ARTÍCULO DE REVISIÓN

Technologies in Underground Mining: A Bibliometric Review

Tecnologías en Minería subterránea: Una revisión bibliométrica

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Abstract

This study presents a global bibliometric review of technologies applied to underground mining based on Scopus records published between 2016 and 2025. A total of 739 documents were analyzed using Bibliometrix/BiblioShiny through performance analysis and science mapping. The review examined publication trends, leading sources, authors, countries, collaboration patterns, keyword dynamics, and thematic structure. The results show sustained growth in the field, with a marked rise after 2019 and a high-output phase in recent years. Scientific production is led by China and India, followed by the United States and Australia, within a geographically concentrated but internationally connected landscape. Publication channels are broad and non-hegemonic, while authorship remains decentralized. The thematic structure reveals a consolidated core around underground mining, mining, the Internet of Things, and automation, together with the rapid expansion of artificial intelligence-related topics, especially machine learning and deep learning. Overall, the evidence suggests a transition from isolated technological applications toward more integrated digital systems for monitoring, prediction, control, logistics, and safety. This study provides a structured baseline for understanding the evolution of the field and outlines a future agenda centered on data standardization, multi-mine validation, cybersecurity in 5G/edge environments, and digital twins for safer and more efficient underground operations.

Keywords: bibliometrics, underground mining, automation, internet of things, machine learning, digital twin

Resumen

Este estudio presenta una revisión bibliométrica global de tecnologías aplicadas a la minería subterránea basada en registros Scopus publicados entre 2016 y 2025. Se analizaron un total de 739 documentos utilizando Bibliometrix/BiblioShiny a través de análisis de desempeño y mapeo científico. La revisión examinó las tendencias de publicación, las principales fuentes, los autores, los países, los patrones de colaboración, la dinámica de las palabras clave y la estructura temática. Los resultados muestran un crecimiento sostenido en el campo, con un marcado aumento después de 2019 y una fase de alta producción en los últimos años. La producción científica está liderada por China e India, seguidas de Estados Unidos y Australia, dentro de un panorama geográficamente concentrado pero conectado internacionalmente. Los canales de publicación son amplios y no hegemónicos, mientras que la autoría permanece descentralizada. La estructura temática revela un núcleo consolidado en torno a la minería subterránea, la minería, el Internet de las cosas y la automatización, junto con la rápida expansión de temas relacionados con la inteligencia artificial, especialmente el aprendizaje automático y el aprendizaje profundo. En general, la evidencia sugiere una transición de aplicaciones tecnológicas aisladas hacia sistemas digitales más integrados para monitoreo, predicción, control, logística y seguridad. Este estudio proporciona una base estructurada para comprender la evolución del campo, y describe una agenda futura centrada en la estandarización de datos, la validación de múltiples minas, la ciberseguridad en entornos 5G/edge y los gemelos digitales para operaciones subterráneas más seguras y eficientes.

Palabras clave: bibliometría, minería subterránea, automatización, internet de las cosas, aprendizaje automático, gemelo digital

1. INTRODUCTION

Underground mining supports key industrial chains ranging from metals for the energy transition to fertilizers and strategic materials, but it operates in environments that put pressure on safety, productivity, and costs: complex geometries, reduced visibility, GNSS-denied environments, demanding connectivity, and geomechanical constraints. In this context, several technologies have moved from pilot projects to operational base platforms: loading-hauling automation, 3D perception and mapping, IoT/5G connectivity, and analytics such as AI for control and prediction (Xiao *et al*., 2022; Yu *et al*., 2025).

The current state of the art can be divided into three areas; the automation of haulage using intelligent LHDs. Technical and industrial reviews outline the transition from tele-remote LHDs to functional autonomy, incorporating multi-sensor perception architectures (LiDAR/vision/RGB-D), trajectory planning, diagnostics, and human supervision, and document improvements in utilization and safety by removing the operator from the front line, furthermore, in low-visibility environments, using stereo vision and topological algorithms, waste rock piles are detected and segmented to determine optimal attack points and enable fully automatic loading cycles, as demonstrated in real mines (Hennen *et al*., 2025); On the other hand, perception, localization, and mapping in GNSS-denied environments. SLAM 2D/3D solutions are being consolidated that integrate LiDAR-IMU, scan-to-map cloud registration, and Bayesian filters for global localization in repetitive galleries, validated in operating mines (Baek *et al*., 2022). In parallel, RTLS with UWB/LoRa/BLE and 5G/edge networks improve fleet and personnel tracking. In addition, bio-inspired haptic sensors (whiskers) are being explored to maintain situational awareness in dust/fog, complementing optical and radar sensory fusion (Gomez *et al*., 2024; P. Zhang & Zhao, 2025). Finally, analytics and AI for process control and geotechnics, machine learning models, and hybrid ensembles predict particle vibration (PPV) in underground blasting, separate directional components, and reduce damage to labor and infrastructure (Tao *et al*., 2024). In terms of costs and geometric compliance, the prediction of overbreak/underbreak together with the optimization of drilling-blasting parameters reduces dilution and rework; recent literature extends these approaches to coal pillars and rock mass deformation with supervised learning frameworks (Anticona-Cueva *et al*., 2024).

The triptych extends with lines that scale the underground factory that is 5G/IoT, robotic swarms on coal fronts, and digital twins for coordination, accompanied by an agenda for standardization and cooperative control (Huang *et al*., 2024); edge computing that brings perception and decision-making closer to the source (He *et al*., 2025); and the standardization of transport databases to design suspended monorails and systematically evaluate traction capacity (Pääkkönen *et al*., 2024). In operational safety, inspections and gas monitoring are reported using field robots and autonomous platforms for explosive environments (Nordström *et al*., 2025), and sensor-based information systems to identify inefficiencies and risky behaviors in operation (Brodny & Tutak, 2022). Converging evidence points to four benefits: safety, by reducing human exposure and strengthening situational awareness; productivity, through less downtime in the LHD cycle and optimized routes; energy, through on-demand ventilation and load control; and cost, through less dilution, fewer reprocesses, and less damage to infrastructure (Anticona-Cueva *et al*., 2024; Hennen *et al*., 2025; Tao *et al*., 2024; Xiao *et al*., 2022).

However, this technological transition faces gaps that bibliometrics highlights. On the technical side, bottlenecks persist in semantic interoperability, cybersecurity due to the expansion of the attack surface in 5G/edge, and robustness of perception under dust/water, where alternative sensors, radar, and haptics still require multi-mine validation (Gomez *et al*., 2024; Zhang & Zhao, 2025). At the organizational level, there are deficits in labeled data, single-site evaluation biases, and change management challenges such as digital capabilities, process redesign, and supervisory roles, along with asymmetries between technology leaders in countries such as Australia or the EU, and contexts of accelerated adoption seen mainly in Latin America or Asia, with different standardization trajectories. Furthermore, underground communications studies show that the selection (Han *et al*., 2025; Pakkala *et al*., 2025; Stefaniak *et al*., 2023) of carriers such as UWB/LoRa/BLE/5G and their deployment architecture determine accuracy, latency, and consumption, directly affecting the feasibility of autonomy and high-fidelity RTLS (Ikeda *et al*., 2022; Nguyen *et al*., 2023).

The research questions are as follows:

1. How many studies have been published over the years?
2. Who are the most active authors in the field?
3. Which scientific journals have published the most on this topic?
4. What levels of collaboration have there been between authors, institutions, countries, etc.?
5. Which documents are most cited worldwide?
6. From which areas of knowledge has research been conducted?

Based on the above, the main objective of this study is to conduct a bibliometric analysis of the current state of research on underground mining technologies. Thus, the review seeks to guide engineers and operations managers in the design of technology portfolios that maximize safety and productivity and consolidate more predictable, efficient, and safer underground mining.

2. METHODOLOGY

2.1. Search strategy

This bibliometric review was conducted using Scopus as the sole data source, because it offers broad multidisciplinary coverage and standardized bibliographic metadata across mining engineering, automation, sensing, robotics, and applied computer science; this improves consistency during bibliometric processing and, at the same time, avoids the overlap that often appears when records from different databases are merged. The search was carried out on 25 October 2025, and the time window was restricted to 2016–2025. Since the extraction was performed before the end of 2025, the records indexed for that year were considered partial and interpreted with caution.

The search was applied in the TITLE-ABS-KEY fields, combining the underground mining context with descriptors associated with digital and automation technologies. The query used was TITLE-ABS-KEY ("underground mining" OR "underground mine") AND TITLE-ABS-KEY ("artificial intelligence" OR digitalization OR automation OR tele-remote OR robotics OR "Internet of Things" OR "digital twin" OR "machine learning" OR "deep learning" OR "Industry 4.0" OR "Mining 4.0" OR "smart mining" OR "IoT") AND NOT TITLE-ABS-KEY ("open-pit" OR "civil tunnels"). In addition, the search was restricted to PUBYEAR > 2015 AND PUBYEAR < 2026, PUBSTAGE = final, English language, and the document types article, review, conference paper, and book chapter. Broader descriptors such as "digitalization", "Industry 4.0", "Mining 4.0", and "smart mining" were retained because they are frequently used in the literature as umbrella terms that capture integrated digital transformation processes in mining, including automation, connectivity, sensing, and cyber-physical systems; however, their combination with the underground mining block preserved thematic specificity.

The initial search retrieved 1,165 records. After applying the predefined filters, 426 records were excluded, corresponding to publication year outside the target period, publication stage other than final, non-English language, and document types outside the inclusion criteria. The final dataset comprised 739 records included in the bibliometric analysis (Figure 1). Because the study was based on a single search conducted exclusively in Scopus and exported once, no duplicate records were identified.

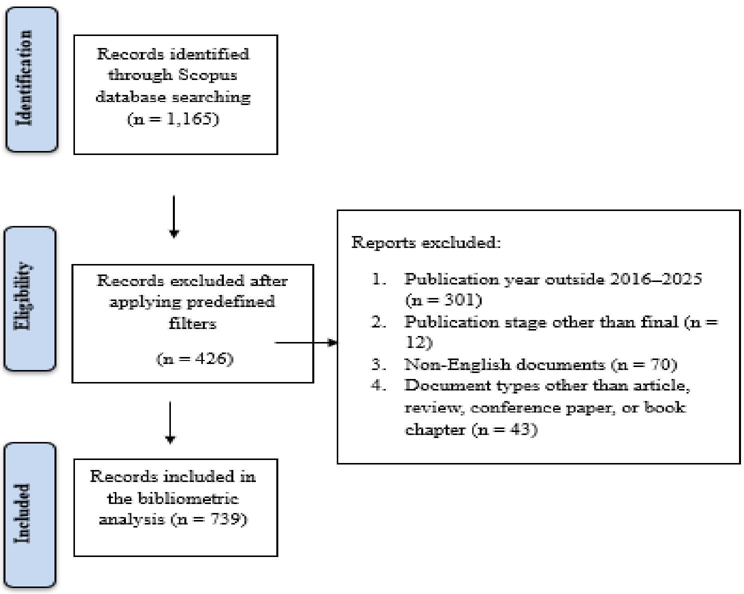

Figure 1. Flowchart showing the process for obtaining final records according to the PRISMA model.

2.2. Data analysis

The records were exported from Scopus in CSV format and processed in Bibliometrix through the BiblioShiny interface. The analysis combined performance indicators with science mapping, which made it possible to describe the evolution of the field and, at the same time, examine its collaboration patterns and thematic structure. The performance analysis focused on annual scientific production, the most relevant sources, the most productive authors, the most cited documents, and the main publication areas represented in the dataset.

Science mapping was used to examine co-authorship networks at the author, institution, and country levels, together with keyword co-occurrence patterns, in order to identify dominant topics, relational structures, and emerging lines of research within underground mining technologies. Thematic evolution was examined across three comparable periods, 2016–2019, 2020–2022, and 2023–2025, which allowed the field to be interpreted in terms of early adoption, acceleration, and later consolidation. To preserve interpretive clarity and avoid fragmented visualizations, conservative thresholds were applied in the network analyses; likewise, complete counting was used and normalization was performed through association strength, thereby ensuring a consistent reading of links across maps and thematic structures.

The decision to work with Scopus as a single source responded not only to its breadth of coverage, but also to the need to ensure metadata consistency, comparability across records, and a cleaner bibliometric workflow. Even so, this choice may have excluded relevant studies indexed exclusively in other databases, such as Web of Science, and this should be recognized as a limitation of the study.

3. RESULTS

3.1. Evolution of scientific output

Research on underground mining technologies showed a clear upward trajectory across the study period, moving from an early stage of limited output to sustained expansion in recent years. The sharp increase after 2019 suggests that the field gained visibility as digital and automation-oriented approaches became more firmly integrated into underground mining research. Although a slight decline appears in 2025, the overall pattern still indicates a consolidated high-production stage rather than a contraction, especially considering that records for the last year were only partially indexed at the time of data extraction. Overall, the annual trend reflects a field that has shifted from gradual development to accelerated and sustained scientific growth (Figure 2).

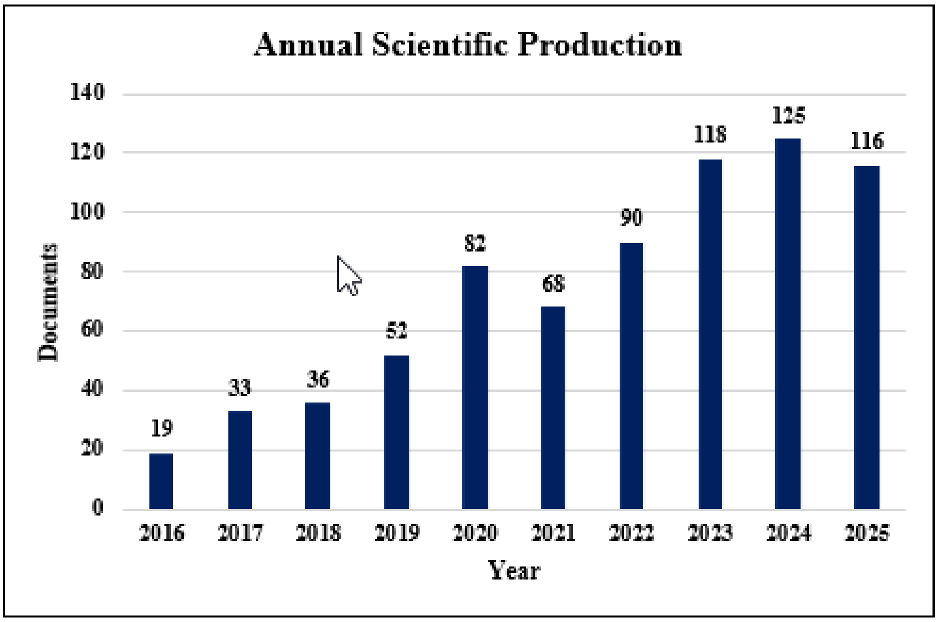

Figure 2. Annual scientific production on underground mining technologies in Scopus from 2016 to 2025, showing a marked rise after 2019 and a sustained high-output phase during the most recent years.

3.2. Most productive journals

The publication landscape is broad and only moderately concentrated, which suggests that research on underground mining technologies is being disseminated through a diverse set of outlets rather than through a single dominant journal. Although Applied Sciences (Switzerland) and Sensors occupy the leading position, their share remains limited in relation to the full corpus, while the rest of the output is distributed across journals and conference proceedings linked to mining engineering, automation, robotics, sensing, and applied artificial intelligence. This pattern is consistent with a field that is still expanding across disciplinary boundaries, where technological development is connected not only with mining-specific venues, but also with wider engineering and digital innovation platforms (Figure 3).

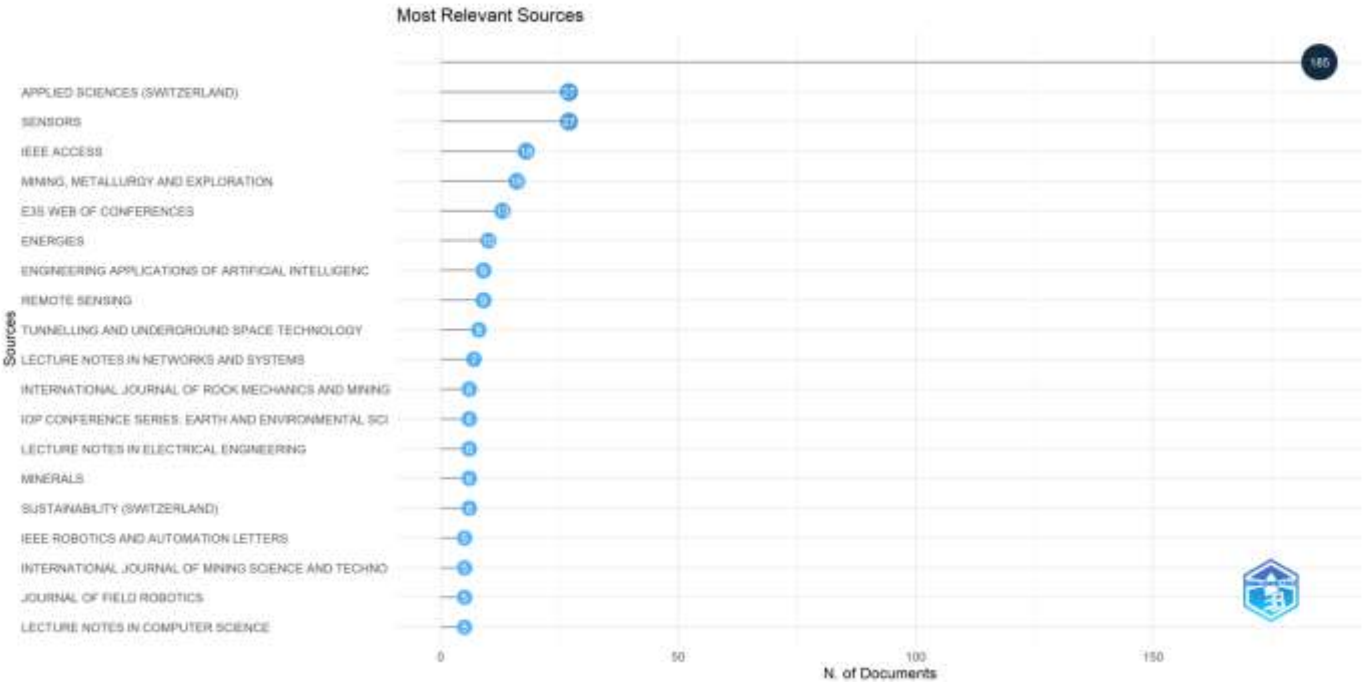

Figure 3. Most relevant publication sources in the Scopus corpus on underground mining technologies, showing a dispersed dissemination pattern led by Applied Sciences (Switzerland) and Sensors, with additional contributions from mining, automation, sensing, and conference-based outlets.

3.3. Most relevant authors

Authorship in this field appears decentralized rather than dominated by a small core of highly prolific researchers. Although a few authors stand out at the top, the gap between the first positions and the rest is relatively small, which suggests that scientific production is distributed across several active contributors instead of being concentrated in a single leading group. This pattern is consistent with the interdisciplinary nature of underground mining technologies, where advances emerge from the convergence of mining engineering, automation, robotics, sensing, and artificial intelligence, thereby favoring a broad and diversified authorship structure (Figure 4).

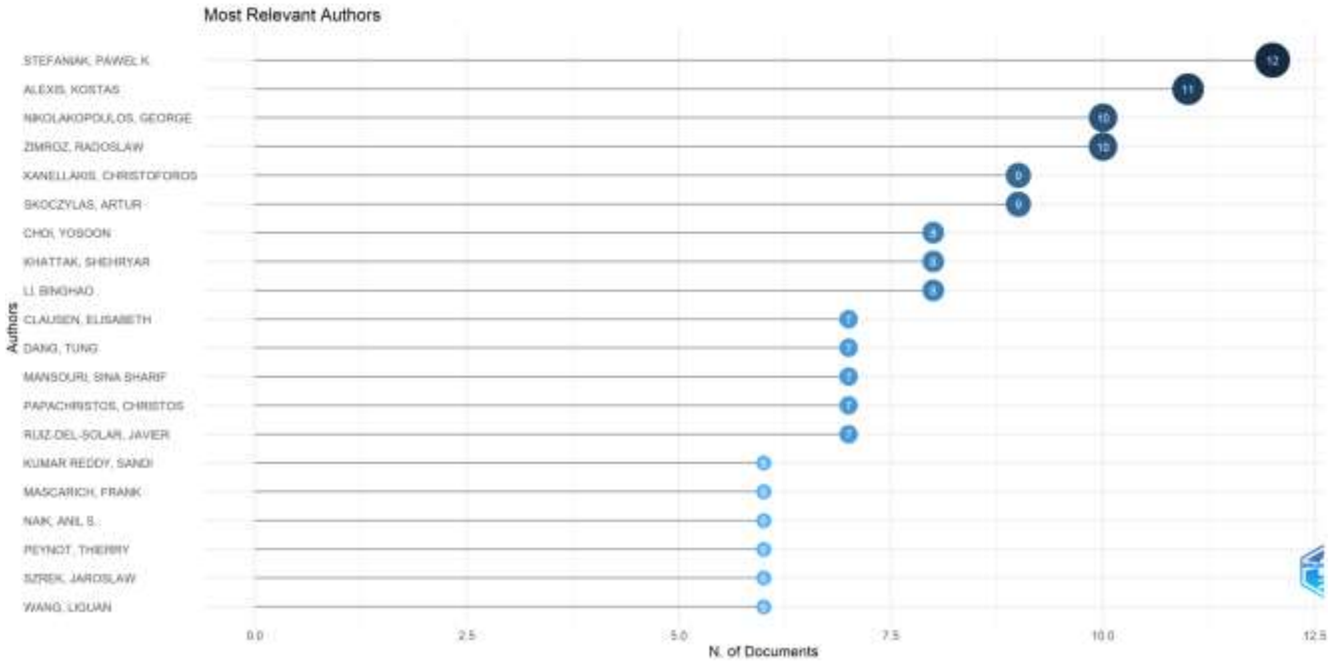

Figure 4. Most relevant authors in the Scopus corpus on underground mining technologies, showing a decentralized productivity pattern, with several authors contributing actively.

3.4. Scientific output by country

International collaboration in underground mining technologies shows a clearly connected structure, but not a uniform one. The strongest links are concentrated around a limited set of countries that act as articulation hubs, especially in the Asia-Pacific sphere, while other nations participate with lower intensity. Rather than a fragmented landscape, the map suggests a field organized through cross-regional corridors that connect Asia with North America, Europe, and Oceania. This pattern indicates that knowledge production in the area is not only geographically dispersed, but also increasingly shaped by strategic international partnerships around automation, sensing, digital infrastructure, and applied mining technologies (Figure 5).

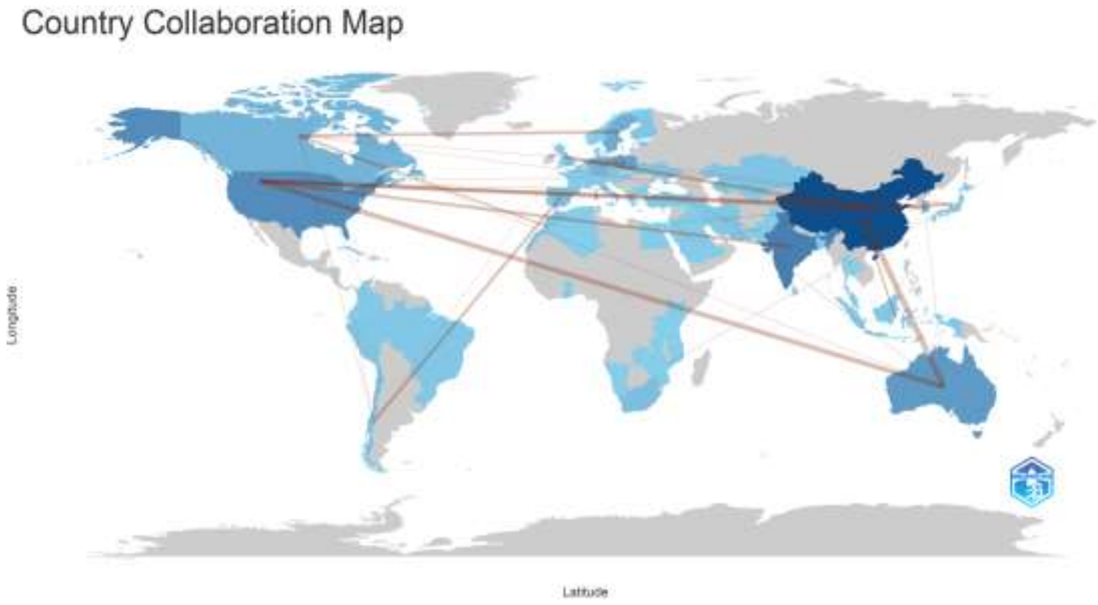

Figure 5**.** Country collaboration map of the Scopus corpus on underground mining technologies, showing an internationally connected network structured around a limited number of high-intensity cross-regional links.

3.5. Most cited documents worldwide

The citation structure shows that the most influential contributions in this field are not confined to mining-specific outlets, but are distributed across engineering, robotics, sensing, communications, safety, and applied technology journals. This pattern suggests that underground mining technologies have developed through strong interdisciplinary exchange, where highly cited work often comes from adjacent domains that provide methods, systems, or analytical approaches later adapted to mining environments. At the same time, the citation rates per year indicate that influence is not limited to older publications; several recent papers have reached a rapid impact, which reflects the accelerated incorporation of digital, automated, and data-driven solutions into underground mining research (Table 1).

Table 1**.** Top 20 most cited documents worldwide in the Scopus corpus on underground mining technologies, highlighting influential contributions from engineering, robotics, sensing, communications

Paper	**DOI**	**Total Citations**	**TC per Year**
RANJTIH, 2017, ENGINEERING	10.1016/J.ENG.2017.04.024	486	54.00
BEHERA, 2021, CONSTR. BUILD. MATER.	10.1016/j.conbuildmat.2021.125120	252	50.40
DANG, 2020, J. FIELD ROBOT.	10.1002/rob.21993	194	32.33
MODARRES, 2018, STRUCT. CONTROL. HEALTH MONIT.	10.1002/stc.2230	178	22.25
PU, 2019, INT. J. MIN. SCI. TECHNOL.	10.1016/j.ijmst.2019.06.009	170	24.29
HUANG, 2018, TUNN. UNDERGR. SPACE TECHNOL.	10.1016/j.tust.2018.07.006	159	19.88
BARNEWOLD, 2020, INT. J. MIN. SCI. TECHNOL.	10.1016/j.ijmst.2020.07.003	156	26.00
DANG, 2019, IEEE INT. CONF. INTELL. ROBOT. SYST.	10.1109/IROS40897.2019.8968151	153	21.86
DHARMADHIKARI, 2020, PROC. - IEEE INT. CONF. ROBOT. AUTOM.	10.1109/ICRA40945.2020.9196964	150	25.00
REN, 2019, SENSORS	10.3390/s19132915	110	15.71
DONG, 2020, IEEE TRANS. VEH. TECHNOL.	10.1109/TVT.2020.2970842	95	15.83

DEY, 2021, PROCESS. SAF. ENVIRON. PROT.	10.1016/j.psep.2021.06.005	93	18.60
WU, 2019, SAF. SCI.	10.1016/j.ssci.2018.11.003	91	13.00
SINGH, 2018, AD HOC NETWORKS	10.1016/j.adhoc.2018.06.008	86	10.75
JO, 2018, SENSORS	10.3390/s18040930	86	10.75
SZREK, 2020, APPL. SCI.	10.3390/app10144984	84	14.00
KUMAR SINGH, 2023, INT. J. MIN. SCI. TECHNOL.	10.1016/j.ijmst.2022.09.022	83	27.67
MANSOURI, 2020, ROBOT. AUTON. SYST.	10.1016/j.robot.2020.103472	78	13.00
MITTAL, 2018, PROC. - GREAT LAKES SYMPOSIUM ON VLSI	10.1145/3194554.3194594	77	9.63
ZHANG, 2023, DIGIT. COMMUN. NETWORKS	10.1016/j.dcan.2022.08.002	75	25.00

3.6. Keyword analysis

Keyword growth confirms that the field has not only expanded in volume, but also become more explicitly shaped by digital and intelligent technologies over time. The dominant trajectory remains anchored in the core descriptors of the domain, especially underground mine, underground mining, and mining, which indicates conceptual continuity throughout the period. At the same time, the strongest upward movement is visible in terms linked to technological transformation, particularly machine learning, Internet of Things, deep learning, and automation; this suggests that the recent evolution of the literature is increasingly driven by data-based monitoring, predictive models, connectivity, and autonomous or semi-autonomous operational systems. Overall, the figure reflects a transition from a predominantly operational vocabulary toward a more digital and analytical research profile (Figure 6).

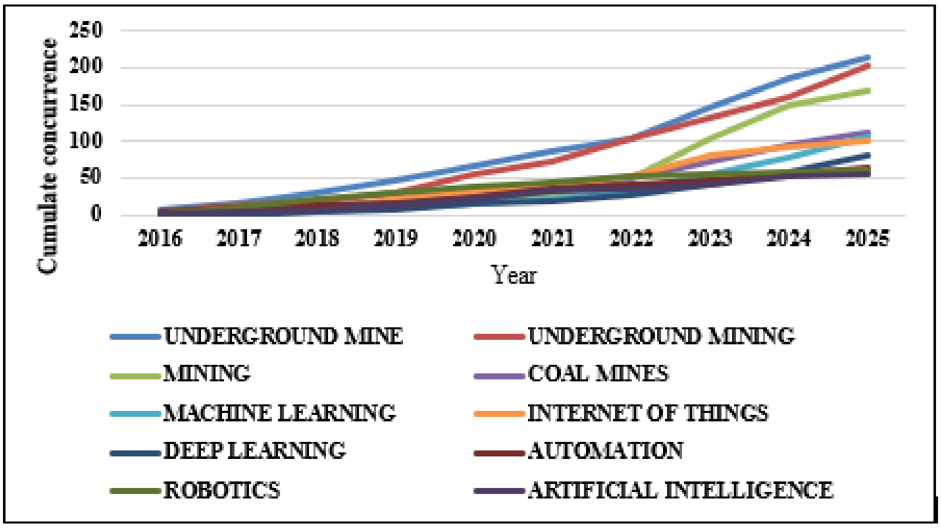

Figure 6. Growth of the most frequent keywords in the Scopus corpus on underground mining technologies from 2016 to 2025, showing the persistence of core mining descriptors and the accelerating rise of digitalization-related terms such as machine learning, IoT, deep learning, and automation.

3.7. Thematic analysis

The thematic map of co-words summarizes the conceptual structure of the field and the level of maturity achieved. The clusters are arranged along two axes: centrality (X), which indicates how many external connections they have with the rest of the network, i.e., their structural relevance, and density (Y), which reflects the degree of internal development, cohesion, and specialization. By combining both indicators, Figure 7 distinguishes four roles: driving themes (high centrality and high density), which act as a driving force; basic themes (high centrality and low density), cross-cutting pillars still in consolidation; niches (low centrality and high density), solid but poorly connected specialized lines; and emerging or declining (low centrality and low density), incipient or retreating topics.

The upper-right quadrant contains the motor themes of the field because it combines high centrality and high density. Here, underground mining, mining, coal mines, Internet of Things, and automation form the most cohesive and connected cluster in the map. This position indicates that these topics are not only well developed internally, but also strongly linked to the wider conceptual structure of the literature. In practical terms, the field is no longer treating digitalization as a secondary complement to mining operations; instead, connectivity, monitoring, and operational control already appear as part of the research core. The presence of coal mines also suggests that many technological applications continue to be tested and consolidated in coal-related underground environments.

The lower-right quadrant groups the basic themes, that is, topics with high centrality but lower internal density. In this map, machine learning, artificial intelligence, forecasting, learning systems, and the variant machine-learning occupy that position. Their placement shows that these concepts are already central to the field, although they still display a more heterogeneous internal structure than the motor themes. This suggests that AI-related approaches are being applied across many underground mining problems, including prediction, monitoring, and decision support, but often through different terminologies and analytical frameworks. As a result, their relevance is clear, yet their conceptual consolidation remains incomplete. This quadrant therefore reflects a transition area where AI methods are essential, though still maturing as a coherent thematic block.

The upper-left quadrant represents niche themes, which combine high density with lower centrality. In this map, robotics, mapping, optical radar, robots, and antennas are located in that area. Their position suggests specialized subfields with strong internal development, but still limited integration with the broader conceptual network of underground mining technologies. This result indicates that some of the most technically advanced lines are progressing in focused communities, especially around perception, navigation, underground communications, and autonomous platforms. These topics are mature within their own technical logic, which explains their density. However, their lower centrality shows that they are not yet fully connected to the dominant operational discourse of the field. This quadrant therefore points to specialized knowledge with clear future potential for broader integration.

The lower-left quadrant groups emerging or declining themes, characterized by low centrality and low density. In this figure, underground mine, deep learning, underground mine transportation, convolutional neural networks, and condition appear in that zone. Their position suggests topics that are either still consolidating or remain fragmented within the wider network. In this case, the interpretation leans more toward emergence than decline, especially for deep learning and convolutional neural networks, since these approaches have gained visibility more recently than broader descriptors such as machine learning or automation. A similar situation may apply to underground mine transportation, which still appears as a narrower line of research. Overall, this quadrant captures the least consolidated frontier of the field, where promising but still weakly integrated themes are developing.

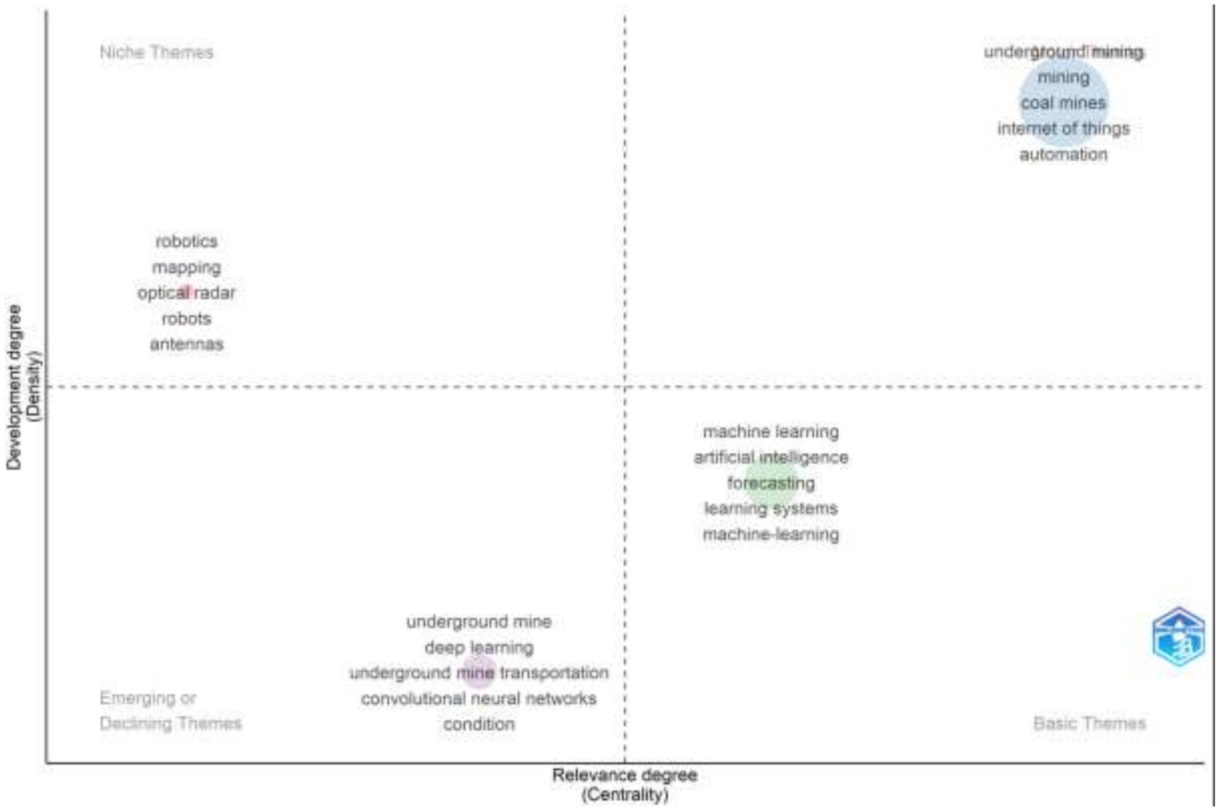

Figure 7**.** Thematic map of the Scopus corpus on underground mining technologies, organized by centrality and density, showing a consolidated core around underground mining, mining, IoT, and automation, together with central but still developing AI-related themes and more specialized niche topics.

The thematic map organizes the descriptors of the 2016–2025 corpus based on two axes: centrality—structural relevance in the co-word network—and density with degree of internal development. This reading allows us to identify which topics form the backbone of the field, which are mature but peripheral, and which remain in early or fragmented stages within technology-oriented underground mining.

In Motor Themes (high centrality and density), a compact cluster is recognized that brings together underground mining, mining, coal mines, internet of things, and automation. Its location points to topics that are both highly connected and robust, operating as a platform for integration between underground operation and digitization: IoT instrumentation for ventilation and environmental conditions, traceability of equipment and personnel, haulage control, and real-time safety monitoring. The concurrence of coal mines suggests that a substantial part of the experimentation and technological validation is supported by coal mines, where there are histories of sensing and standardized operating protocols.

Basic Themes (high centrality, low density) group together machine learning, artificial intelligence, forecasting, learning systems, and the machine-learning variant. These are key concepts for the domain, but they are still heterogeneous: vision applications, predictive maintenance, and planning coexist alongside problems of synonymy, data quality, and task standardization. If taxonomies and data sets in IoT, ventilation, stability, and productivity are consolidated, this block will tend to migrate toward the Engine zone.

Niche Themes (low centrality, high density) include robotics/robots, mapping, optical radar, and antennas: specialized and mature communities linked to perception, navigation, and communications, still peripheral to the global network but critical for tele-operation and underground autonomy. Finally, in Emerging/Declining (low centrality and density) are underground mine, deep learning, underground mine transportation, convolutional neural networks, and condition; their location indicates recency and fragmentation associated with synonymy.

4. DISCUSSION

The bibliometric evidence indicates that research on underground mining technologies has moved from gradual development to a more consolidated expansion phase. The rise in publication output after 2019, together with the sustained high volume observed in 2023–2025, suggests that the field is no longer dominated by isolated pilot experiences, but by a broader transition toward integrated operational systems. This interpretation is also supported by the dispersion of publication sources, which shows that the topic is being developed across mining, sensing, robotics, automation, and applied engineering outlets rather than within a single dominant journal, as well as by the decentralized authorship pattern, which points to a field built through multiple active contributors rather than a narrow core of specialists. In thematic terms, the prominence of automation, Internet of Things, and mining-related descriptors, together with the rising visibility of machine learning and deep learning, reflects a research agenda increasingly shaped by digital integration, predictive capabilities, and operational control. On this basis, the discussion can be read as the qualitative expression of the main quantitative patterns identified in the corpus.

A first implication concerns loading and hauling automation. Its relevance in the discussion is consistent with the thematic structure of the corpus, where automation appears within the most central clusters and with the sharp publication increase recorded after 2019, a period strongly associated with digital acceleration in underground operations. In this context, the literature shows that LHD systems have evolved from tele-remote operation toward functional autonomy, integrating multi-sensor perception, planning, and diagnostic layers that improve utilization and reduce direct human exposure in critical areas (Xiao *et al*., 2022). Material perception remains decisive in this transition, since robust pile detection, segmentation, and attack-point selection directly affect the stability of the loading cycle (Hennen *et al*., 2025). Recent contributions further connect these developments with productivity and safety analysis, reinforcing the operational logic of moving the operator away from high-risk zones (Correa *et al*., 2022; Mariz *et al*., 2025; Vallejo-Molina *et al*., 2024). Even so, persistent bottlenecks remain around human–machine handover, calibration under rapidly changing pile geometry, and the need for multi-shift validation under real mine variability.

A second area is localization and mapping in GNSS-denied environments, which is also coherent with the bibliometric structure observed in the study. The country collaboration pattern and the presence of specialized thematic niches related to robotics, mapping, sensing, and communications suggest that this line is both technically active and internationally connected. At the empirical level, 2D/3D SLAM combined with LiDAR–IMU fusion already enables global localization and coherent mapping in repetitive tunnel environments (Baek *et al*., 2022), while RTLS architectures based on UWB, LoRa, or BLE, deployed over 5G/edge environments, are improving the tracking of personnel and fleets under near-real-time requirements. In parallel, non-optical redundancy through bio-inspired haptic sensing expands situational awareness under dust and fog conditions (Gomez *et al*., 2024), and complementary work with stereoscopic vision, radar, and light mapping is opening more cost-sensitive solutions for medium-scale operations (Fahle *et al*., 2022; Kirsch *et al*., 2023; Ziegler *et al*., 2023). However, the literature still shows fragmentation in semantic interoperability, variable robustness under water, reflectivity, and multipath effects, and a lack of shared inter-mine benchmarks that would allow fairer performance comparison across systems.

Artificial intelligence for blasting and geotechnical control represents another area where the link between results and discussion becomes especially clear. The growth of keywords such as machine learning and deep learning, together with the central but still developing position of AI-related themes in the thematic map, suggests that these methods are no longer peripheral, although they remain internally heterogeneous. In applied terms, machine learning models for peak particle velocity prediction help optimize loads and delays, thereby reducing vibration-related impacts on workings and nearby infrastructure; in that context, the GWO-GBR model has shown strong performance for directional PPV prediction (Tao *et al*., 2024). In parallel, overbreak and underbreak prediction, as well as chamber stability assessment through ensemble-based approaches, are increasingly supporting drilling–blasting design and support decisions, with direct implications for dilution and rework (Anticona-Cueva *et al*., 2024). Other studies extend this line toward parameter optimization, monitoring, and explainable learning environments (Naik *et al*., 2024; Pattnaik *et al*., 2022; Tripathi *et al*., 2023). Even so, the same weakness appears repeatedly, many models remain validated in single-mine contexts, with uneven historical data quality and limited external transferability. For that reason, the field would benefit from multi-site datasets, traceable measurement protocols, and comparable evaluation metrics such as R^2, dilution rate, PPV, and energy-related indicators.

Transportation and logistics can also be interpreted more directly from the bibliometric findings. The centrality of mining, IoT, and automation, together with the broader shift from an operational vocabulary toward a more digital one, suggests that underground logistics is increasingly being addressed through coordinated and data-supported systems rather than isolated engineering fixes. In this sense, the move from ad hoc solutions toward standardized database-supported designs, such as suspended monorail systems with systematic traction-capacity evaluation, enables more reproducible decisions and better assessment of energy demand on long ramps (Pääkkönen *et al*., 2024). At the operational level, routing and scheduling studies are incorporating fleet awareness and intersection-priority logic in ways that reduce non-productive time and improve traffic management underground (Clero *et al*., 2025; Thanh & Bun, 2022; Zhang *et al*., 2024). When connected to digital twins, these developments also create a safer testing environment for scenario analysis without interrupting production, which gives logistics a stronger role within integrated underground decision architectures (Huang *et al*., 2024).

Finally, safety, communications, and monitoring emerge as a transversal discussion axis, and this is consistent with the motor-theme cluster identified in the map, where mining, IoT, coal mines, and automation appear tightly connected. The implication is clear, safety is not being treated as a separate line, but as a dimension increasingly embedded in digital underground operations. The literature shows that 5G/edge infrastructures provide the latency and bandwidth required for autonomy, tracking, and machine vision, although they also increase the cyber-physical attack surface and expose uneven levels of defensive maturity across operations (Kim & Choi, 2025; Nguyen *et al*., 2023). At the same time, robotics for post-blast inspection and gas monitoring is advancing toward platforms suitable for hazardous and explosive conditions (Nordström *et al*., 2025), while sensor-based monitoring and behavioral analytics are being used to identify downtime, unsafe conditions, and operational inefficiencies (Brodny & Tutak, 2022; Hasan *et* *al*., 2025; Ichpas *et al*., 2025; Jasmine *et al*., 2024). Taken together, these lines suggest that the strongest convergence in the field lies not in isolated devices, but in combined systems where autonomous loading, SLAM or RTLS, robust communications, and AI-supported monitoring contribute simultaneously to safety, productivity, energy efficiency, and lower operational losses.

5. CONCLUSIONS

- Based on the Scopus corpus for 2016–2025, this bibliometric review shows that research on underground mining technologies has moved from a stage of gradual development to one of accelerated and sustained expansion. The marked increase in publication output after 2019, followed by a high-production plateau in recent years, indicates that the field is increasingly organized around integrated technological solutions rather than isolated pilot initiatives. This pattern is consistent with the broader transition of underground mining toward digitalized, connected, and data-driven operational environments.

- The results also show that the field is geographically concentrated but internationally connected. Asia, led by China and India, occupies the strongest position in publication output, while the United States, Australia, and several European countries act as important hubs of scientific contribution and collaboration. At the same time, authorship remains decentralized, with multiple active contributors and no overwhelming dominance by a single research group. This confirms that underground mining technologies constitute a cross-cutting field built through the convergence of mining engineering, automation, sensing, robotics, communications, and applied artificial intelligence.

- From a thematic perspective, the study identifies a consolidated conceptual core structured around underground mining, mining, Internet of Things, and automation, together with a rapidly expanding layer of artificial intelligence-related topics, particularly machine learning and deep learning. This configuration suggests that the technological transformation of underground mining is being driven not only by digital tools in isolation, but by their growing integration into monitoring, control, prediction, logistics, and safety systems. In this sense, the bibliometric evidence supports the view that the field is evolving toward more connected, predictable, and operationally coordinated mining environments.

- These findings also point to a forward-looking agenda. Future progress in underground mining technologies will likely depend on stronger data and semantic standardization, broader multi-mine validation, more robust cybersecurity for 5G/edge environments, and the development of digital twins capable of integrating loading, hauling, monitoring, ventilation, and inspection into unified decision-support systems. In that regard, the main contribution of this review lies in offering a structured baseline for understanding how the field has expanded, where its current thematic core is located, and which technological fronts appear most promising for future development.

- This study has several limitations that should be acknowledged. First, the analysis was based exclusively on Scopus, which, although broad and consistent for bibliometric processing, may have excluded relevant studies indexed only in other databases. Second, the review was limited to English-language documents, which may have reduced the visibility of contributions published in other languages. Third, although the search equation was designed to capture the main technological descriptors associated with underground mining, it may not have retrieved all potentially relevant records, especially those using alternative terminology. Finally, the inclusion of 2025 introduces a temporal bias, since the last year was only partially indexed at the time of data extraction and should therefore be interpreted with caution.

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Additional Information

Conflicts of interest

The authors declare no conflict of interest.

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