UDC [622:004.9:528.8].0001.2 DOI: https://doi.org/10.15407/geotm2026.176.080

Maryna Batur[1,2,*], https://orcid.org/0000-0001-9284-8858
Oleh Hovorukha[3], https://orcid.org/0009-0001-8574-8717

[1]*Technical University "Metinvest Polytechnic" LLC, Mining and Metallurgy Faculty, Department of Mining, Zaporizhzhia, Ukraine*
[2]*Alumni (Ph.D., Istanbul Technical University, Faculty of Civil Engineering, Department of Geomatics Engineering), Maslak, Istanbul, Turkiye*
[3]*M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine, Dnipro, Ukraine*
**Corresponding author e-mail:* maryna.batur@mipolytech.education

GIS IN MINING: A COMPREHENSIVE REVIEW AND BIBLIOMETRIC ANALYSIS OF APPLICATIONS, CHALLENGES, AND FUTURE DIRECTIONS

Abstract. Mining is inherently spatial, requiring detailed knowledge of geology, topography, hydrology, and infrastructure for informed decision-making across the lifecycle. Geographic Information Systems (GIS) have become essential for managing spatial complexity, integrating multidimensional datasets, and supporting predictive analytics in mining engineering and management. This review adopts a structured approach to synthesize current knowledge on GIS applications across the mining lifecycle, drawing from peer-reviewed journals, conference proceedings, and technical reports published between 2000 and 2025. Literature was systematically analyzed and categorized according to exploration, mine planning, operation and production, environmental monitoring, and post-mining land use. In exploration, GIS facilitates mineral potential mapping by integrating geological, geophysical, and geochemical data with remote sensing imagery, using multi-criteria decision analysis and fuzzy logic to handle uncertainty. During mine planning, GIS supports site selection, pit design, infrastructure layout, and resource estimation, often linked with 3D modeling and specialized mine planning software. In operations, GIS dashboards combined with IoT and SCADA systems enable real-time monitoring of equipment, personnel, and environmental conditions, enhancing production efficiency and safety. GIS also underpins environmental monitoring and post-mining rehabilitation through pollution mapping, tailings dam assessment, land-use suitability analysis, and time-series remote sensing. Despite its versatility, GIS adoption faces challenges, including data availability, integration complexity, computational demands, and skill gaps. Emerging technologies such as AI, machine learning, IoT, cloud-based platforms, and Augmented Reality and Virtual Reality (AR/VR) offer opportunities to overcome these limitations and advance smart, sustainable mining. This review highlights GIS as a transformative tool for optimizing operations, mitigating risks, and supporting environmental stewardship, emphasizing the need for continued innovation, interdisciplinary collaboration, and standardized workflows to fully realize its potential.

Keywords: GIS, mining lifecycle, spatial analysis, remote sensing, sustainable mining, bibliometric analysis.

1. Introduction

Mining remains one of the world's most spatially dependent industries, requiring detailed knowledge of geology, landform, hydrology, and infrastructure [1]. Decision-making in mining is inherently geographic: mineral deposits are distributed unevenly, environmental impacts are site-specific, and operational efficiency depends on spatial optimization. Over the last three decades, Geographic Information Systems (GIS) have evolved from simple mapping tools to advanced platforms capable of integrating multidimensional datasets, performing spatial modeling, and supporting predictive analytics in mining engineering and management [2].

GIS allows mining professionals to visualize, analyze, and interpret spatial relationships between geological features and operational parameters. From exploration targeting to mine closure and post-mining land rehabilitation, GIS provides a unified framework for data-driven decision-making. Modern GIS systems are increasingly integrated with remote sensing, Global Navigation Satellite Systems (GNSS), LiDAR, and unmanned aerial vehicles (UAVs), enabling high-resolution monitoring and dynamic updating of mine conditions [3]. Moreover, the integration of machine

Received: 13.12.2025 Accepted: 10.02.2026 Available online: 31.03.2026

learning and big data analytics with GIS enhances predictive capacity, helping to optimize resource extraction while minimizing environmental risk [4].

The mining lifecycle typically comprises four major phases: (1) Exploration, where potential deposits are identified and assessed; (2) Planning and Design, where spatial data supports resource estimation, pit optimization, and infrastructure layout; (3) Operation and Production, where GIS assists in daily monitoring, safety management, and logistics; and (4) Closure and Post-Mining, where it supports environmental rehabilitation, land-use planning, and long-term monitoring. In each phase, GIS plays a different yet complementary role supporting both technical efficiency and sustainability goals. For example, during exploration, GIS-based mineral prospectively mapping combines geochemical, geophysical, and geological data layers to identify target zones [5]. In contrast, during closure, GIS supports reclamation planning, monitoring vegetation regrowth and landform stability using time-series satellite imagery [6].

Several studies have demonstrated the benefits of GIS in mining contexts. For instance, [7] illustrated how GIS-based multi-criteria analysis improves mineral potential mapping, while [8] applied GIS and Remote Sensing (RS) to assess the environmental footprint of open-pit coal mines. Similarly, GIS has been used for subsidence risk mapping [9], tailings dam monitoring [10], and mine water management [11].

The aim of this paper is to systematically review and quantify the evolution of GIS applications across the entire mining lifecycle using a bibliometric analysis of peer-reviewed literature published between 2000 and 2025. Specifically, the study maps research trends, dominant themes, and geographic contributions to identify key application domains, knowledge gaps, and emerging directions for GIS-supported smart and sustainable mining.

2. Methods

This review adopts a structured approach to synthesize current knowledge on GIS applications across the mining lifecycle, emphasizing both theoretical and practical perspectives. Relevant literature was collected from peer-reviewed journals, conference proceedings, and technical reports using databases such as Scopus, Web of Science, and Google Scholar. Search terms included combinations of “GIS,” “mining,” “exploration,” “mine planning,” “environmental monitoring,” “remote sensing,” “LiDAR,” “UAV,” “3D mapping,” and “post-mining land use.” Studies published between 2000 and 2025 were prioritized to capture recent technological advancements, particularly the integration of GIS with remote sensing, UAVs, LiDAR, Artificial Intelligence and Machine Learning (AI/ML), IoT, and cloud-based mining platforms.

Selected studies were systematically reviewed and categorized according to mining lifecycle stages: exploration, mine planning, operation and production, environmental monitoring and safety, and mine closure and post-mining land use.

The review also incorporates bibliometric mapping to quantify trends and patterns in the literature. Selected studies were systematically categorized according to mining lifecycle stages: exploration, mine planning, operation and production, environmental monitoring and safety, and mine closure and post-mining land use. For each stage, GIS applications were analyzed in terms of spatial data types (raster, vector), data sources (geological, geophysical, geochemical, topographic, socio-environmental), analytical techniques (MCDA, geostatistics, network analysis, hydrological modeling, 3D visualization), and integration with emerging technologies. Case studies demonstrating practical GIS implementations are highlighted in Section 4 of this manuscript to illustrate methodological approaches and outcomes. Table 1 below lists search queries for each mining lifecycle stage used in Scopus to collect scientific literature.

Table 1 – Scopus search queries for GIS application across different stages of open-pit mining

Mining stage	Search query
Exploration	(TITLE-ABS-KEY(“GIS” AND “mineral exploration”) AND TITLE-ABS-KEY(“mineral potential mapping” OR “MCDA” OR “AHP” OR “fuzzy logic” OR “kriging” OR “cokriging” OR “lineament mapping”) AND TITLE-ABS-KEY(“remote sensing” OR ASTER OR “Landsat 8” OR “Sentinel-2” OR “hydrothermal alteration” OR “PCA” OR “band ratio”))
Mine planning	(TITLE-ABS-KEY(“GIS” AND “mine planning”) AND TITLE-ABS-KEY(“open-pit design” OR “site selection” OR “haul road optimization” OR “3D GIS” OR “geological modeling” OR “cartographic overlay” OR “PCA” AND coal AND deposit))
Operation and production	(TITLE-ABS-KEY(“GIS” AND mining AND operation) AND TITLE-ABS-KEY(“IoT” OR “SCADA” OR “real-time monitoring” OR “fleet management” OR “GPS tracking” OR “slope stability” OR “blast zone” OR “air quality” OR “extraction volume” OR Voronoi OR Thiessen))
Environmental monitoring and safety	(TITLE-ABS-KEY(“GIS” AND mining AND environment) AND TITLE-ABS-KEY(“NDVI” OR “Landsat” OR “InSAR” OR “tailings dam” OR “acid mine drainage” OR “heavy metal contamination” OR “kriging” OR “IDW” OR “land cover change” OR “Google Earth Engine”))
Mine closure and post-mining land use	(TITLE-ABS-KEY(“GIS” AND “mine closure”) AND TITLE-ABS-KEY(“post-mining land use” OR “reclamation” OR “rehabilitation” OR “land-use suitability” OR “fuzzy logic” OR “NDVI” OR “socioeconomic transition” OR “lignite mine”))

The search was conducted for literature published in the English language, considering document types such as research articles, review papers, conference papers, books, and book chapters. Queries were formulated using the TITLE-ABS-KEY syntax in Scopus to ensure retrieval of publications highly relevant to both GIS applications and the corresponding mining stage.

3. Theoretical background and technological framework

3.1. Fundamentals of GIS in mining

GIS is a digital environment that capture, store, analyze, and visualize spatial data [12]. In mining, GIS provides a multidimensional perspective that integrates geological, geophysical, environmental, and socio-economic information within a single spatial framework. This integration allows mining engineers and geoscientists to analyze relationships and patterns that would otherwise remain hidden in isolated datasets. At its core, GIS operates on layers of spatially referenced information such as geological formations, fault lines, ore zones, hydrological networks, and infrastructure layouts. Through overlay analysis, spatial interpolation, and geostatistical modeling, GIS supports informed decision-making throughout the mining value chain. An example of this is shown in Figure 1, where different layers were combined into one single layer [13].

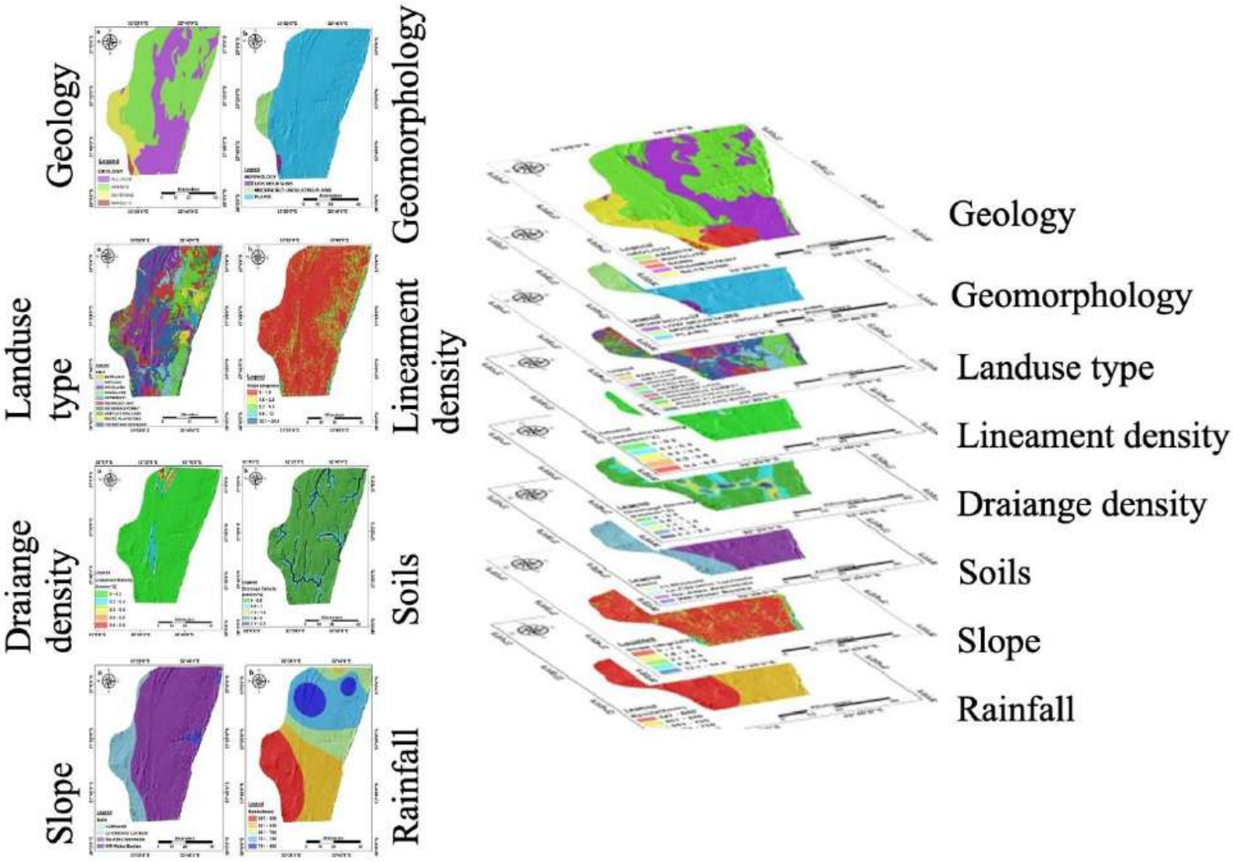


Figure 1 – Integration of thematic layers in GIS (Figure is modified from [13])

GIS applications in mining generally rely on two key data models: (1) Raster data, used for continuous variables such as topography, RS imagery, or geochemical concentrations; and (2) Vector data, used for discrete features like boreholes, roads, faults, and boundaries [12]. Spatial operations such as buffering, overlay, network analysis, and spatial interpolation enable users to assess proximity, connectivity, and spatial distribution of features critical to exploration and operations. For example, spatial buffering can identify safety zones around blast areas, while overlay analysis can evaluate land-use conflicts or geological overlaps between mineral zones and protected areas.

3.2. Spatial data sources and integration

Mining GIS projects draw from a wide range of spatial data sources, each providing different scales, accuracies, and temporal resolutions [12]. The major categories include:

- Geological data: lithological maps, structural maps, and borehole logs obtained from field surveys or government databases.
- Geophysical data: magnetic, gravity, and radiometric datasets acquired through airborne or ground-based surveys.
- Geochemical data: point-based sampling results representing concentrations of specific elements.
- Topographical data: derived from LiDAR or photogrammetry to represent elevation, slope, and terrain morphology.
- RS data: satellite or UAV imagery providing spectral information on surface materials and vegetation.
- Socio-environmental data: land use, water bodies, population density, and protected area boundaries for sustainability and risk assessment.

Table 2 represents expanded examples for each category.

Table 2 – Major categories of spatial data sources used in mining GIS projects

Data category	Description	Common data types	Typical sources
Geological data	Represents subsurface and surface geological characteristics essential for mineral exploration and mine planning.	Lithological and structural maps; Stratigraphic columns; Borehole logs; Fault and fracture networks; Orebody models.	Geological surveys USGS; Mine exploration reports; Academic research datasets.
Geophysical data	Provides information on the chemical composition of rocks, soils, and sediments for anomaly detection.	Sil and stream sediment geochemistry; Rock and drill-core assays; Hydrogeochemical data; Biogeochemical samples.	Geochemical survey agencies; Laboratory analysis; Mineral exploration companies.
Topographical data	Captures the shape and features of the Earth's surface, used for terrain analysis and mine design.	Digital elevation models (DEM); LiDAR point clouds; Contour maps; Slope, aspect, and curvature maps.	LiDAR and photogrammetry surveys; National mapping agencies; UAV or drone-based mapping.
RS data	Provides spectral and spatial information for identifying minerals, vegetation, and land cover.	Multispectral and hyperspectral imagery; UAV or drone imagery; Thermal infrared and SAR data; NDVI, mineral index map.	Satellite missions (NASA, ESA); UAV surveys; Commercial imagery providers (Planet, Maxar).
Socio-environmental data	Integrates human and environmental factors for sustainable and safe mine management.	Land Use and Land Cover maps; Water bodies and watershed boundaries; Population density and settlements; Protected areas, cultural heritage zones; Infrastructure.	National statistics offices; Environmental agencies; OpenStreetMap, WorldPop, UNEP, FAO.

The integration of these datasets requires spatial referencing (georeferencing) to a common coordinate system, projection harmonization, and often data fusion techniques to combine multisource datasets. Modern GIS environments (e.g., ArcGIS Pro, Quantum Geographic Information System (QGIS), ERDAS Imagine) offer advanced tools for 3D visualization and dynamic model linking with mine planning software such as Surpac, Datamine, and Vulcan.

3.3. Remote sensing and image analysis

RS has become one of the most powerful complements to GIS in mining, providing spatially continuous and temporally repeatable information. RS involves acquiring information about the Earth's surface without direct contact that is typically through satellites (e.g., Landsat, or Sentinel) or drones equipped with multispectral or hyperspectral sensors [14].

Key RS applications in mining include:

- Mineral exploration: detecting alteration zones using spectral signatures (e.g., iron oxides, clay minerals, carbonates).
- Environmental monitoring: assessing vegetation stress, water quality, and tailings dam integrity.
- Subsidence detection: using Synthetic Aperture Radar (SAR) interferometry to identify ground deformation caused by underground mining.
- Mine closure assessment: tracking land rehabilitation progress through Normalized Differential Vegetation Index (NDVI) and other vegetation indices.

Table 3 lists these key RS applications.

Table 3 – Key RS applications in mining and representative techniques

Application area	Common RS techniques	Example of data	Data sources
Mineral exploration	Multispectral and hyperspectral imaging; Spectral unmixing and mineral mapping; Principal component analysis.	Iron oxides; Clay minerals; Carbonates; Hydrothermal.	ASTER; Landsat8/9; Sentinel-2.
Environmental monitoring	Multitemporal NDVI; Change detection; UAV-based thermal and multispectral imaging.	Vegetation stress and deforestation; Water quality; Tailings dam seepage or leak detection.	Sentinel-2; MODIS; UAV imagery.
Subsidence detection	InSAR; DInSAR; PSI.	Millimeter-level ground displacement; Slope instability mapping; Monitoring of surface cracks and collapse zones.	Sentinel-1; TerraSAR-X; ALOS.
Mine closure and rehabilitation assessment	NDVI time-series analysis; Object-based classification of land cover; UAV or drone-based photogrammetry.	Vegetation cover percentage; Soil moisture estimation; Land Use transition from barren to vegetated areas.	Sentinel-2; Landsat-9; UAV surveys; MODIS.

For example, in study [15] authors applied the Independent Component Analysis (ICA) algorithm to short-wave infrared (SWIR) ASTER satellite data to delineate the southern extension of base metal-bearing dolomites of the Mochia Formation in the Zawar region, Udaipur Sector, India. By integrating RS analysis with field validation, petrological examination, and laboratory techniques (XRD, XRF, and reflectance spectroscopy), the authors successfully mapped dolomite occurrences and confirmed their association with Pb-Zn-Cu sulphide minerals such as galena, sphalerite, chalcopyrite, and pyrite. The research demonstrated that E-W trending faults and brecciated zones served as conduits for hydrothermal mineralization and highlighted the potential of ICA-applied ASTER data for dolomite and base metal deposit mapping in similar geological settings worldwide. Similarly, the study [16] applied an integrated approach combining multi-seasonal Sentinel-2 imagery with environmental variables (e.g., soil moisture, rainfall, slope, evapotranspiration, and albedo) to monitor land degradation. Using stratified random sampling and field validation, land cover fractions Photosynthetic Vegetation (PV), Non-Photosynthetic Vegetation (NPV), and Bare Soil (BS) were modeled with the Random Forest algorithm. The pooled (dry and wet season) model achieved high accuracies (R^2 up to 0.93), demonstrating the effectiveness of Sentinel-2 and machine learning for near real-time land degradation assessment.

3.4. LiDAR, UAVs, and 3D Mapping

Light Detection and Ranging (LiDAR) technology provides highly accurate three-dimensional representations of terrain and surface features. In mining, LiDAR is used for pit volume calculation, slope stability assessment, and monitoring structural deformations [17]. Airborne LiDAR systems generate dense point clouds that can be processed into DEMs with centimeter-level accuracy [18]. UAVs or drones in its turn have recently become essential tools for rapid data collection in mining. UAV-based photogrammetry enables frequent monitoring of pit geometry, waste dumps, haul roads, and environmental parameters [19]. When integrated with GIS, UAV data facilitate near real-time decision-making. A notable example is the use of drone-based LiDAR for slope failure monitoring in open-pit mines [20]. The high temporal resolution allowed operators to detect micro-movements before major failures occurred, improving worker safety and operational planning.

3.5. Spatial modeling and analysis techniques

GIS supports a range of modeling approaches relevant to mining, including:

- Multi-Criteria Decision Analysis (MCDA) for mineral prospectivity or site selection (e.g., Analytical Hierarchy Process - AHP).
- Geostatistical interpolation (e.g., kriging, inverse distance weighting) for ore grade estimation or pollution mapping.
- Network analysis for optimizing haul road routes or transportation logistics.
- Hydrological modeling for groundwater flow and contamination risk.
- 3D geovisualization for subsurface modeling and volumetric analysis.

In exploration, GIS-based MCDA methods have been used to integrate geological, geochemical, and geophysical indicators for mineral potential mapping [13]. In environmental monitoring, spatial interpolation and temporal analysis help map dust dispersion, acid mine drainage, and heavy metal contamination [21].

3.6. Integration with emerging technologies

Recent years have seen increasing convergence of GIS with other digital mining technologies:

- Artificial Intelligence (AI) and Machine Learning (ML) are used for predictive modeling of mineralization or equipment failure, leveraging spatial data within GIS frameworks.
- Internet of Things (IoT) and real-time monitoring systems provide continuous spatial data streams from sensors, allowing GIS dashboards to visualize dynamic conditions.
- Cloud-based GIS platforms (e.g., ArcGIS Online, Google Earth Engine) support big data storage, collaborative analysis, and scalable computing for remote operations.
- Virtual and Augmented Reality (VR/AR) tools extend GIS-based 3D models into immersive environments for training and planning.

For instance, in this study [22] authors integrates GIS with Artificial Intelligence (AI) to modernize coal mining operations through intelligent automation, enhanced safety, and improved efficiency. By combining spatial data analytics with AI-driven prediction and detection models, it enables real-time monitoring, risk forecasting, and data-informed decision-making across the entire mining workflow.

4. GIS applications across the mining lifecycle

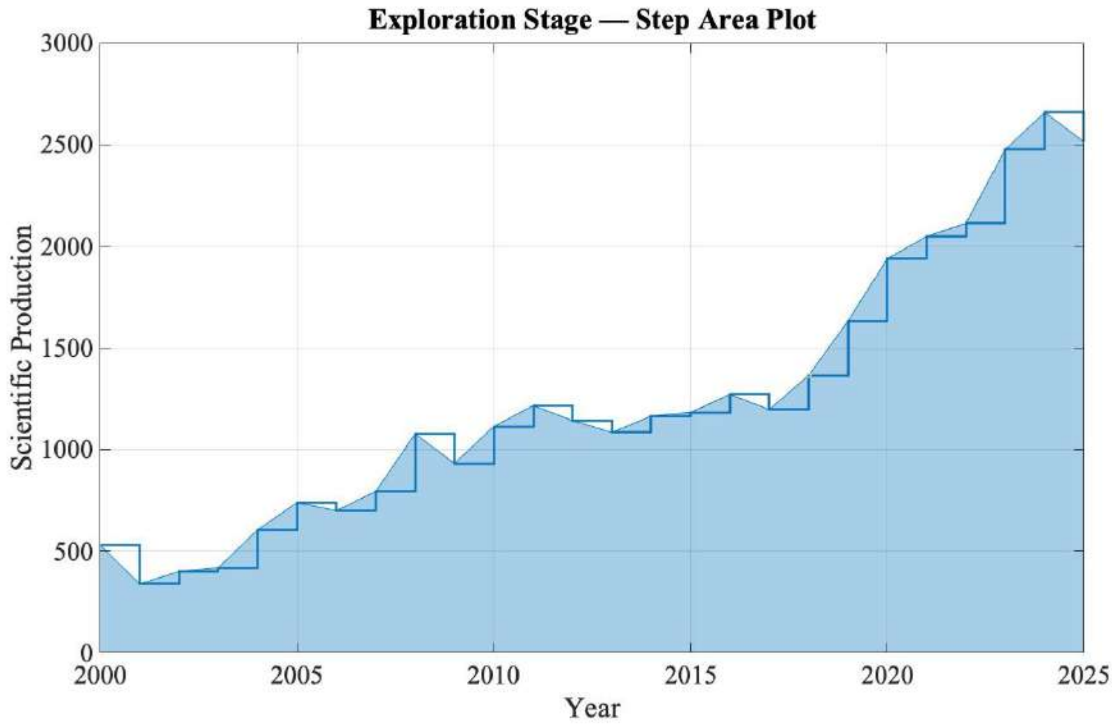
4.1. Exploration stage

Exploration is the first and most uncertain phase of the mining lifecycle, where identifying promising mineral targets determines the economic feasibility of subsequent operations [23]. The spatial complexity of geological systems makes GIS indispensable for integrating geological, geophysical, and geochemical data to support mineral potential mapping and anomaly detection. GIS-based mineral potential mapping typically involves compiling multiple spatial layers representing lithology, lineaments, structural intersections, geochemical anomalies, and RS indices. Through MCDA methods such as the AHP and fuzzy logic, experts assign weights to each factor according to its relevance to mineralization. The weighted layers are then combined through overlay analysis to produce predictive maps highlighting high-probability zones. Fuzzy logic approaches, in particular, are beneficial for handling geological uncertainty, as they allow continuous degrees of membership rather than binary classifications, representing mineralization potential as a spectrum. Integration with geostatistical tools such as kriging or co-kriging further enhances spatial prediction accuracy. RS complements GIS by providing synoptic and spectral information for mapping surface lithology and alteration minerals. Satellites such as ASTER, Landsat 8, and Sentinel-2 offer multispectral and hyperspectral data that can be processed into thematic layers showing the distribution of iron oxides, hydroxyl, and clay minerals commonly associated with hydrothermal alteration. These layers can then be incorporated into GIS for spatial modeling and target delineation. Techniques such as Principal Component Analysis (PCA) and band rationing enhance spectral contrasts, enabling precise identification of alteration zones. The integration of RS and GIS provides a cost-effective approach to reducing exploration uncertainty, particularly in remote or inaccessible regions.

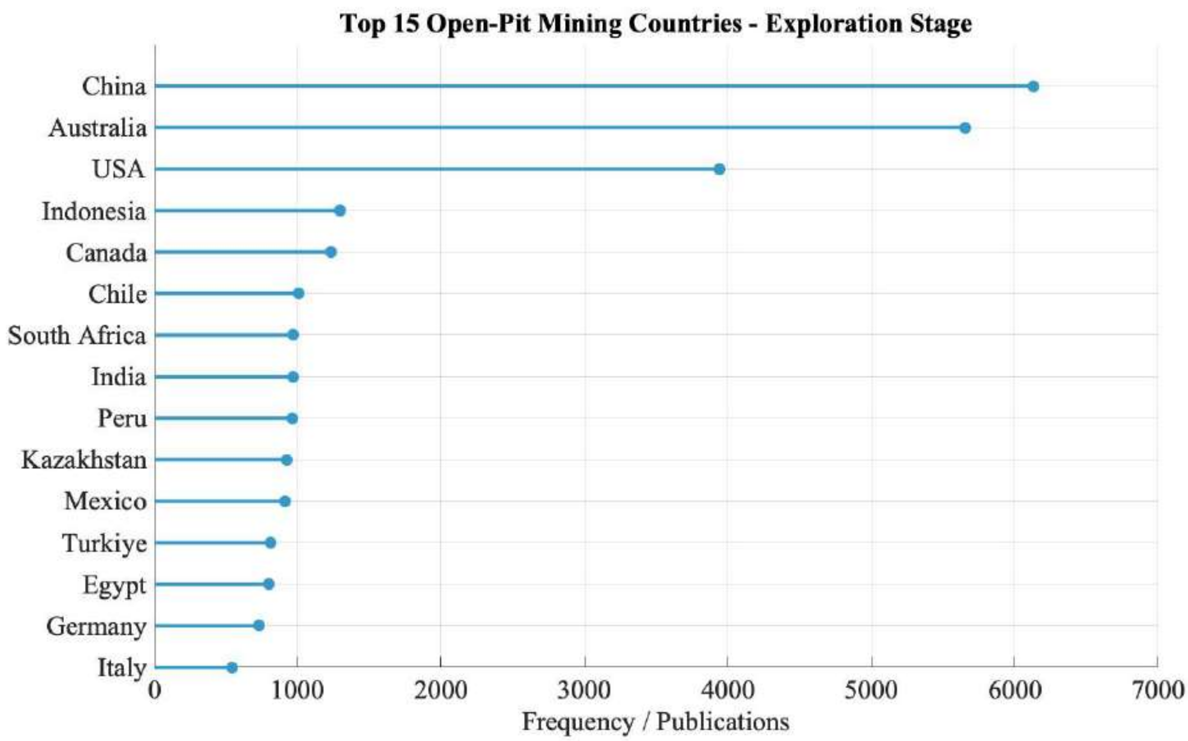
A practical demonstration of GIS in mineral exploration is provided by [23] where the authors developed a GIS-based model to explore hydrothermal mineral resources in an area of the Arabian Nubian Shield, Egypt. Specifically, they combined multispectral and hyperspectral satellite data (ASTER, Landsat OLI and Sentinel-2) with field observations, to derive hydrothermal alteration zones (HAZs). Then they used a fuzzy-logic overlay in GIS to integrate alteration zones, lineament density and other criteria, and classified the area into ranked zones of mineralization potential (from "very low" to "excellent"). The high potential zones corresponded spatially with known gold-sulfide mineralization and structural features. The resulting HAZ map allowed to highlight areas with a very high probability of mineralization.

Figure 2a shows the trend of scientific publications across exploration mining lifecycle stage. The trend shows a strong upward trajectory overall. After moderate growth in the early 2000s, exploration related research accelerates sharply from around 2007 onward, reaching several peaks most notably in 2024 year and remaining very high in 2025. Figure 2b shows the distribution of publications across the top open-pit mining countries in the overall period (2000-2025). It is seen that such countries as China, Australia, and the United States are the global leaders, with China (6,131) and Australia (5,655) producing the highest number of documents. Middle producers include Indonesia, Canada, Chile, South Africa, India, and Peru, all of which maintain active exploration sectors tied to their mineral-rich territories. Countries such as Kazakhstan, Mexico, Turkiye, Egypt, and Italy show more moderate but still substantial contributions.

The word cloud generated from the keyword frequency data and which is shown in Figure 3 highlights several dominant research themes in the context of mineral exploration and open-pit mining. The most frequently occurring terms such as "Mineral exploration", "Remote sensing", "Landsat", "Sentinel-2", "ASTER", "Principal Component Analysis (PCA)", "Geostatistics", "Kriging", and "Environmental impact" indicate that contemporary research is strongly driven by geospatial data integration and advanced analytical techniques. Remote sensing platforms and spectral analysis methods appear prominently, reflecting their widespread use in mapping, lithological discrimination, and anomaly detection. Similarly, the high frequency of geostatistical concepts such as kriging, hotspot analysis, and spatial interpolation underscores the importance of quantitative modelling and uncertainty assessment in exploration workflows. Several emerging topics can also be identified from the prominence of keywords related to machine learning, including Random Forest, SVM, neural networks, deep learning, and predictive modelling. Moreover, keywords associated with environmental and geotechnical concerns such as land cover change, tailings characterization, hydrogeological assessment, and slope stability also highlight growing attention to sustainability and risk mitigation within modern mining research.



(a)



(b)

(a) step-area plot showing the number of publication between 2000–2025 years; (b) number of publications between 2000–2025 years for the top open-pit mining countries in the World

Figure 2 – Results of bibliometric analysis for exploration stage

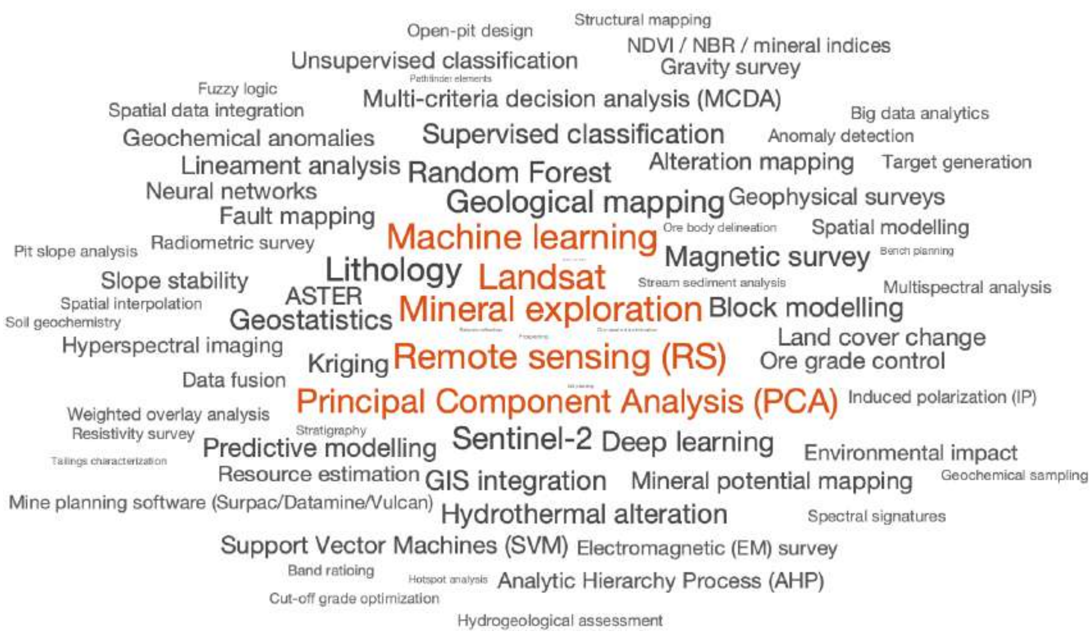


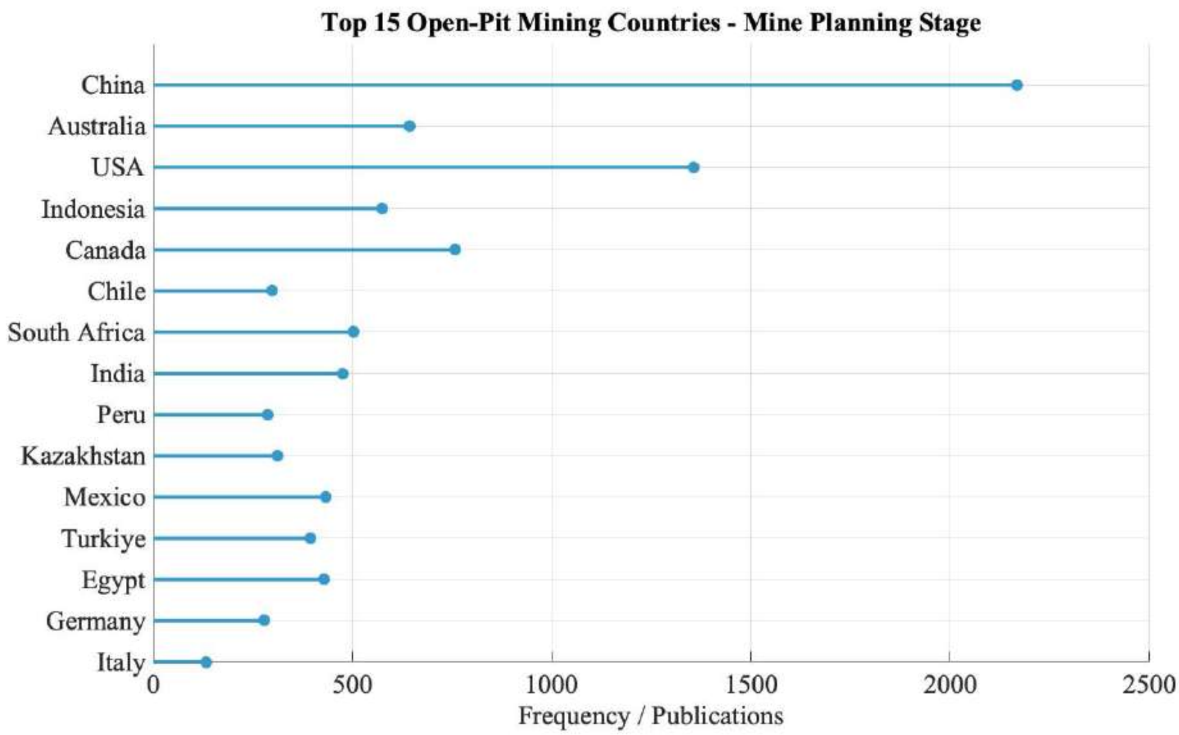
Figure 3 – Word cloud of keywords associated with the exploration stage of the open-pit mining lifecycle

4.2. Mine planning stage

Following successful exploration, GIS plays a critical role in mine planning and design, where the main objective is to optimize the extraction process while minimizing environmental and social impacts. GIS assists engineers in site selection, open-pit design, infrastructure layout, and resource estimation [24]. GIS-based site selection involves evaluating potential mining and infrastructure locations according to topographic suitability, proximity to resources, accessibility, hydrological conditions, and environmental constraints. Through spatial overlay and buffering operations, engineers can identify optimal areas for tailings storage, waste dumps, and processing facilities while avoiding ecologically sensitive zones. For instance, slope gradient maps help determine areas suitable for road construction, while hydrological models can predict runoff and sediment transport to reduce contamination risks. Additionally, network analysis tools are used to optimize the routing of haul roads between pit faces, crushers, and waste dumps. Modern GIS environments also allow 3D visualization and modeling, enabling the integration of geological block models, DEMs, and infrastructure layouts. This three-dimensional representation supports resource estimation, pit optimization, and mine scheduling. By linking GIS with mine planning software such as Surpac or Vulcan, engineers can dynamically simulate different pit expansion scenarios, calculate cut-and-fill volumes, and assess economic feasibility. The application of 3D geostatistical modeling within GIS further enhances accuracy in resource classification, particularly in heterogeneous ore bodies.

In the paper [24], the authors used GIS in combination with PCA to model a multi-seam coal deposit. They processed spatial geologic and survey data to identify dominant patterns in deposit structure, then integrated these patterns in a GIS environment to support decisions about mine development and layout. The method allowed them to visualize the deposit geometry and thus provide better mine-planning information for sequencing and design of extraction.

(a)



(b)

(a) step-area plot showing the number of publication between 2000–2025 years; (b) number of publications between 2000–2025 years for the top open-pit mining countries in the World

Figure 4 – Results of bibliometric analysis for mine planning stage

Step are area shown in Figure 4a exhibits steady, gradual growth throughout the period. Starting at 530 documents in 2000, it increases to around 700–800 after 2016 and reaches its highest value in 2024 (791 documents). Across the top open–pit mining countries (Figure 4b), in the mining planning stage, the United States (1,356), China (2,167), and Canada (759) emerge as leading contributors. Australia, despite being a major mining nation, shows a lower relative output (645). Other countries including Indonesia, Chile, South Africa, India, and Peru contribute moderately. While Kazakhstan, Mexico, Turkiye, Egypt and Germany display lower but still notable levels of research output.

The word cloud for the mine planning stage shown in Figure 5 highlights strong emphasis on optimization-based approaches, with frequently occurring terms such as mine scheduling, open-pit optimization, ultimate pit limit, and block model optimization indicating that computational efficiency and resource maximization remain key themes. The prominence of algorithms including the Lerchs-Grossmann method, genetic algorithms, and various stochastic and mixed-integer programming techniques shows that advanced mathematical modelling continues to shape planning research. Operational topics like truck-shovel allocation, haul route optimization, and fleet management also appear prominently, reflecting efforts to improve productivity and reduce costs in daily operations. Emerging interest is visible in machine learning also, simulation modelling, and uncertainty analysis.

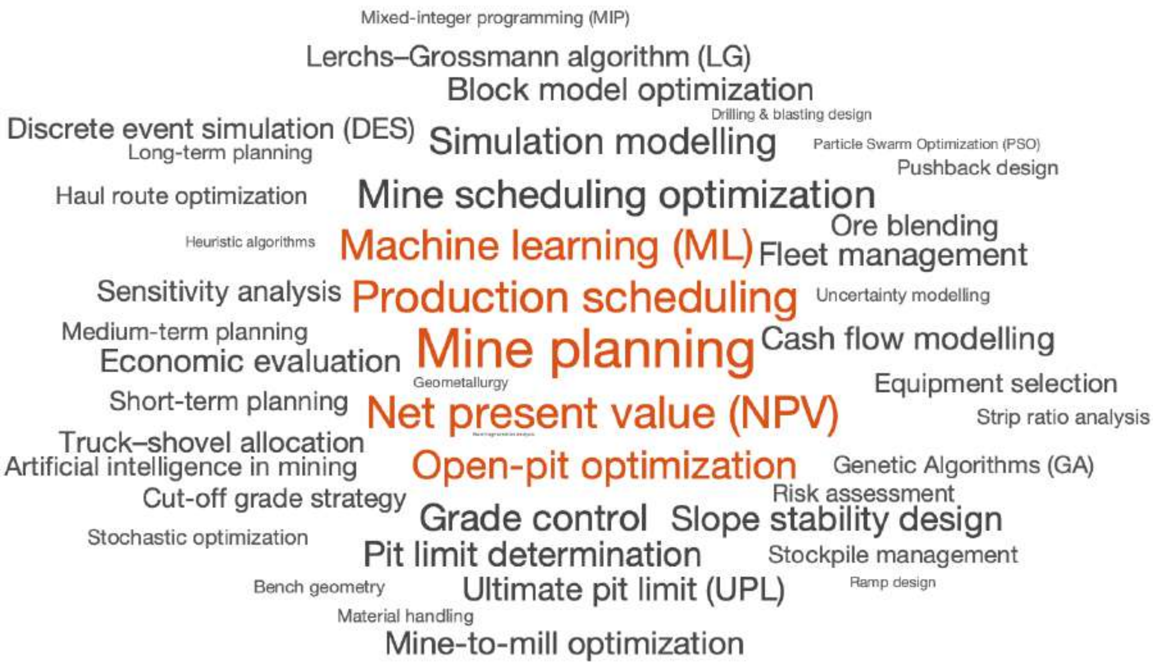


Figure 5 – Word cloud of keywords associated with the mine planning stage of the open-pit mining lifecycle

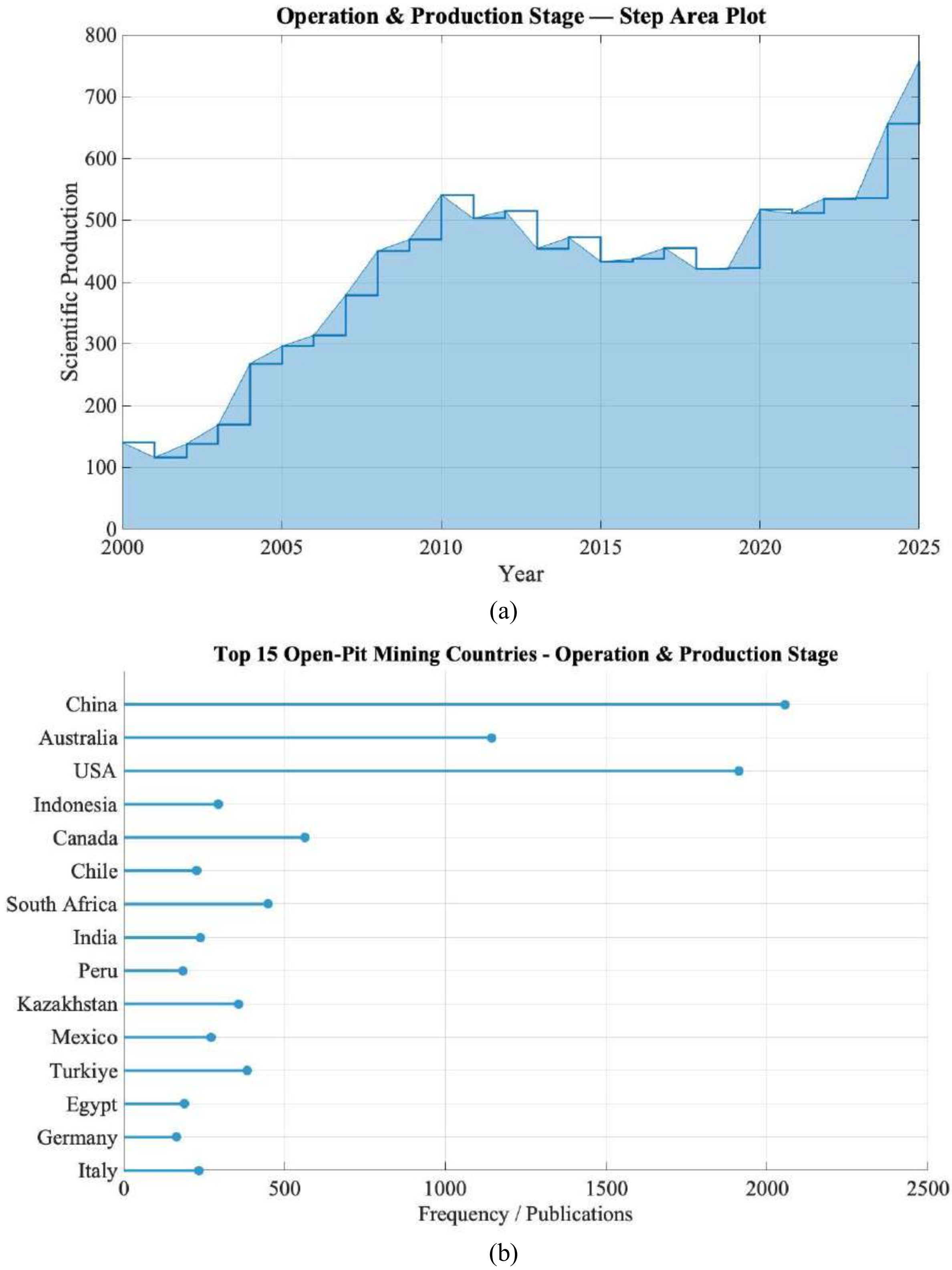
4.3. Operation and production stage

During the operational phase, GIS functions as a real-time management and monitoring platform [25]. Integration with IoT (Internet of Things) and SCADA (Supervisory Control and Data Acquisition) systems enables continuous tracking of equipment, personnel, and environmental conditions. Spatial information is crucial for optimizing production efficiency, ensuring worker safety, and minimizing environmental impact. GIS-based dashboards visualize the spatial movement of haul trucks, excavators, and conveyors in real time. Sensors and GPS transmit data to control centers, where spatial analytics track performance, fuel consumption, and maintenance schedules. Heat maps and route optimization algorithms help reduce traffic congestion and idle time within large open-pit operations. Spatial monitoring also supports safety management, including blast zone delineation, slope stability monitoring, and groundwater mapping. GIS models integrate slope geometry data, rainfall patterns, and soil moisture information to predict potential landslide zones. Buffer zones around blasting areas can be automatically updated in GIS to ensure worker exclusion during detonation. Through integration with IoT sensors and SCADA systems, GIS can represent real-time parameters such as air quality, noise levels, and gas concentrations. This integration enables automatic alerts and spatial visualization of hazardous conditions, improving response time and safety compliance.

In the paper [25], the authors developed a GIS-based automated procedure for calculating the volume of material extracted during a given year from an open-pit mine. They used a sequence of vector layers (point layers with elevation data and a polygon for the extraction area), created Voronoi (Thiessen) polygons around surveyed points, and automated the computational workflow in QGIS to derive annual extraction volumes. The case study focused on an open-pit mine near Tarnów, Poland, demonstrating how spatial data and GIS processing can streamline production monitoring in mining operations.

The results of bibliometric analysis are shown in Figure 6 and 7. From Figure 6a, it is seen a clear moderate but less consistent trend. Research output increases slowly from 2000 to around 2011, fluctuates between 430–540 through the mid-2010s, and then rises more noticeably after 2019, reaching its highest value in 2025 (758). The operation and production stage show strong research intensity in countries with large-scale open-pit operations (Figure 6b). The highest publication counts are observed in China (2,055) and the United States (1,912), followed by Australia (1,144). Countries such as South Africa, Canada, Kazakhstan, Mexico, and Turkiye show moderate output, while lower counts observed in Peru, Chile, India, Egypt, and Germany.

The word cloud for mine operations shown in Figure 7 emphasizes a strong focus on production optimization and operational efficiency, with high-frequency keywords including mine operations, production management, production rate optimization, and ore extraction. Advanced operational strategies such as truck dispatching, fleet optimization, real-time monitoring, and mine automation also appear prominently, highlighting the integration of digital technologies, IoT, and autonomous systems in modern mining. Emphasis on equipment performance and maintenance is evident from terms like predictive maintenance, condition monitoring, and equipment health monitoring, reflecting the critical role of reliability and uptime in operational success. Other recurrent themes, such as material flow analysis and plant performance optimization indicate a focus on maximizing productivity across the mining-to-processing chain. Additionally, keywords related to safety and operational risk underscore ongoing attention to workforce protection and risk management.



(a) step-area plot showing the number of publication between 2000–2025 years; (b) number of publications between 2000–2025 years for the top open-pit mining countries in the World

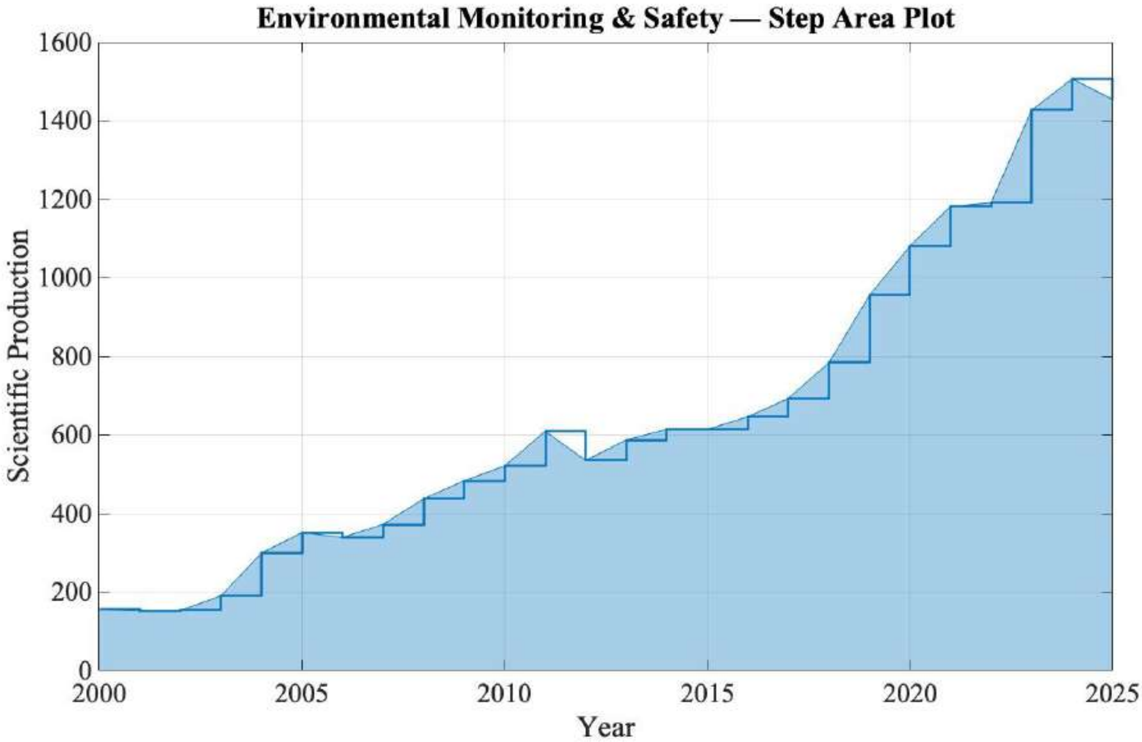
Figure 6 – Results of bibliometric analysis for operation and production stage

Figure 7 – Word cloud of keywords associated with the operation and production stage of the open-pit mining lifecycle

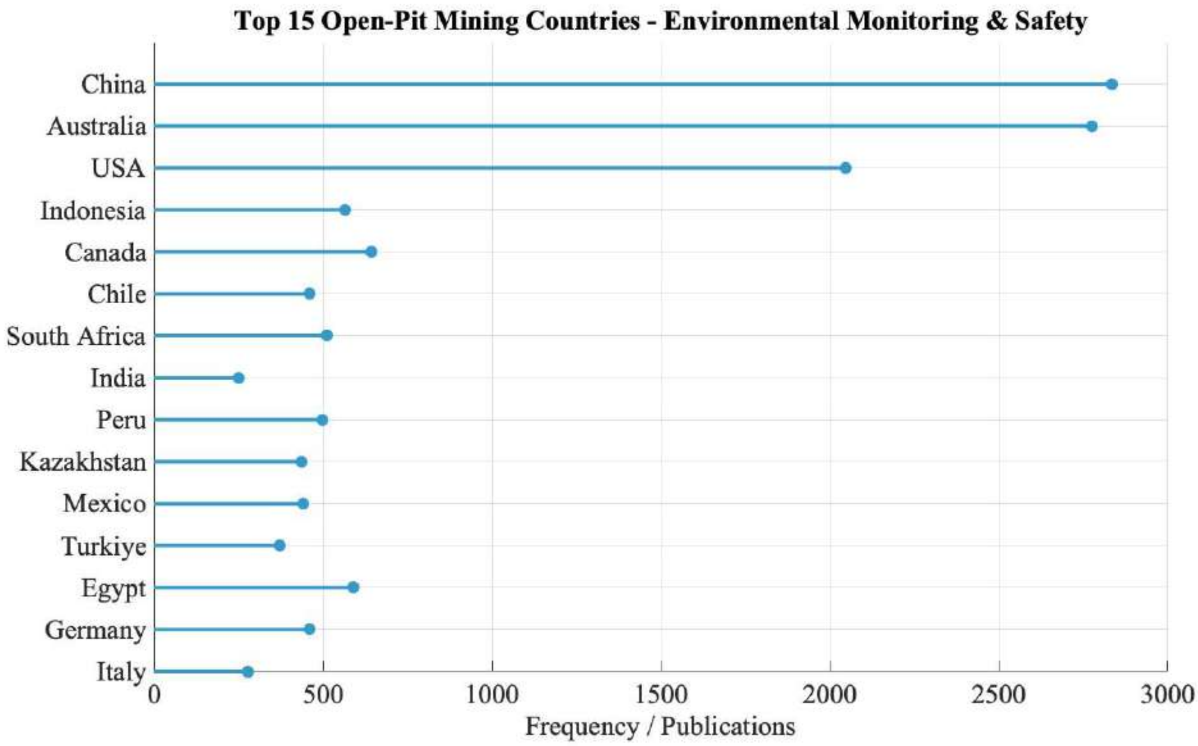
4.4. Environmental monitoring and safety

Environmental sustainability has become an integral component of modern mining, with regulators and communities demanding rigorous oversight. GIS is indispensable for mapping, monitoring, and mitigating environmental impacts, including air and water pollution, noise, biodiversity loss, and waste management [26]. GIS supports the spatial assessment of dust dispersion, acid mine drainage, and heavy metal contamination. Spatial interpolation techniques, such as kriging and IDW, generate continuous pollution maps from point-sample data, helping identify hotspots for remediation. Time-series satellite imagery is also used to monitor vegetation stress as an indirect indicator of contamination. Tailings storage facilities pose one of the most critical geotechnical and environmental risks in mining. GIS and RS enable real-time monitoring of dam stability by integrating InSAR data with topographic and hydrological models. Risk maps classify dams based on factors such as proximity to populated areas, slope gradients, and material type. Spatial analysis in GIS also aids in biodiversity conservation and reclamation planning. By evaluating soil quality, drainage, and vegetation potential, and overlaying ecological and topographical layers, planners can prioritize reforestation zones and buffer ecologically sensitive areas.

In the paper [26], the authors used a long-term time series of Landsat satellite imagery (1984–2023) together with cloud processing via Google Earth Engine (GEE) to monitor open-pit mining sites in Catalonia, Spain. They calculated the NDVI annually and used it to assess both the progression of extractive activity (bare soil expansion) and subsequent rehabilitation/vegetation regrowth over nearly 40 years. Their approach enabled efficient, repeatable, and spatially consistent monitoring of mining-induced land cover changes, offering a scalable tool for regulators and mine operators to track restoration success and environmental compliance. Figure 8a illustrates the time series of environmental monitoring and safety research and demonstrates continuous and significant growth over the entire period.



(a)



(b)

(a) step-area plot showing the number of publication between 2000–2025 years; (b) number of publications between 2000–2025 years for the top open-pit mining countries in the World

Figure 8 – Results of bibliometric analysis for environmental monitoring and safety stage

Starting from 140 documents in 2000, the values increase steadily, surpassing 600 around 2014, 900 in 2019, and exceeding 1,500 by 2024. Environmental monitoring and safety research have grown substantially worldwide, and this is reflected clearly in the country-level distribution shown in Figure 8b. China with 2,836, Australia with 2,776, and the United Stated with 2,047 documents lead this category. Middle level contributors such as Canada, South Africa, Peru, Mexico, and Kazakhstan show significant involvement. Countries like Turkiye, Egypt, Germany, and India also produced noteworthy research output.

The word cloud for environmental monitoring and safety (Figure 9) highlights a strong emphasis on environmental protection and regulatory compliance, with high-frequency keywords such as environmental monitoring, environmental management, and post-mining land use. Air and water quality, tailings stability, and soil contamination are prominent themes, reflecting growing research attention to pollution control, acid mine drainage, and sustainable reclamation practices. Remote sensing and UAV- or satellite-based monitoring feature prominently, indicating the wide use of geospatial and digital technologies in environmental assessment. Safety-related topics also emerge strongly, with keywords like mine safety management, occupational health and safety, hazard identification, and real-time safety monitoring, showing that workforce protection and risk mitigation are central concerns.

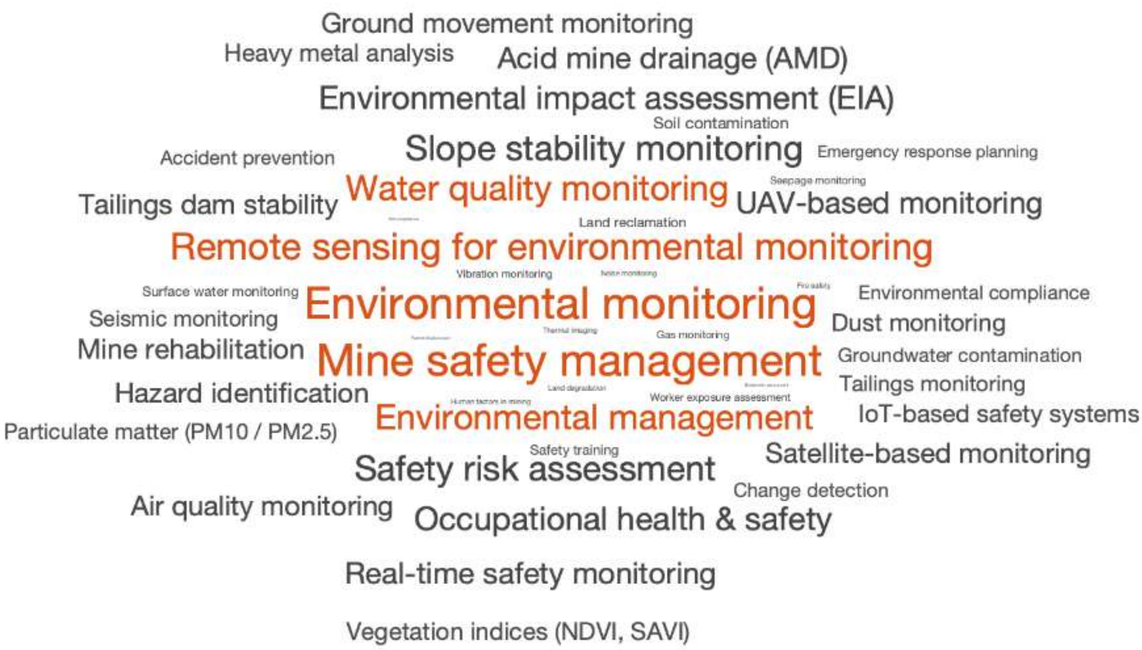


Figure 9 – Word cloud of keywords associated with the environmental monitoring and safety stage of the open-pit mining lifecycle

4.5. Mine closure and post-mining land use

Mine closure and post-mining land management represent the final phase of the mining lifecycle. GIS plays a key role in ensuring sustainable rehabilitation, land reuse, and community transition by integrating ecological, geological, and socioeconomic data [27]. GIS-based land-use suitability analysis evaluates post-mining land options such as agriculture, forestry, or urban development. Factors including soil pH, slope, drainage, and proximity to infrastructure are weighted using AHP or fuzzy logic. The resulting suitability maps guide restoration priorities and inform policy decisions. Time-series analysis of NDVI from Landsat or Sentinel imagery is used to track vegetation regrowth after mine closure. GIS enables comparisons between reclaimed and natural areas, quantifying the effectiveness of rehabilitation efforts. GIS also supports socioeconomic analysis during post-mining transition by mapping population density, employment shifts, and infrastructure reuse potential. This spatial understanding aids regional planning and facilitates the conversion of former mining zones into new economic or recreational hubs.

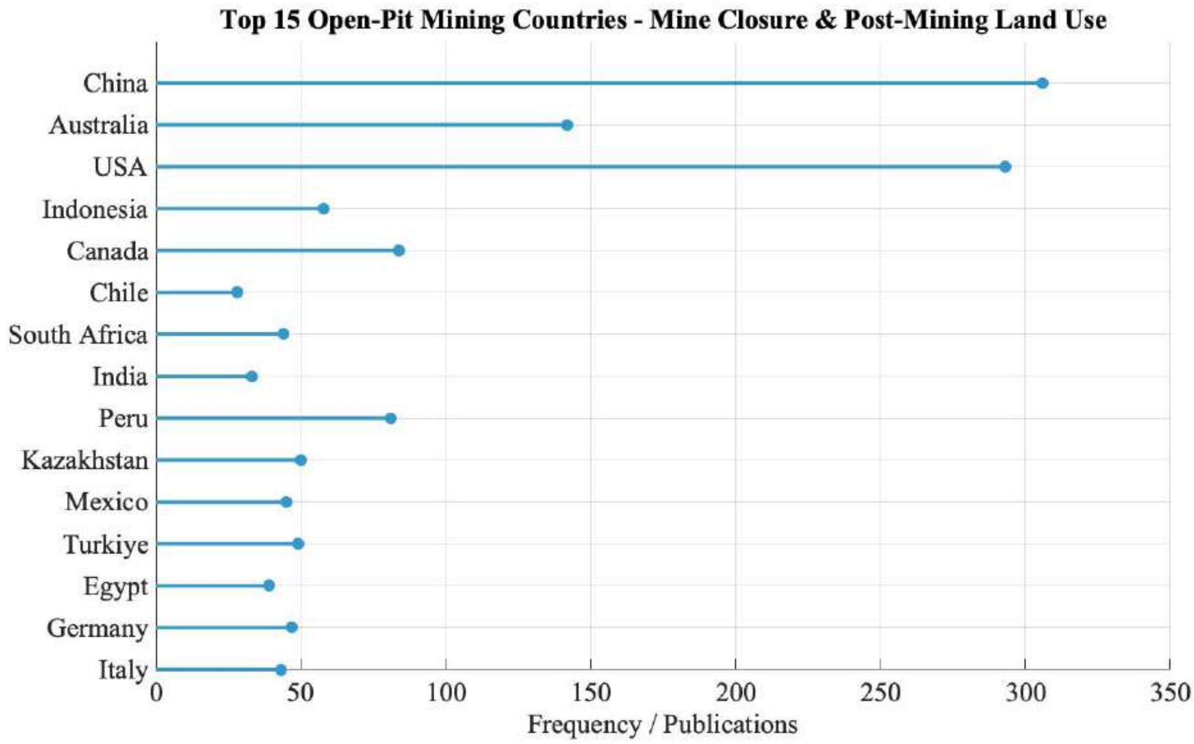
In the article [27], the authors developed a GIS-based algorithm to help select the most suitable land uses for a large closed surface lignite mine in northern Greece. They considered six spatial criteria (slope, elevation, distance to villages, rivers, roads, and transmission lines) plus parameters specific to the mining area (graded vs undisturbed land, existing infrastructure, closure planning). Using a fuzzy logic overlay technique in a GIS environment, they generated suitability maps for different possible post-mining land uses (agriculture, forest, industrial/photovoltaic, recreation) and integrated the mining-derived spatial parameters. The result is a comprehensive suitability map that supports decision-makers in planning reclamation and post-closure land use in an informed, spatially explicit way.

From the bibliometric analysis results shown in Figure 10a it is seen that mine closure and post-mining land use though being the smallest category still shows meaningful long-term growth.

From just 12 papers in 2000, the numbers rise gradually, reaching over 100 by 2023–2025. Figure 10b shows that mine closure and post-mining land use shows meaningful engagement in several leading mining nations. Thus, China (306) and the United States (293) are the most active. Other countries including Australia, Canada, Peru, Kazakhstan, Mexico, Turkiye, and Germany contributed modestly, while minimal output from Chile, India, and South Africa suggest that research on this topic is still emerging there.

The word cloud for mine closure and post-mining land use illustrated in Figure 11 highlights a strong focus on sustainable rehabilitation and ecosystem restoration, with frequently occurring keywords including mine closure, closure planning, progressive rehabilitation, final landform design, and land reclamation. Environmental recovery strategies, such as tailings closure, soil remediation, water treatment, and acid mine drainage mitigation, appear prominently, reflecting the critical role of minimizing long-term environmental impacts. Biodiversity and ecosystem restoration, including revegetation, habitat reconstruction, and wetland creation, indicate growing attention to ecological sustainability. Advanced tools such as GIS, remote sensing, and UAV-based monitoring are also emphasized, showing the adoption of digital technologies for closure planning and performance assessment.

(a)



(b)

(a) step-area plot showing the number of publication between 2000–2025 years; (b) number of publications between 2000–2025 years for the top open-pit mining countries in the World.

Figure 10 – Results of bibliometric analysis for mine closure and post-mining land use stage

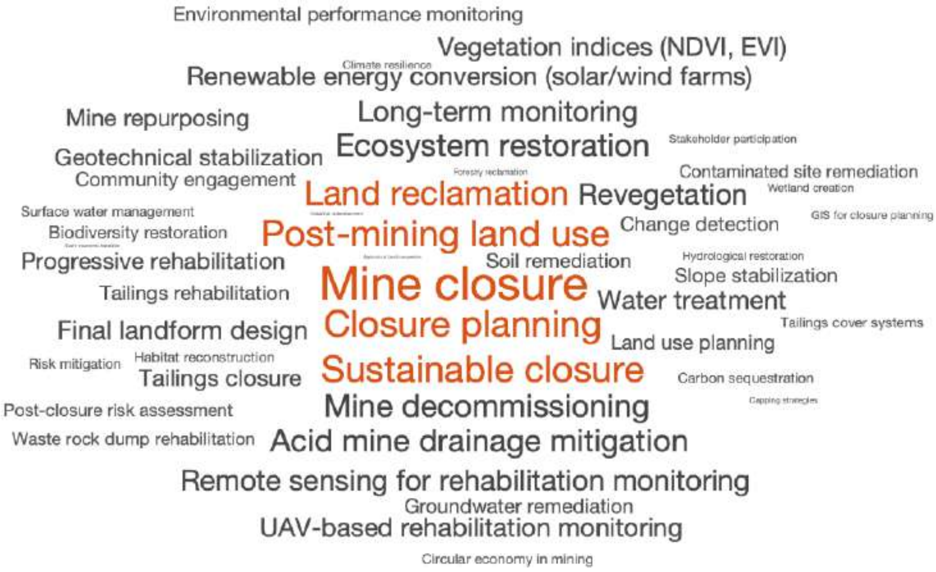


Figure 11 – Word cloud of keywords associated with the mine closure and post-mining land use stage of the open-pit mining lifecycle

5. Discussions

The temporal dynamics observed across the mining lifecycle stages reveal shifting research priorities within the global mining sector over the past twenty-five years. Exploration research shows the most sustained and accelerated growth, largely driven by technological advancements in GIS, remote sensing, and machine-learning-assisted mineral modeling [28]. In contrast, the mine planning and operation and production stages follow more moderate and cyclical trajectories, likely reflecting commodity price volatility and cost-driven decision-making [29]. Meanwhile, environmental monitoring and safety demonstrates consistent growth, underscoring the sector's increasing orientation toward sustainability, real-time monitoring, and risk mitigation and these particularly after the widespread adoption of UAVs and sensor networks [30]. Although mine closure and post-mining land use remains the least represented category, its gradual upward trend suggests a growing commitment to long-term ecological responsibility [31].

Cross-country comparisons reveal that China, Australia, and the United States dominate research outputs across most lifecycle stages of mining, reflecting their extensive technical capacities and sustained investment in exploration, innovation, and sustainability studies. This is evident in bibliometric profiles where China and the USA often lead in publication volume, with Australia and Canada also frequently appearing among the most prolific contributors across environmental and closure research domains [32]. Mine planning and operation research tend to be concentrated in technologically mature countries such as Canada and the United States, where advanced frameworks for digital mine design, modeling, and operational optimization appear prominently in specialized bibliometric subfields such as mine ventilation and wastewater management [33]. Environmental monitoring and safety research show broader geographic distribution, with notable contributions from South Africa, Brazil, and other emerging research regions alongside major producers like China, Australia, and the USA, demonstrating the global engagement driven by regulatory and health imperatives [34]. Although mine closure research remains comparatively limited worldwide, scientometric analyses indicate a growing trend in countries with long mining histories including Australia, Canada, and South Africa, underscoring a rising commitment to long-term ecological and socio-environmental concerns [35].

In the context of this global landscape, the findings of this study highlight a noteworthy and emerging research trajectory for Ukraine. Although Ukraine contributes less overall volume than major mining economies, the country shows increasing engagement in GIS-based studies related to environmental monitoring, mine safety, and land rehabilitation [36]. This trend is particularly relevant in regions affected by long-term coal extraction, iron ore mining, and recent war-related disruptions [37, 38]. The expanding use of remote sensing to assess subsidence, tailings stability, and environmental degradation signals a shift toward evidence-based environmental risk assessment [39]. Looking ahead, Ukraine's mining sector is poised to grow in several strategic research directions, including: (1) post-war environmental diagnostics supported by GIS and UAV systems; (2) mine-closure design and long-term land-use planning during reconstruction; (3) digital twins and real-time monitoring for legacy coal mines; and (4) critical minerals exploration supported by AI-driven mapping. These areas represent major opportunities for Ukraine to expand its contribution to sustainability-oriented mining research. The analysis of keyword frequency across lifecycle stages further supports these conclusions. Exploration is dominated by geospatial data integration, remote sensing, and analytical approaches such as multicriteria decision-making, geostatistics, and machine learning. Mine planning emphasizes optimization algorithms, 3D modeling, and computational design. Operation and production research focus on automation, equipment reliability, and real-time monitoring systems. Environmental monitoring and safety increasingly incorporate UAV imaging, satellite-based pollution tracking, and occupational risk analysis. Finally, mine closure and post-mining land use research centers on rehabilitation, ecosystem restoration, and long-term land management using GIS and remote sensing.

Despite these advancements, significant challenges remain. Key limitations include data gaps, inconsistent spatial resolution, and restricted access to high-quality geological or environmental datasets [40]. Integrating heterogeneous data types like those from LiDAR and UAV imagery to IoT sensors and legacy survey records still remains technically complex and resource intensive. A shortage of multidisciplinary expertise in geoscience, remote sensing, and spatial analytics further restricts effective GIS adoption [41, 42].

6. Conclusions

GIS has become a foundational technology across the entire mining lifecycle, enabling integrated spatial analysis that supports exploration targeting, mine planning, operational monitoring, environmental oversight, and post-mining land management. Its capacity to handle complex, multidimensional datasets provides the spatial intelligence necessary for data-driven decisions that enhance technical efficiency, safety performance, and long-term sustainability. The continued integration of GIS with RS, LiDAR, UAVs, IoT sensor networks, AI and ML algorithms, and cloud-based platforms is rapidly expanding its analytical capabilities. These developments facilitate near-real-time monitoring, predictive modeling, and advanced spatial analyses that strengthen both operational optimization and environmental risk management. As demonstrated by global case studies and cross-country research patterns, GIS plays an increasingly central role in improving exploration efficiency, supporting digital mine design, monitoring environmental change, and guiding mine-closure and land-rehabilitation efforts.

Despite these advances, persistent challenges such as data quality and availability, integration of heterogeneous datasets, computational demands, model uncertainty, and shortages of multidisciplinary expertise still continue to limit the full realization of GIS potential in many mining regions. Overcoming these constraints will require continued technological innovation, expanded training, improved regulatory frameworks, and the development of standardized, interoperable geospatial workflows.

Looking forward, GIS will always remain a critical tool of smart and sustainable mining. The evolving research landscape suggests growing emphasis on real-time monitoring, digital twins, 3D and even 4D modeling, and sustainability-based applications. In Ukraine, GIS offers particular promise for improving environmental monitoring, supporting post-conflict land rehabilitation, enhancing mine-closure planning, and enabling modern exploration strategies based on advanced spatial analytics. As the mining sector increasingly balances resource development with environmental and societal responsibilities, GIS will continue to provide the essential spatial foundation for informed, responsible, and future decision-making.

Conflict of interest

Authors state no conflict of interest.

REFERENCES

1. Suh, J., Kim, S. M., Yi, H. and Choi, Y. (2017), "An overview of GIS-based modeling and assessment of mining-induced hazards: Soil, water, and forest", *International journal of environmental research and public health*, no. 14(12), pp.1463. https://doi.org/10.3390/ijerph14121463

2. Anselmo, S. and Ferrara, M. (2023), "Trends and evolution of the GIS-based photovoltaic potential calculation", *Energies*, no. 16(23), pp. 7760. https://doi.org/10.3390/en16237760

3. Kyriou, A., Nikolakopoulos, K., Koukouvelas, I. and Lampropoulou, P. (2021), "Repeated UAV campaigns, GNSS measurements, GIS, and petrographic analyses for landslide mapping and monitoring", *Minerals*, no. 11(3), pp. 300. https://doi.org/10.3390/min11030300

4. Choi, Y. (2023), "GeoAI: Integration of artificial intelligence, machine learning, and deep learning with GIS", *Applied Sciences*, no.13(6), pp. 3895. https://doi.org/10.3390/app13063895

5. Ott, N., Kollersberger, T. and Tassara, A. (2006), "GIS analyses and favorability mapping of optimized satellite data in northern Chile to improve exploration for copper mineral deposits", *Geosphere*, no. 2(4), pp.236–252. https://doi.org/10.1130/GES00017.1

6. Hu, J., Ye, B., Bai, Z. and Feng, Y. (2022), "Remote sensing monitoring of vegetation reclamation in the Antaibao open-pit mine", *Remote Sensing*, no. 14(22), pp. 5634. https://doi.org/10.3390/rs14225634

7. Yalcin, M. and Gul, F. K. (2017), "A GIS-based multi criteria decision analysis approach for exploring geothermal resources: Akarcay basin (Afyonkarahisar)", *Geothermics*, no. 67, pp. 18–28. https://doi.org/10.1016/j.geothermics.2017.01.002

8. Xianfeng, A. I., Changqing, S. H. I., Jianying, Y. A. N. G. and Yanqing, Z. H. A. N. G. (2023), "Mining rights setting of open-pit coal mines based on GIS and environmental impacts in arid areas", *Journal of Resources and Ecology*, no. 14(4), pp. 717–726. https://doi.org/10.5814/j.issn.1674-764x.2023.04.004

9. Suh, J. (2020), "An overview of GIS-based assessment and mapping of mining-induced subsidence", *Applied Sciences*, no. 10(21), pp. 7845. https://doi.org/10.3390/app10217845

10. Chevrel, S., Croukamp, L., Bourguignon, A. and Cottard, F. (2008), "A Remote-Sensing and GIS-Based Integrated Approach for Risk-Based Prioritization of Gold Tailings Facilities - Witwatersrand, South Africa", *Mine Closure 2008: Proceedings of the Third International Seminar on Mine Closure,* Crawley, Australia, 16–18 September 2008, pp. 639–650. https://doi.org/10.36487/ACG_repo/852_59

11. Isniarno, N. F., Aziz, G. and Iswandaru, I. (2020), "Hydrological monitoring in open PIT mining areas using geodatabase attribute in Geographic Information Systems (GIS)", *IOP Conference Series: Materials Science and Engineering,* Bandung, Indonesia, 26 November 2019, Vol. 830, No. 4, p. 042043. https://doi.org/10.1088/1757-899X/830/4/042043

12. Reddy, G. O. (2018), "Spatial data management, analysis, and modeling in GIS: principles and applications", *Geospatial Technologies in Land Resources Mapping, Monitoring and Management* , Cham: Springer International Publishing. pp. 127–142. https://doi.org/10.1007/978-3-319-78711-4_7

13. Ponnusamy, D., Rajmohan, N., Li, P., Thirumurugan, M., Chidambaram, S. and Elumalai, V. (2022), "Mapping of potential groundwater recharge zones: a case study of Maputaland plain, South Africa", *Environmental Earth Sciences*, no. 81(16), pp. 418. https://doi.org/10.1007/s12665-022-10540-4

14. Belal, A. A., El-Ramady, H. R., Mohamed, E. S. and Saleh, A. M. (2014), "Drought risk assessment using remote sensing and GIS techniques", *Arabian Journal of Geosciences*, no. 7(1), pp. 35–53. https://doi.org/10.1007/s12517-012-0707-2

15. Jain, R., Bhu, H. and Purohit, R. (2022), "ASTER remote sensing data for delineation of base metal-bearing dolomites in south-east of Aravalli Craton, India", *Arabian Journal of Geosciences*, no. 15(21), pp. 1620. https://doi.org/10.1007/s12517-022-10879-9

16. Nzuza, P., Ramoelo, A., Odindi, J., Kahinda, J. M. and Madonsela, S. (2021), "Predicting land degradation using Sentinel-2 and environmental variables in the Lepellane catchment of the Greater Sekhukhune District, South Africa", *Physics and Chemistry of the Earth, Parts A/B/C*, no. 124, pp. 102931. https://doi.org/10.1016/j.pce.2020.102931

17. Murphy, R. J., Taylor, Z., Schneider, S. and Nieto, J. (2015), "Mapping clay minerals in an open-pit mine using hyperspectral and LiDAR data", *European Journal of Remote Sensing*, no. 48(1), pp. 511–526. https://doi.org/10.5721/EuJRS20154829

18. Lin, C. and Zou, S. (2025), "An Approach to Filter Elevation Errors in UAV LiDAR Scanning on Open Pit Mine Slopes", *2025 IEEE 20th International Symposium on Antenna Technology and Applied Electromagnetics*, St. John's, Newfoundland and Labrador, Canada, 20-23 July 2025, pp. 117–120. https://doi.org/10.1109/ANTEM64578.2025.11114240

19. Esposito, G., Mastrorocco, G., Salvini, R., Oliveti, M. and Starita, P. (2017), "Application of UAV photogrammetry for the multi-temporal estimation of surface extent and volumetric excavation in the Sa Pigada Bianca open-pit mine, Sardinia, Italy", *Environmental Earth Sciences*, no. 76(3), pp. 103. https://doi.org/10.1007/s12665-017-6409-z

20. Tsachouridis, S., Pavloudakis, F., Sachpazis, C. and Tsioukas, V. (2025), "Monitoring Slope Stability: A Comprehensive Review of UAV Applications in Open-Pit Mining", *Land*, no. 14(6), pp. 1193. https://doi.org/10.3390/land14061193

21. Batur, M. and Babii, K. (2022), "Spatial assessment of air pollution due to mining and industrial activities: a case study of Kryvyi Rih, Ukraine", *IOP Conference Series: Earth and Environmental Science*, Dnipro, Ukraine, 06–08 October 2021, Vol. 970, no. 1, pp. 012004. https://doi.org/10.1088/1755-1315/970/1/012004

22. Shi, W., Li, J., Chen, Z., Zhang, C. and Yang, H. (2024), "Smart Mine: The Role of Artificial Intelligence in Modern Coal Extraction", *2024 IEEE/WIC International Conference on Web Intelligence and Intelligent Agent Technology*. IEEE, Bangkok, Thailand, 9–12 December 2024, pp. 874–879. https://doi.org/10.1109/WI-IAT62293.2024.00142

23. Abdelkareem, M. and Al-Arifi, N. (2021), "Synergy of remote sensing data for exploring hydrothermal mineral resources using GIS-based fuzzy logic approach", *Remote Sensing*, no. 13(22), pp. 4492. https://doi.org/10.3390/rs13224492

24. Louloudis, G., Roumpos, C., Theofilogiannakos, K. and Stathopoulos, N. (2019), "Multi-seam coal deposit modeling via principal component analysis & GIS", *Minerals*, no. 9(9), pp. 532. https://doi.org/10.3390/min9090532

25. Szafarczyk, A. and Siwek, M. (2025), "GIS-Based Process Automation of Calculating the Volume of Mineral Extracted from a Deposit", *Geosciences*, no. 15(8), pp. 315. https://doi.org/10.3390/geosciences15080315

26. Montero, P., Bustos, E., Padró, J. C. and Carabassa, V. (2024), "Monitoring of Open-Pit Mining Areas Using Landsat Series Imagery (1984–2023) and Cloud Processing", *Land*, no. 13(8), pp. 1301. https://doi.org/10.3390/land13081301

27. Servou, A., Paraskevis, N., Roumpos, C. and Pavloudakis, F. (2023), "A Geospatial Analysis Model for the Selection of Post-Mining Land Uses in Surface Lignite Mines: Application in the Ptolemais Mines, Greece", *Sustainability*, no. (19), pp. 14388. https://doi.org/10.3390/su151914388

28. Jung, D. and Choi, Y. (2021), "Systematic review of machine learning applications in mining: Exploration, exploitation, and reclamation", *Minerals*, no. 11(2), pp. 148. https://doi.org/10.3390/min11020148

29. Gholami, A., Tokac, B. and Zhang, Q. (2024), "Knowledge synthesis on the mine life cycle and the mining value chain to address climate change", *Resources Policy*, no. 95, pp. 105183. https://doi.org/10.1016/j.resourpol.2024.105183a

30. Kapoor, C., Bhat, M. F., Radhakanta, K., Yewuhalashet, F., Rao, C. N., Taoufik, S. and Hajime, I. (2025), "Open-Pit Mine Reclamation Monitoring and Management for a Sustainable Future Using Drone Technology: A Review", *Drones*, no. 9(9), pp. 601. https://doi.org/10.3390/drones9090601

31. Pagouni, C., Pavloudakis, F., Kapageridis, I. and Yiannakou, A. (2024), "Transitional and Post-Mining Land Uses: A Global Review of Regulatory Frameworks, Decision-Making Criteria, and Methods", *Land*, no. 13(7), pp. 1051. https://doi.org/10.3390/land13071051

32. Zine, H., El Mansour, A., Hakkou, R., Papazoglou, E. G. and Benzaazoua, M. (2023), "Advancements in mine closure and ecological reclamation: A comprehensive bibliometric overview (1980–2023)", *Mining*, no. 3(4), pp. 798–813. https://doi.org/10.3390/mining3040044

33. Xue, Y., Wang, J. and Xiao, J. (2024), "Bibliometric analysis and review of mine ventilation literature published between 2010 and 2023", *Heliyon*, no. 10(4). https://doi.org/10.1016/j.heliyon.2024.e26133

34. Zeng, F. and Jiang, Z. (2023), "Spatial and temporal evolution of mine dust research: visual knowledge mapping analysis in Web of Science from 2001 to 2021", *Environmental Science and Pollution Research*, no. 30(22), pp. 62170–62200. https://doi.org/10.1007/s11356-023-26332-7

35. Ndaguba, E. and Marais, L. (2024), "A scientometric analysis of mine closure research", *Environment, Development and Sustainability*, no. 26(11), pp. 27787–27803. https://doi.org/10.1007/s10668-023-03785-x

36. Bazaluk, O., Petlovanyi, M., Sai, K., Chebanov, M. and Lozynskyi, V. (2024), "Comprehensive assessment of the earth's surface state disturbed by mining and ways to improve the situation: case study of Kryvyi Rih Iron-ore Basin, Ukraine", *Frontiers in Environmental Science*, no. 12, pp. 1480344. https://doi.org/10.3389/fenvs.2024.1480344

37. Ivanov, Y. (2023), "Formation and Development of Post-Mining Geosystems in the Lviv-Volyn Coal Basin", *Managing the Change: Tasks of Post-Mining in Ukraine*, no. 153. https://doi.org/10.48771/C2D6-2060

38. Uruskyi, O., Stankevich, S., Dudar, T., Mosov, S. and Prysiazhnyi, V. (2024), "Integrated Assessment of Disturbed Ecosystems Using Remote Sensing Technique", *Science and Innovation*, no. 20(5), pp. 3–15. https://doi.org/10.15407/scine20.05.003

39. Ulytsky, O. and Boiko, K. (2021), "RSE-based flooding prediction within territories of closed coal mines of Ukraine", *Ukrainian Journal of Remote Sensing*, no. 8(1), pp. 18–25. https://doi.org/10.36023/ujrs.2021.8.1.188

40. Abdelmajeed, A. Y. A. and Juszczak, R. (2024), "Challenges and limitations of remote sensing applications in northern peatlands: present and future prospects", *Remote Sensing*, no. 16(3), pp. 591. https://doi.org/10.3390/rs16030591

41. Szafarczyk, A. and Agbasi, O. E. (2025), "Emerging trends in gis and remote sensing technologies for environmental monitoring: innovations, applications, and future directions", *Geoinformatica Polonica*, no. 24, pp. 25–41. https://doi.org/10.4467/21995923GP.25.002.22857

42. Calka, B. and Szostak, M. (2025), "GIS-Based Environmental Monitoring and Analysis", *Applied Sciences*, no. 15(6), pp. 3155. https://doi.org/10.3390/app15063155

ГІС У ГІРНИЧІЙ СПРАВІ: ВСЕОХОПНИЙ ОГЛЯД ТА БІБЛІОМЕТРИЧНИЙ АНАЛІЗ ЗАСТОСУВАНЬ, ВИКЛИКІВ ТА НАПРЯМІВ МАЙБУТНЬОГО

Батур М.О., Говоруха О.В.

Анотація. Гірнича справа за своєю природою є просторово орієнтованою, що вимагає детальних знань про геологію, топографію, гідрологію та інфраструктуру для прийняття обґрунтованих рішень на всіх етапах життєвого циклу. Геоінформаційні системи (ГІС) стали ключовим інструментом для управління просторовою складністю, інтеграції багатовимірних наборів даних і підтримки прогнозної аналітики у гірничій інженерії та менеджменті. Цей огляд побудований на системному підході до узагальнення сучасних знань про застосування ГІС на всіх етапах життєвого циклу гірничого виробництва, базуючись на аналізі рецензованих журналів, матеріалів конференцій і технічних звітів, опублікованих у 2000–2025 роках. Література була систематично проаналізована та класифікована за етапами: розвідка, планування родовищ, експлуатація та виробництво, екологічний моніторинг і після гірниче землекористування.

На етапі розвідки ГІС сприяє створенню карт мінерального потенціалу шляхом інтеграції геологічних, геофізичних і геохімічних даних із дистанційними знімками, використовуючи методи багатокритеріального аналізу рішень та нечіткої логіки для врахування невизначеності. Під час планування ГІС підтримує вибір ділянки, проектування кар'єру, розташування інфраструктури та оцінку ресурсів, часто у поєднанні з 3D-моделюванням і спеціалізованим програмним забезпеченням для планування. На етапі експлуатації інтегровані ГІС-панелі з системами IoT і SCADA забезпечують моніторинг у реальному часі обладнання, персоналу та стану навколишнього середовища, підвищуючи ефективність виробництва та безпеку. ГІС також є основою екологічного моніторингу та після гірничої рекультивації, зокрема картування забруднення, оцінки стану хвостосховищ, аналізу придатності земель і моніторингу змін за допомогою часових рядів супутникових даних.

Попри свою універсальність, впровадження ГІС стикається з низкою викликів – обмеженою доступністю даних, складністю інтеграції, високими обчислювальними вимогами та нестачею кваліфікованих кадрів. Новітні технології, такі як штучний інтелект (AI), машинне навчання, Інтернет речей (IoT), хмарні платформи та AR/VR, відкривають нові можливості для подолання цих обмежень і розвитку розумного, сталого гірничого виробництва. Цей огляд підкреслює, що ГІС є трансформаційним інструментом для оптимізації операцій, зниження ризиків і підтримки екологічної відповідальності, акцентуючи на необхідності подальших інновацій, міждисциплінарної співпраці та стандартизації робочих процесів для повного розкриття її потенціалу.

Ключові слова: ГІС, життєвий цикл гірничого виробництва, просторовий аналіз, дистанційне зондування, сталий розвиток гірничої справи, бібліометричний аналіз.