth Syst. Sci.* **2016**, *16*, 2473–2484. [\[CrossRef\]](#)
42. LeBlanc, T.J.; Butler, S.L. Detection of a permeable aquifer geohazard above potash mines using in-mine time-domain electromagnetics. *J. Environ. Eng. Geophys.* **2024**, *29*, 127–141. [\[CrossRef\]](#)
43. Zhang, Y.; Li, L.; Mu, W.; Wei, T.; Wang, X.; Yu, G. CNN-KA: A hybrid P-phase picking method for microseismic source location in deep mine with complex geological conditions. *IEEE Trans. Geosci. Remote Sens.* **2025**, *63*, 5904812. [\[CrossRef\]](#)
44. Tzampoglou, P.; Loupasakis, C. Mining geohazards susceptibility and risk mapping: The case of the Amyntaio open-pit coal mine, West Macedonia, Greece. *Environ. Earth Sci.* **2017**, *76*, 542. [\[CrossRef\]](#)
45. Zhang, Y.; Wu, H.; Li, M.; Kang, Y.; Lu, Z. Investigating ground subsidence and the causes over the whole Jiangsu Province, China using Sentinel-1 SAR data. *Remote Sens.* **2021**, *13*, 179. [\[CrossRef\]](#)
46. Kimijima, S.; Nagai, M. Monitoring mining-induced geo-hazards in a contaminated mountainous region of Indonesia using satellite imagery. *Remote Sens.* **2023**, *15*, 3436. [\[CrossRef\]](#)
47. Chaussard, E.; Kerosky, S. Characterization of black sand mining activities and their environmental impacts in the Philippines using remote sensing. *Remote Sens.* **2016**, *8*, 100. [\[CrossRef\]](#)
48. Termizi, A.K.; Mohamed, T.R.T.; Roslee, R. An overview of sinkhole geohazard incidence recorded in the Kinta Valley area, Perak. *ASM Sci. J.* **2018**, *11*, 19–28.
49. Wang, T.; Zhao, F.; Wang, Y.; Zhang, N.; Zhou, D.; Diao, X.; Zhao, X. An algorithm for locating subcritical underground goaf based on InSAR technique and improved probability integral model. *IEEE Trans. Geosci. Remote Sens.* **2023**, *61*, 5214914. [\[CrossRef\]](#)
50. Wang, Y.; Yang, Z.; Li, Z.; Zhu, J.; Wu, L. Fusing adjacent-track InSAR datasets to densify the temporal resolution of time-series 3-D displacement estimation over mining areas with a prior deformation model and a generalized weighting least-squares method. *J. Geod.* **2020**, *94*, 47. [\[CrossRef\]](#)
51. Liu, H.; Yuan, M.; Li, M.; Li, B.; Chen, N.; Wang, J.; Li, X.; Wu, X. TDFPI: A three-dimensional and full parameter inversion model and its application for building damage assessment in Guotun coal mining areas, Shandong, China. *Remote Sens.* **2024**, *16*, 698. [\[CrossRef\]](#)
52. Zhang, Y.; He, K.; Hu, X.; Liu, W.; Zhang, S.; Wu, J.; Xi, C. Mechanism of surface subsidence and sinkhole formation in mining areas: Insights from MPM. *Bull. Eng. Geol. Environ.* **2024**, *83*, 330. [\[CrossRef\]](#)

53. Liang, R.; Huang, C.; Zhang, C.; Canbulat, I.; Munsamy, L.; Carstens, R.; Prinsloo, L. Multi-factor integrated data analytics and data-driven decision-making for ground control management. In Proceedings of the Australasian Ground Control Conference (AusRock 2022), Melbourne, Australia, 29 November–1 December 2022; p. 4.
54. Donnelly, L. Introduction to geological hazards in the UK: Their occurrence, monitoring and mitigation. *Geol. Soc. Lond. Eng. Geol. Spec. Publ.* **2020**, *29*, 291–309. [\[CrossRef\]](#)
55. Przytucka, M.; Perski, Z.; Cisło, M. Interferometric monitoring of the terrain surface of Poland. *Prz. Geol.* **2025**, *73*, 631–639. [\[CrossRef\]](#)
56. De Aguiar Accioly, A.C.; Fernandes da Silva, S.; Rodrigues Pinto, L.G.; De Oliveira Dantas, C.E. Geoscience for public policy: The role of the Geological Survey of Brazil in supporting national development strategies. *J. Geol. Surv. Braz.* **2025**, *9*, SI3. [\[CrossRef\]](#)
57. Pereyra, F.; Boujon, P.; Gómez, A.; Tello, N.; Tobío, M.I.; Lapido, O. Geoscientific study applied to the evaluation of urbanisation suitability at the Carboniferous Basin of Río Turbio, Santa Cruz. *Rev. Asoc. Geol. Argent.* **2010**, *66*, 505–519.
58. Fajfer, J.; Rolka, M. Assessment of the environmental impact of hard coal mining waste disposal sites using machine learning algorithms, with an indication of important features influencing the selection of learning algorithms. *Geol. Q.* **2025**, *69*, 65. [\[CrossRef\]](#)
59. Mehdi-pour Ghazi, J.; Audra, P. Travertine Park in Azarshahr (NW Iran): An opportunity for geoheritage conservation and diminishing geohazards risk. *Geoheritage* **2022**, *14*, 99. [\[CrossRef\]](#)
60. Battistini, A.; Segoni, S.; Manzo, G.; Catani, F.; Casagli, N. Web data mining for automatic inventory of geohazards at national scale. *Appl. Geogr.* **2013**, *43*, 147–158. [\[CrossRef\]](#)
61. Jones, L.; Hobbs, P. The application of terrestrial LiDAR for geohazard mapping, monitoring and modelling in the British Geological Survey. *Remote Sens.* **2021**, *13*, 395. [\[CrossRef\]](#)
62. Kovanič, L.; Peťovský, P.; Topitzer, B.; Blišťan, P. Spatial analysis of point clouds obtained by SfM photogrammetry and the TLS method: Study in quarry environment. *Land* **2024**, *13*, 614. [\[CrossRef\]](#)
63. Tapete, D.; Cigna, F. InSAR data for geohazard assessment in UNESCO World Heritage Sites: State-of-the-art and perspectives in the Copernicus era. *Int. J. Appl. Earth Obs. Geoinf.* **2017**, *63*, 24–32. [\[CrossRef\]](#)
64. Read, R.S.R.; Rizkalla, M. Bridging the gap between qualitative, semi-quantitative and quantitative risk assessment of pipeline geohazards: The role of engineering judgment. In *ASME 2015 International Pipeline Geotechnical Conference*; ASME: New York, NY, USA, 2015. [\[CrossRef\]](#)
65. Alexander, G.T. The subsidence as a geohazard in pipelines. In Proceedings of the Rio Pipeline Conference, Rio de Janeiro, Brazil, 26 September 2013.
66. Commerci, V.; Vittori, E.; Cipolloni, C.; Di Manna, P.; Guerrieri, L.; Nisio, S.; Succhiarelli, C.; Ciuffreda, M.; Bertolotti, E. Geohazards monitoring in Roma from InSAR and in situ data: Outcomes of the PanGeo project. *Pure Appl. Geophys.* **2015**, *172*, 2997–3028. [\[CrossRef\]](#)
67. Kratzsch, H. *Mining Subsidence Engineering*; Springer: Berlin, Germany, 1983. [\[CrossRef\]](#)
68. Blachowski, J. Application of GIS spatial regression methods in assessment of land subsidence in complicated mining conditions: Case study of the Wałbrzych coal mine (SW Poland). *Nat. Hazards* **2016**, *84*, 997–1014. [\[CrossRef\]](#)
69. Carnec, C.; Delacourt, C. Three years of mining subsidence monitored by SAR interferometry near Gardanne, France. *J. Appl. Geophys.* **2000**, *43*, 43–54. [\[CrossRef\]](#)
70. Raucoules, D.; Maisons, C.; Carnec, C.; Le Mouelic, S.; King, C.; Hosford, S. Monitoring of slow ground deformation by ERS radar interferometry on the Vauvert salt mine (France). *Remote Sens. Environ.* **2003**, *88*, 468–478. [\[CrossRef\]](#)
71. Colesanti, C.; Ferretti, A.; Prati, C.; Rocca, F. Monitoring landslides and tectonic motions with the Permanent Scatterers Technique. *Eng. Geol.* **2003**, *68*, 3–14. [\[CrossRef\]](#)
72. Falorni, G.; Del Conte, S.; Bellotti, F.; Colombo, D. InSAR monitoring of subsidence induced by underground mining operations. In *Proceedings of the Fourth International Symposium on Block and Sublevel Caving*; Australian Centre for Geomechanics: Perth, Australia, 2018; pp. 705–712. [\[CrossRef\]](#)
73. Dramsch, J.S. 70 years of machine learning in geoscience in review. *Adv. Geophys.* **2020**, *61*, 1–55. [\[CrossRef\]](#)
74. Ma, Z.; Mei, G. Deep learning for geological hazards analysis: Data, models, applications, and opportunities. *Earth-Sci. Rev.* **2021**, *223*, 103858. [\[CrossRef\]](#)
75. Gorelick, N.; Hancher, M.; Dixon, M.; Ilyushchenko, S.; Thau, D.; Moore, R. Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sens. Environ.* **2017**, *202*, 18–27. [\[CrossRef\]](#)
76. Handwerger, A.L.; Huang, M.-H.; Jones, S.Y.; Amatya, P.; Kerner, H.R.; Kirschbaum, D.B. Generating landslide density heatmaps for rapid detection using open-access satellite radar data in Google Earth Engine. *Nat. Hazards Earth Syst. Sci.* **2022**, *22*, 753–773. [\[CrossRef\]](#)
77. Gao, Y.; Yang, J.; Chen, X.; Wang, X.; Li, J.; Azad, N.; Zvomuya, F.; He, H. Using advanced InSAR techniques and machine learning in Google Earth Engine to monitor regional black soil erosion: A case study of Yanshou County, Heilongjiang Province, Northeastern China. *Remote Sens.* **2024**, *16*, 3842. [\[CrossRef\]](#)

78. Porter, M.; Lato, M.; Quinn, P.; Whittall, J. Challenges with use of risk matrices for geohazard risk management for resource development projects. In *Proceedings of the First International Conference on Mining Geomechanical Risk*; Australian Centre for Geomechanics: Perth, Australia, 2019; pp. 71–84. [[CrossRef](#)]
79. Zhang, Y.; Sun, Y.; Yan, Y.; Wang, S.; Ge, L. Research status, challenges and future perspectives of geological hazard monitoring methods in mining areas. *Remote Sens.* **2026**, *18*, 1333. [[CrossRef](#)]
80. Madziwa, L.; Pillalamarri, M.; Chatterjee, S. Integrating flexibility in open pit mine planning to survive commodity price decline. *Resour. Policy* **2023**, *81*, 103428. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.