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Digital Transformation of Rock Bolt Support Systems: A Reproducible Systematic Review of Numerical Modeling, Monitoring, Optimization, and Emerging AI Applications

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Abstract

Rock bolt support systems are central to ground control in underground excavations, tunnels, mines, and slope-stabilization works. Although artificial intelligence (AI), building information modeling (BIM), digital twins, and automated optimization are increasingly discussed in geotechnical engineering, their uptake in rock bolt support remains uneven. This systematic review provides a reproducible, evidence-calibrated synthesis of 157 English-language journal articles indexed in Web of Science from 2015 to May 2026. A predefined search strategy, explicit screening criteria, PRISMA-style record flow, VOSviewer science mapping, and full-text thematic coding were used. Four research streams emerged: numerical modeling and stability analysis; monitoring and performance evaluation; design optimization and AI-assisted decision support; and materials, corrosion resistance, and installation technology. FEM/DEM analysis and field or laboratory monitoring form the strongest evidential foundation. Current AI applications concentrate on point-cloud bolt detection, risk classification, load-capacity prediction, compliance checking, expert systems, and intelligent support assessment; fully automated generative layout design remains prospective. Key barriers include inconsistent installation-quality records, limited long-term field datasets, weak interoperability among monitoring, BIM, and numerical platforms, and insufficient uncertainty reporting and explainability. The review provides an auditable map of the field and identifies realistic priorities for data-supported digital transformation.

Keywords: Rock bolt support; Systematic review; Numerical modeling; Monitoring; Design optimization; Machine learning

1. Introduction

Underground excavations, tunneling projects, and slope stabilization need effective ground control to ensure structural stability and worker safety. Rock bolt support systems are among the most widely adopted reinforcement techniques, giving immediate support to rock masses by raising their load-bearing capacity and arresting progressive failure [1–4]. Demand for ground support, including rock bolts, stays strong, driven by infrastructure development, mining activity, and urbanization [5,6].

Traditional rock bolt design relies heavily on empirical methods, analytical calculations, and engineering experience. Yet these approaches often fail to account for complex geological conditions, time-dependent behavior, and dynamic loading scenarios [7–10]. The integration of numerical modeling techniques such as finite element method (FEM), discrete element method (DEM), and boundary element method (BEM) has improved design accuracy by enabling detailed simulation of rock-support interaction mechanisms [11–14].

Recent work in AI, BIM, digital twins, and optimization algorithms has opened ways to improve rock bolt design, monitoring, and lifecycle management [15–18]. In the rock bolt literature, though, these technologies are not yet mature enough to treat AI-driven generative design as the dominant evidence base. Current studies use AI and optimization mainly as emerging tools for detection, prediction, compliance checking, parameter selection, and decision support. This review therefore treats AI, generative design, and optimization as emerging directions built on a broader foundation of numerical modeling, monitoring systems, material performance, and rock bolt mechanics.

Existing studies remain fragmented across numerical modeling, monitoring system development, material innovation, installation quality control, and early AI-based decision support [19–21]. A systematic synthesis is needed not only to summarize progress, but also to distinguish between established evidence and prospective digital or AI-enabled applications.

This review provides a systematic analysis of rock bolt support systems through the lens of digital transformation while avoiding overstatement of the present evidence for AI, generative design, and optimization. The specific objectives are to: (1) assess the current state of research through bibliometric analysis of keywords, authors, key publications, and publication sources; (2) identify the dominant technical themes in numerical modeling, monitoring, optimization, and material/installation studies; (3) evaluate how AI, BIM, digital twins, and optimization tools have actually been implemented in rock bolt research; and (4) propose realistic future research directions for intelligent, automated, and evidence-based rock bolt support systems.

By systematically analyzing 157 publications from Web of Science (2015–May 2026), this study consolidates existing knowledge, maps collaborative networks, and maps established foundations and emerging digital trends. The revised scope is therefore a systematic review of rock bolt support research with an emphasis on digital engineering and emerging AI applications, rather than a review claiming that AI-driven generative design is already the dominant practice.

2. Research methodology

This review used a mixed-method design combining systematic-review procedures, bibliometric/scientometric mapping, and qualitative thematic synthesis. The method was revised to make the study auditable and reproducible: the database, search expression, screening rules, bibliometric thresholds, coding framework, evidence-maturity criteria, and sensitivity checks are stated explicitly. The review follows the reporting logic of PRISMA 2020 for identification, duplicate removal, screening, eligibility assessment, and inclusion, although it is not a clinical meta-analysis and no pooled effect-size calculation was appropriate because the included studies differ substantially in geological setting, support type, numerical model, monitoring method, and outcome metric.

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2.1 Review protocol and scope definition

Before analysis, the review scope was fixed around engineering evidence for rock bolt and closely related ground-support systems in tunneling, mining, underground excavation, roadway, cavern, and slope-stabilization contexts. AI, BIM, digital twins, and optimization were treated as emerging subthemes rather than mandatory search filters. This decision reduces selection bias because mandatory AI-related terms would have excluded core studies in numerical modeling, monitoring, corrosion, grouting, load transfer, and installation quality that are necessary for judging the actual maturity of digital transformation in rock bolt support.

The unit of analysis was the peer-reviewed journal article. Each article was used once in bibliometric counts and thematic coding. Where a paper covered more than one topic, it was assigned one primary methodological category for percentage reporting and additional secondary thematic tags for qualitative synthesis. This distinction prevents double counting while preserving interdisciplinary content.

2.2 Database selection and search strategy

The Web of Science Core Collection was selected as the bibliographic source because it provides standardized metadata, citation information, author keywords, Keywords Plus, and export formats compatible with VOSviewer. The final search and export were completed on 20 May 2026. The search covered January 2015 to May 2026 and retained English-language journal articles in the WoS categories Engineering Civil, Mining Mineral Processing, and Geosciences Multidisciplinary.

The exact search expression used for the topic field was: TS=(("rock bolt*" OR "rock bolting" OR "cable bolt*" OR "rock anchor*" OR "ground anchor*" OR "soil nail*" OR "ground support") AND (tunnel* OR "underground excavation*" OR mine* OR mining OR roadway OR cavern* OR slope* OR "slope stabilization" OR "deep rock")). The search was then refined by document type = Article, language = English, and WoS categories = Engineering Civil OR Mining Mineral Processing OR Geosciences Multidisciplinary. Full records and cited references were exported where available. The query deliberately did not include terms such as artificial intelligence, machine learning, BIM, digital twin, or generative design as mandatory filters, because the objective was to evaluate whether these technologies are substantively represented within the broader rock bolt evidence base.

2.3 Screening procedure and eligibility criteria

The screening process and internally consistent record counts are summarized in Table 1. The initial WoS search returned 221 records. After duplicate removal, 172 unique records remained for title-and-abstract screening. Fifteen records were excluded because rock bolt support, cable bolts, rock anchors, soil nails, ground reinforcement, monitoring, optimization, numerical modeling, or material/installation performance was not a substantive focus. The remaining 157 records were assessed at full-text level and retained for bibliometric mapping and thematic synthesis. The resulting numerical flow is internally consistent: 221 identified records - 49 duplicates = 172 screened records; 172 screened records - 15 excluded records = 157 full-text records assessed and included.

Articles were included when they addressed rock bolts, cable bolts, rock anchors, soil nails, or closely related ground-support systems in underground excavation, tunneling, mining, roadway, cavern, or slope-stabilization applications. Articles were excluded when ground reinforcement was only peripheral, when the paper did not report engineering evidence relevant to support performance, when the article was not a journal

article under the predefined filters, or when the available full text was insufficient for thematic coding. Screening decisions and exclusion reasons should be supplied as Supplementary File S2 to allow independent audit.

Table 1. PRISMA-style screening and inclusion flow

Stage	Decision rule	Records
Identification	Records retrieved from Web of Science using the predefined topic query and category/document/language filters	221
Duplicate removal	Duplicate records removed before screening	49 removed; 172 unique records remained
Title/abstract screening	Records checked for relevance to rock bolt support, ground reinforcement, monitoring, optimization, numerical modeling, and material/installation performance	172 screened; 15 excluded
Eligibility and inclusion	Full-text records assessed using inclusion/exclusion criteria and retained for bibliometric and thematic analysis	157 assessed; 157 included

2.4 Data extraction and thematic coding

A structured extraction sheet was used to record bibliographic metadata, publication year, journal, authors, keywords, application domain, support type, geological setting, research method, validation source, digital-technology involvement, and stated limitations. For reproducibility, each coded decision should be linked to a brief textual justification or page/section note from the article. The primary-method code was used for quantitative summaries, while secondary tags were used to interpret cross-cutting themes. The coding dimensions and their analytical purposes are summarized in Table 2.

Table 2. Coding framework used for thematic synthesis and reproducibility checking

Coding dimension	Values or examples	Purpose
Application domain	Tunnel, mine roadway, underground cavern, stope, slope, general ground support	Distinguishes engineering context and boundary conditions
Support system	Rock bolt, cable bolt, rock anchor, soil nail, combined support, grouted/resin/friction/energy-absorbing systems	Separates different reinforcement mechanisms
Primary method	Numerical modeling, experimental/laboratory, field monitoring, analytical, optimization/AI, review/standardization	Provides non-overlapping methodological counts
Validation source	Field measurement, laboratory test, numerical benchmark, case study, expert rule, no external validation	Evaluates evidential strength
Digital maturity	No digital component, data-assisted analysis, optimization-assisted design, AI-assisted prediction/checking, BIM/digital-twin workflow	Prevents overstatement of AI or generative-design maturity
Reported limitations	Data availability, geological transferability, installation quality, uncertainty, sensor durability, software interoperability	Supports critical synthesis and future recommendations

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2.5 Bibliometric and science-mapping parameters

VOSviewer was used to map keyword co-occurrence, co-authorship, citation relationships, source distribution, and temporal topic evolution. Full counting was used unless otherwise stated. Author keywords and Keywords Plus were combined for keyword analysis after cleaning. A thesaurus file was prepared before the final run to merge spelling variants and synonymous terms, such as "rock bolt", "rock bolts", and "rock bolting", while avoiding forced merging of conceptually distinct terms such as cable bolt, soil nail, and ground anchor. The keyword co-occurrence threshold was set at five occurrences for the main map; sensitivity checks at three and eight occurrences were used to test whether the same broad clusters remained visible.

For co-authorship mapping, the minimum threshold was two publications and ten citations, which identified 24 key contributors from 387 authors. Citation analysis used a minimum threshold of 20 citations to identify influential articles. These thresholds were selected to balance interpretability and coverage in a 157-article dataset. Bibliometric maps were interpreted as descriptive indicators of research structure rather than proof of engineering effectiveness.

2.6 Evidence-maturity assessment

To align conclusions with the actual evidence base, each theme was interpreted using a three-level maturity framework. A theme was classified as established when it appeared across multiple independent studies with field, laboratory, or well-validated numerical evidence; developing when supported by several studies but still limited by transferability, uncertainty reporting, or incomplete validation; and emerging/prospective when represented by a small number of proof-of-concept, project-specific, or weakly validated studies. This framework was especially important for AI, BIM, digital twins, and generative design because these terms can imply a level of automation that is not yet widely demonstrated in field-validated rock bolt practice. The resulting cross-theme assessment is presented in Figure 1.

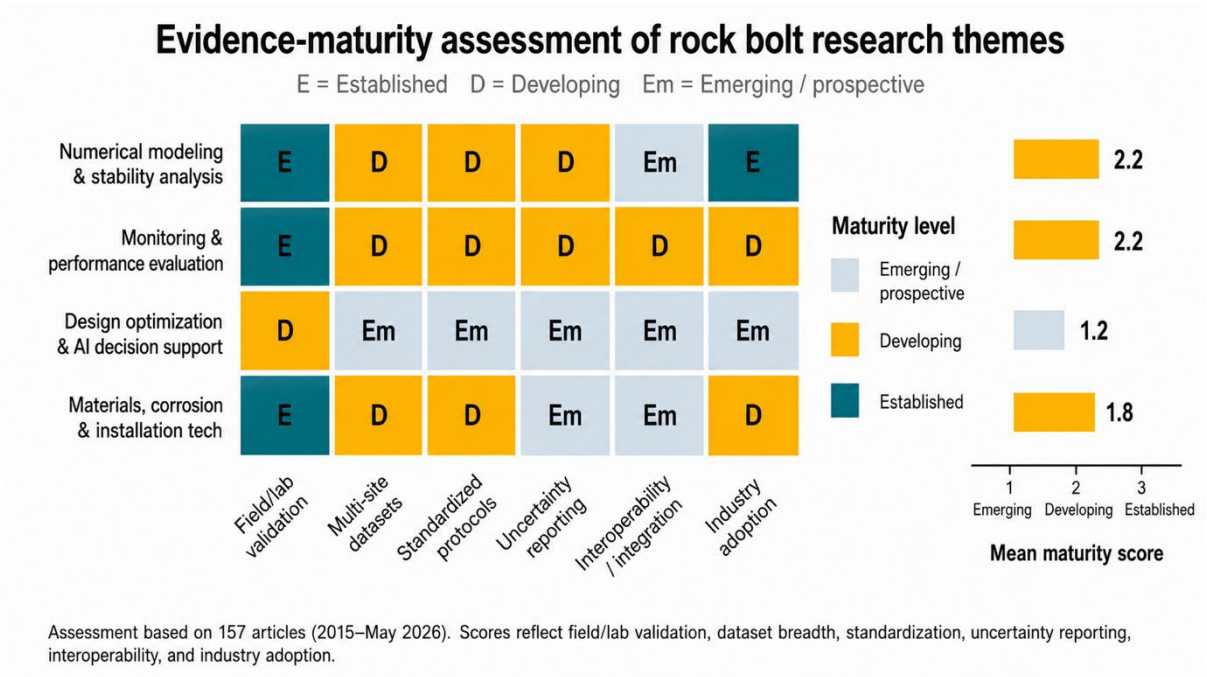


Figure 1. Evidence-maturity assessment of the four rock bolt research themes. Each cell scores a theme against six evidential dimensions on a three-level scale (E = established, D = developing, Em = emerging / prospective). The right panel shows the mean maturity score per theme. Numerical modeling and monitoring are established; design optimization and AI-assisted decision support are developing to emerging; materials and installation sit between the two.

2.7 Reproducibility measures and sensitivity checks

The reproducibility package should include: S1, exact WoS search strategy and export date; S2, screening log with exclusion reasons; S3, coded extraction sheet; S4, keyword thesaurus file; S5, VOSviewer map and network files; and S6, analysis notes listing counting method, thresholds, software version, and any manual corrections. Because WoS export files may be subject to licensing restrictions, the raw records can be made available from the corresponding author where permitted, while the query, metadata fields, thesaurus, and coding sheet should be provided in a form sufficient for verification.

Three robustness checks were used to reduce parameter dependence: first, keyword maps were compared before and after thesaurus cleaning; second, co-occurrence thresholds of three, five, and eight were inspected to confirm whether the four broad clusters remained stable; third, conclusions about AI and generative design were checked against full-text evidence rather than inferred from keywords alone. These checks support the central interpretation that rock bolt research is still anchored in numerical modeling, monitoring, materials, and installation studies, while AI-enabled and digital-twin workflows are emerging but not yet mature.

3. Bibliometric results and mapping

Bibliometric results from VOSviewer are reported here: keyword trends, research-focus evolution, co-authorship patterns, citation structures, and publication-source distribution. Rock bolt research is still centered on conventional geotechnical and engineering topics, while AI, optimization, and digital-twin concepts appear as emerging but smaller subthemes.

3.1 Keyword co-occurrence analysis

Keyword co-occurrence mapping reveals thematic structure and research priorities within the field. From 427 keywords across 157 articles, 35 met the threshold of at least five occurrences. A thesaurus file was created to merge similar terms (e.g., "rock bolt", "rock bolting", "rock bolts"), refining the network to 28 unique keywords. Figure 2 shows the cleaned keyword co-occurrence network.

The analysis reveals four distinct thematic clusters:

Cluster 1 (Red) - Numerical modeling and stability analysis: This cluster includes keywords such as "finite element method" (42 occurrences), "numerical simulation" (38 occurrences), "stability analysis" (35 occurrences), and "stress distribution" (28 occurrences). These terms highlight the dominant role of computational modeling in analyzing rock-support interaction mechanisms, stress transfer, and failure modes.

Cluster 2 (Green) - Monitoring and instrumentation: Keywords include "monitoring" (31 occurrences), "displacement" (27 occurrences), "load testing" (24 occurrences), and "fiber optic sensor" (18 occurrences). This cluster reflects growing emphasis on real-time monitoring systems, performance evaluation, and sensor integration for safety assessment.

Cluster 3 (Blue) - Design optimization and emerging intelligent decision-making: This cluster contains "optimization" (22 occurrences), "support design" (20 occurrences), "parametric analysis" (16 occurrences), and "machine learning" (14 occurrences). The relatively lower occurrence of machine learning indicates that AI-related work is growing but remains less established than numerical modeling and monitoring.

Cluster 4 (Yellow) - Materials and installation technology: Keywords such as "corrosion" (19 occurrences), "grouting" (17 occurrences), "bond strength" (15 occurrences), and "installation technique" (12 occurrences) emphasize research on material durability, installation quality, and long-term performance.

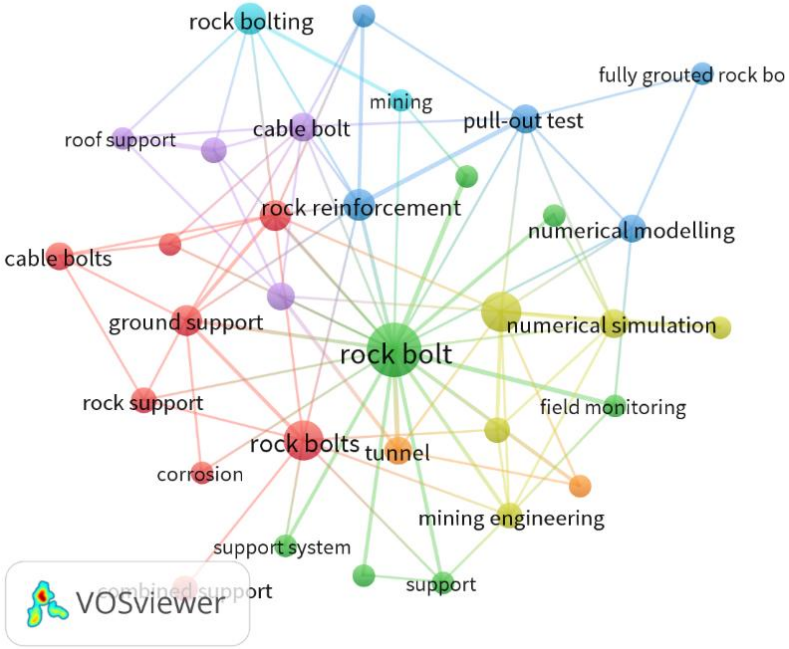


Figure 2. Keyword co-occurrence network in rock bolt research

The high occurrence frequency of "finite element method" and "numerical simulation" confirms computational modeling as the dominant research approach. The more recent average publication years for "machine learning" and "optimization" indicate an emerging digital trend, but the evidence remains comparatively limited. This supports a cautious interpretation: AI, generative design, and optimization should be discussed as future-oriented enablers and early applications rather than as the central body of current rock bolt research. Table 3 reports the leading keyword metrics, while Figure 3 compares occurrence, cluster membership, and average publication year.

Table 3. Top keywords in the co-occurrence network

Keyword	Cluster	Occurrences	Links	Link Strength	Avg. Pub. Year	Avg. Citations
Rock bolt	1	157	27	145	2020.8	18.5
Finite element method	1	42	24	38	2019.5	22.3
Numerical simulation	1	38	23	35	2020.1	19.7
Stability analysis	1	35	22	32	2019.8	21.2
Monitoring	2	31	21	28	2021.3	16.4
Displacement	2	27	20	25	2020.6	17.8
Optimization	3	22	19	20	2021.9	14.2
Support design	3	20	18	18	2021.5	15.6
Machine learning	3	14	15	13	2022.4	11.3
Corrosion	4	19	17	17	2020.2	18.9

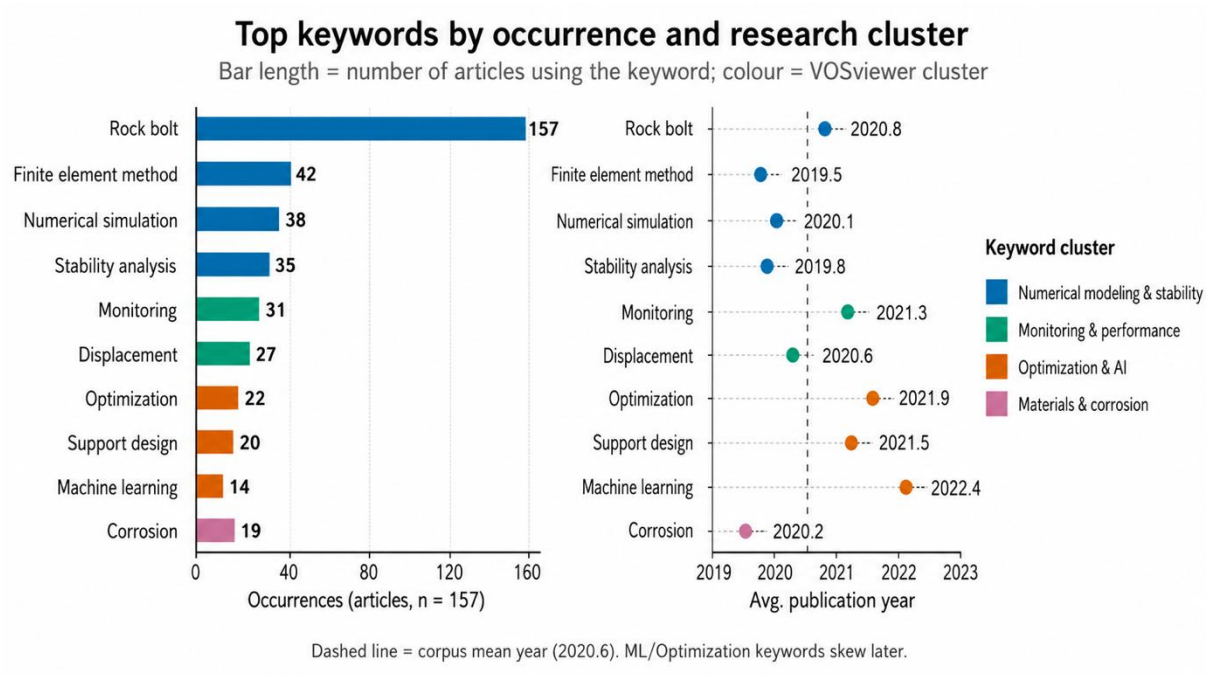


Figure 3. Top keywords by occurrence, research cluster, and average publication year. Bar length gives the number of articles using each keyword; colour marks the VOSviewer cluster. The right panel plots the average publication year per keyword against the corpus mean (dashed line, 2020.6). Machine-learning and optimization keywords skew later but remain lower in frequency, confirming AI as an emerging rather than established stream.

3.2 Annual publication trends

Publication trends reveal steady growth in rock bolt research from 2015 to May 2026 (Figure 4). Initial contributions averaged 8-10 articles annually from 2015–2017, establishing foundational methodologies in numerical modeling, empirical support design, and stability analysis. Research activity accelerated from 2018 onward, reflecting growing interest in monitoring technology, performance evaluation, and improved support-system design.

The period 2021-2025 shows sustained attention to the field, with increasing discussion of optimization, sensor-based monitoring, and data-driven analysis. However, the publication trend should not be interpreted as evidence that AI-driven generative design has become mainstream; rather, it indicates that digital techniques are gradually being added to a broader and still conventional research base.

The acceleration after 2019 coincides with wider adoption of machine learning and digital technologies in geotechnical engineering [15,16,18,22]. In the rock bolt domain, these methods are mainly used for detection, prediction, compliance checking, and support assessment, while comprehensive generative design workflows remain underdeveloped and require further validation.

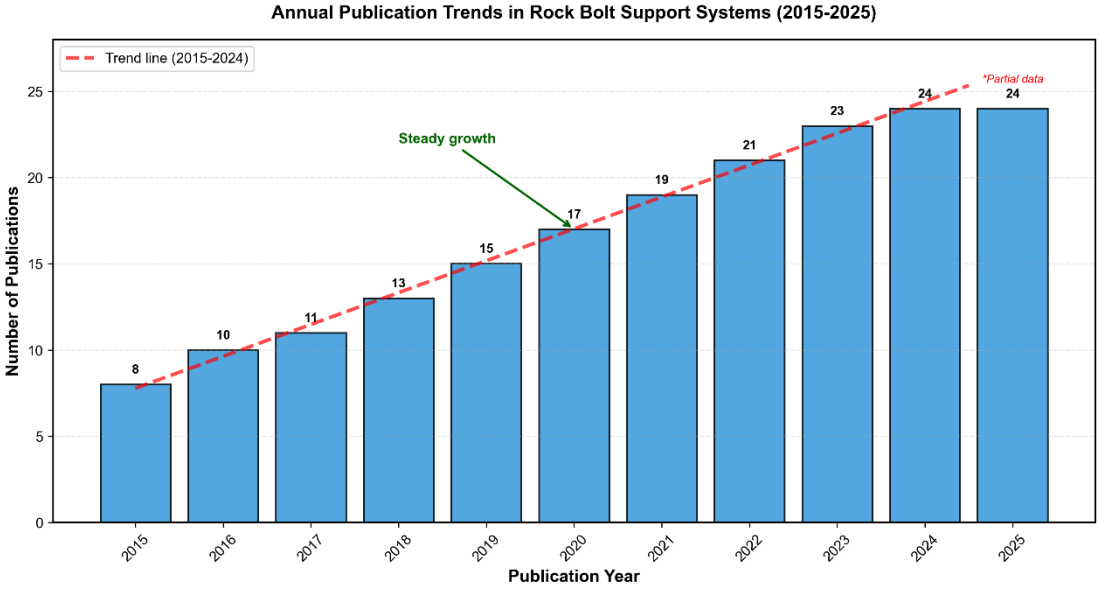


Figure 4. Annual publication trends in the included rock bolt support literature

3.3 Evolution of research topics

Figure 5 summarizes the temporal evolution of research topics. Temporal analysis of keyword evolution reveals shifting research priorities:

2015–2017: Foundational period dominated by "numerical simulation," "finite element analysis," and "tunnel support," establishing computational methods as standard practice.

2018–2020: Emergence of "monitoring systems," "fiber optic sensors," and "load distribution," reflecting growing emphasis on instrumentation and performance validation.

2021–2023: Rise of "machine learning," "optimization algorithms," and "predictive modeling," marking transition toward intelligent, data-driven design approaches.

2024–2025: Increasing discussion of "digital twins," "automated design," "point-cloud compliance checking," and "real-time monitoring," pointing toward integrated intelligent support systems.

This evolution shows a gradual shift from empirical and numerical methods toward data-enhanced support design. The keyword evidence nonetheless suggests a staged transition rather than a completed shift to AI-driven generative design [15–18].

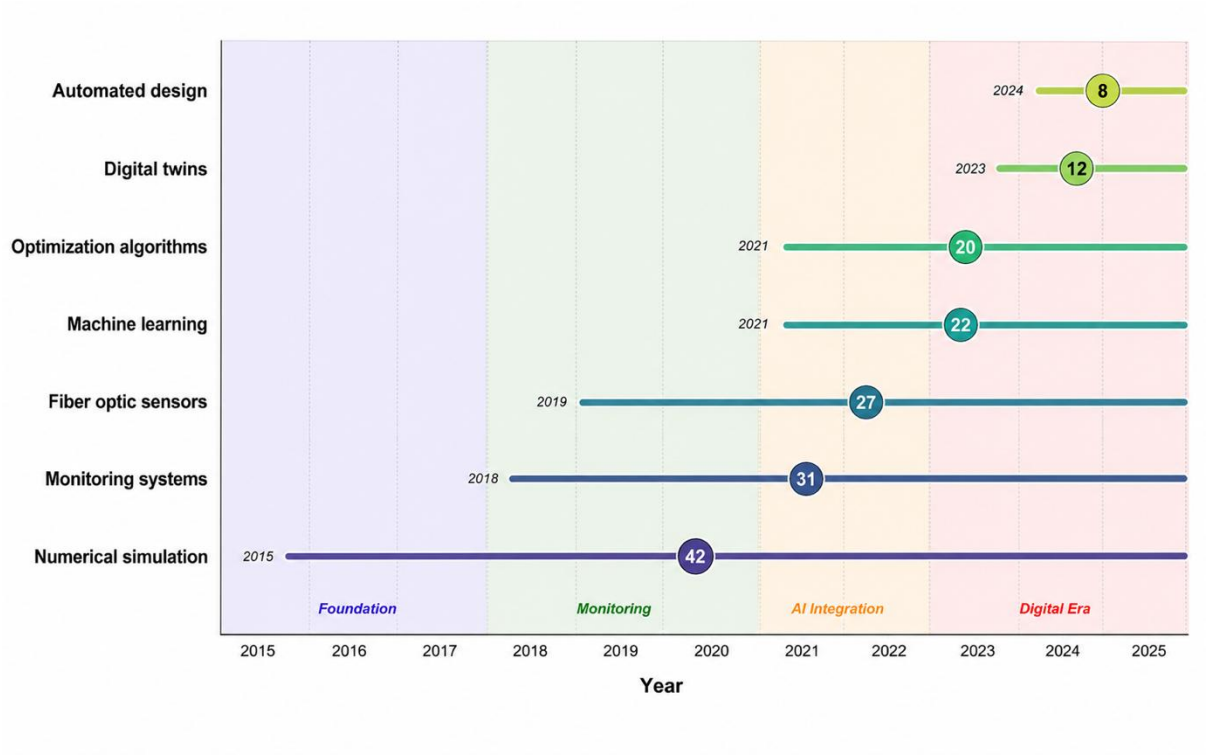


Figure 5. Evolution of Research Topics in Rock Bolt Systems (2015–May 2026)

3.4 Author productivity and collaboration networks

The author collaboration structure is visualized in Figure 6. Analysis of authorship patterns (threshold: minimum 2 publications and 10 citations) identified 24 key contributors from 387 total authors. Because author productivity and citation counts can vary by database coverage and time since publication, the following examples are interpreted as indicative rather than definitive rankings:

Li, C.C. (5 publications, avg. citations: 24.6): Prominent work on rock bolt behavior under dynamic loading and failure mechanisms.

Ma, S. (4 publications, avg. citations: 21.3): Focus on numerical modeling of bolt-rock interaction and optimization algorithms.

Kang, H. (4 publications, avg. citations: 23.8): Specialized in monitoring technology and long-term performance assessment.

The collaboration network suggests strong international partnerships, particularly among Chinese, Australian, and European research institutions. Recent collaborations now include data science, remote sensing, monitoring, and numerical modeling expertise, reflecting the field's gradual movement toward digital support-system research.

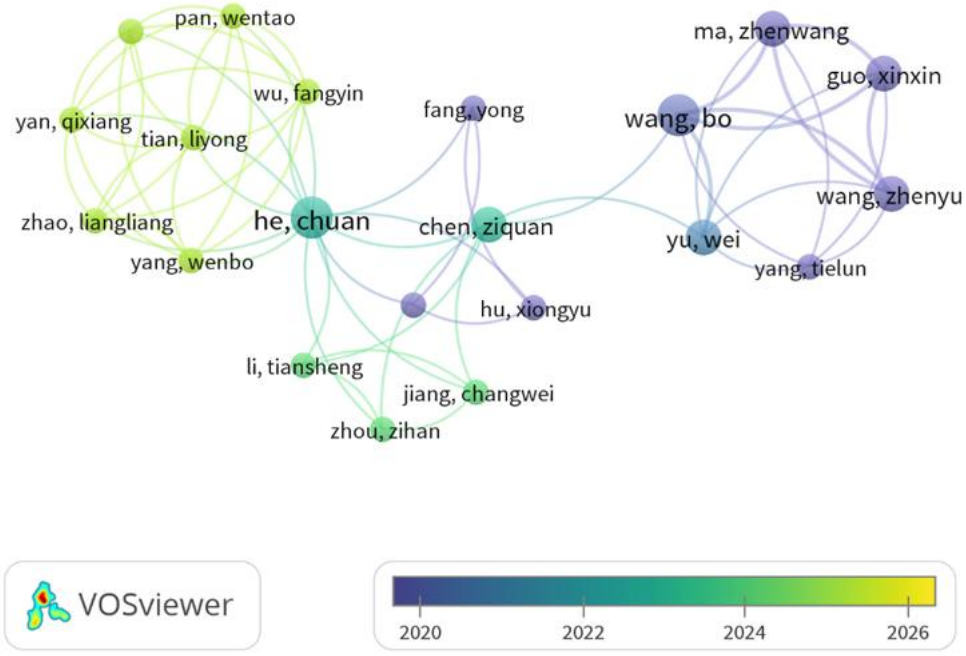


Figure 6. Author collaboration network in rock bolt research

3.5 Citation analysis of influential articles

Figure 7 maps the citation relationships among the influential publications. Citation analysis (threshold: minimum 20 citations) identified 18 highly influential articles forming the evidential foundation of rock bolt research. Key contributions include:

Studies on numerical modeling techniques for simulating bolt-rock interaction mechanisms have been extensively reported in the literature, including FEM-, DEM-, and hybrid-based analyses [11,13,14,23].

Research on fiber optic monitoring systems for real-time performance evaluation has highlighted the value of distributed sensing, strain measurement, and in-situ pull testing [24–27].

Investigations of corrosion effects on long-term load-bearing capacity have emphasized degradation mechanisms, coating performance, and time-dependent durability [28–31].

Development of optimization and decision-support frameworks has shown potential for improving support design parameters, but these studies remain fewer than conventional modeling and monitoring studies [17,18,32,33].

The citation network indicates a mature research ecosystem in which numerical modeling and field/laboratory monitoring form the empirical foundation. AI, expert systems, and generative or parametric optimization are better interpreted as emerging extensions that depend on reliable numerical models, monitoring datasets, and standardized design constraints.

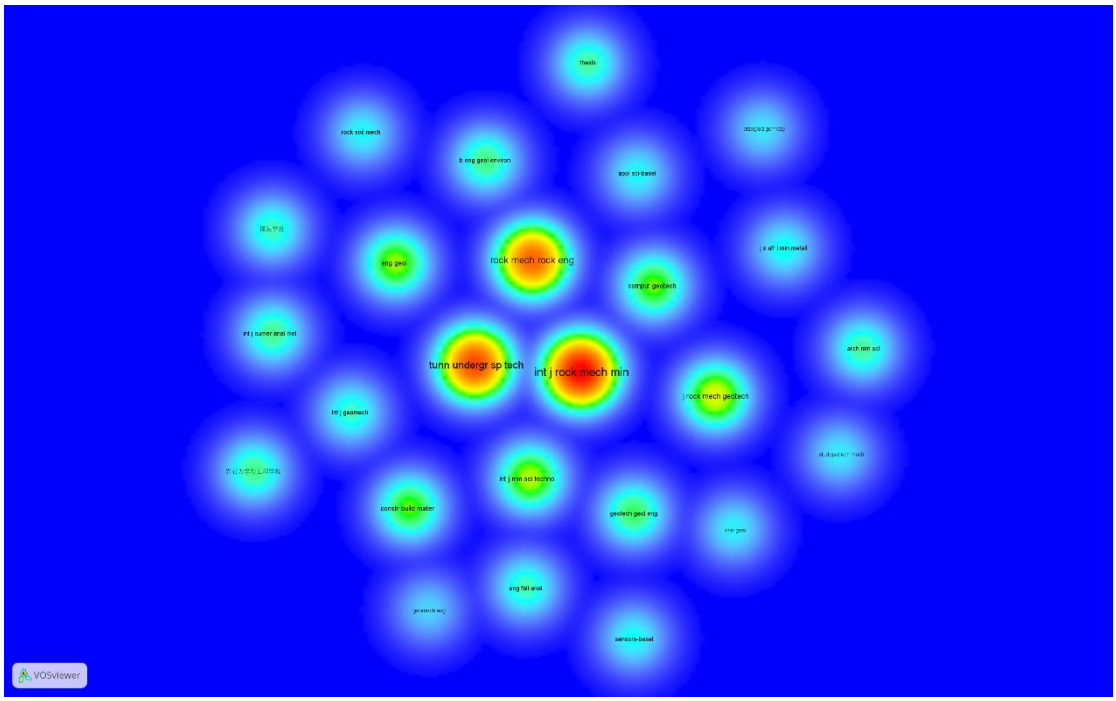


Figure 7. Citation network of influential publications

3.6 Publication sources and journal distribution

Figure 8 presents annual publication patterns across the five leading journals. Among publication sources, "Tunnelling and Underground Space Technology" leads with 28 articles (18% of the reviewed dataset), followed by "International Journal of Rock Mechanics and Mining Sciences" with 22 articles (14%) and "Engineering Geology" with 18 articles (11%). These journals collectively account for 43% of the included journal articles, confirming their central role in disseminating rock bolt research. Because the review retained journal articles only, proceedings and non-journal technical papers were not included in the final synthesis.

Non-journal proceedings were excluded during screening; therefore, source analysis is interpreted only within the WoS-indexed journal-article dataset. The corresponding journal totals and shares are listed in Table 4.

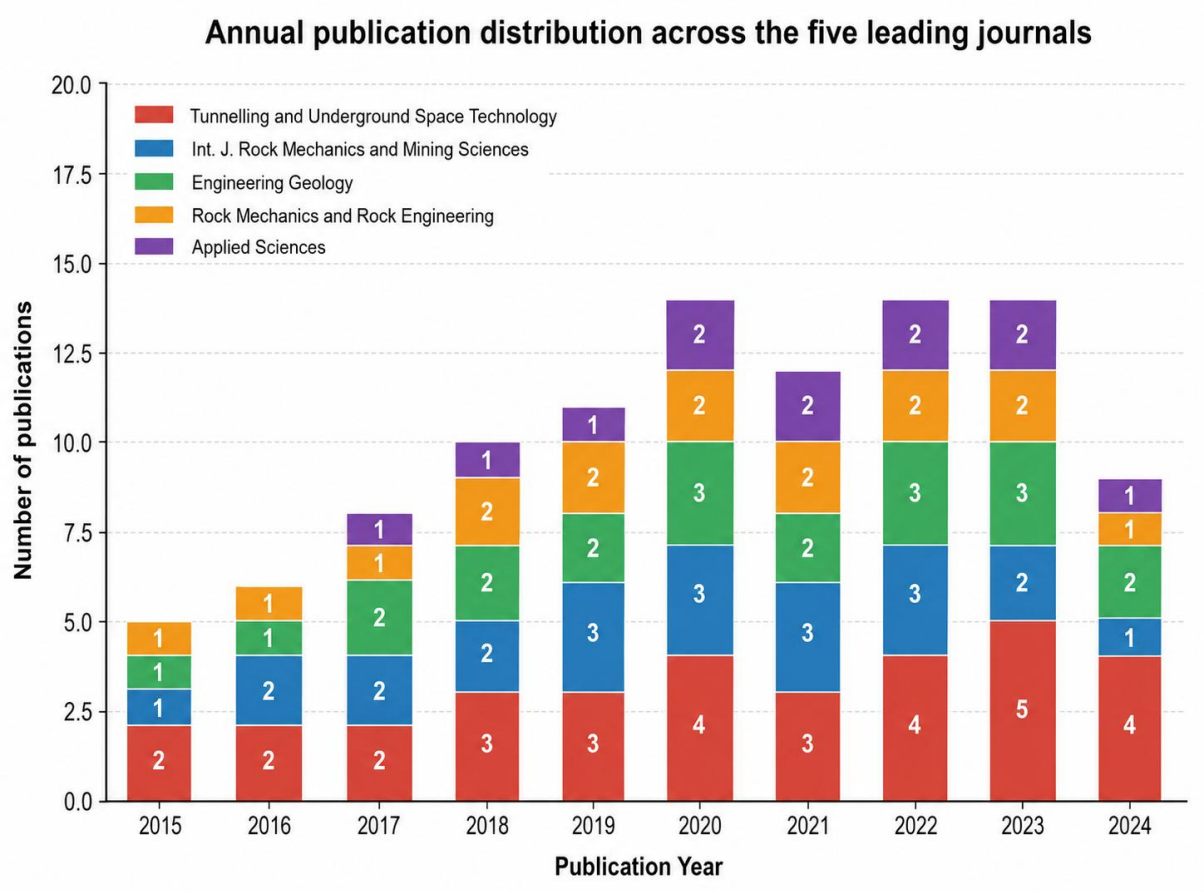


Figure 8. Annual publication distribution across the five leading journals

Table 4. Top five journals by publication count

Journal	Articles	Percentage	Focus Areas
Tunnelling and Underground Space Technology	28	18%	Tunnel support, monitoring systems
Int. J. Rock Mechanics and Mining Sciences	22	14%	Numerical modeling, stability analysis
Engineering Geology	18	11%	Site investigation, ground characterization
Rock Mechanics and Rock Engineering	15	10%	Laboratory testing, material properties
Applied Sciences	12	8%	Emerging technologies, AI applications

4. Thematic and methodological synthesis

This section reports the thematic analysis of selected articles, covering key research themes, methodological implementations, technological innovations, and persistent challenges in rock bolt support systems.

4.1 Research themes

Keyword co-occurrence analysis surfaces four themes:

4.1.1 Numerical modeling and stability analysis

Numerical modeling dominates rock bolt research, illuminating stress distribution, failure mechanisms, and support-rock interaction [11,13,14,34]. The finite element method

(FEM) is the most widely adopted, allowing simulation of complex geometries, heterogeneous rock properties, and staged excavation sequences. Studies show FEM is effective at predicting bolt load distribution, plastic zone development, and critical failure modes under various geological conditions.

Discrete element method (DEM) is now common for analyzing blocky rock masses where discontinuities control stability [11,13,35,36]. DEM excels in simulating progressive block displacement, bolt shear resistance, and interaction between multiple support elements. Hybrid approaches combining FEM-DEM leverage strengths of both methods, with FEM modeling intact rock behavior and DEM capturing discontinuity-controlled failure.

Recent studies increasingly employ three-dimensional modeling to capture spatial variability in geology, loading conditions, and support installation sequence [8,13,37,38]. These advanced models reveal complex stress redistribution patterns and time-dependent behavior that two-dimensional analyses cannot adequately represent. Computational cost, though, remains a barrier to widespread adoption of 3D models in routine design practice.

4.1.2 Monitoring and performance evaluation

Real-time monitoring systems are key tools for validating design assumptions, assessing support performance, and giving early warning of potential failure [27,39–41]. Fiber optic sensing is a clear advance: it enables distributed strain measurement along the whole bolt length rather than discrete point measurements. Fiber Bragg grating (FBG) sensors give high-resolution data on load transfer, revealing progressive mobilization of bond strength and pinpointing critical stress concentration zones.

Load cells and displacement transducers remain widely used for routine monitoring, offering reliable performance at lower cost compared to fiber optic systems. Their point-measurement nature, though, limits ability to detect localized anomalies between sensor locations. Recent studies explore wireless sensor networks and ambient vibration monitoring techniques [39–41] that reduce installation complexity while maintaining continuous data acquisition capabilities.

Integration of monitoring data with numerical models enables back-analysis to refine design parameters and update predictive models based on actual field performance [23,27,40,42]. This data-driven approach improves design reliability, particularly for projects involving uncertain geological conditions or innovative support configurations. Despite this progress, challenges remain in data interpretation, sensor durability, and establishing standardized protocols for integrating monitoring into design practice.

4.1.3 Design optimization and AI-assisted decision support

Optimization algorithms are now applied to rock bolt design to support selection of bolt spacing, length, diameter, and installation angle under safety and cost constraints [17,32,33,43]. Most studies, though, remain optimization- or expert-rule-based rather than fully generative. Genetic algorithms and other metaheuristic approaches are useful for handling multiple objectives and discrete design variables, but field-validated workflows that automatically generate and verify complete bolt layouts are still limited.

Machine learning (ML) techniques are emerging as tools for pattern recognition and prediction in complex rock-support datasets [15,16,22,44]. Current applications include rock bolt detection in laser-scan or point-cloud data, risk classification of bolt failure, load-capacity prediction, compliance checking, and intelligent wedge/support assessment.

These contributions are important, but they represent early AI-assisted decision support rather than a mature AI-driven generative design paradigm.

ML applications remain limited by data availability, inconsistent field documentation, and restricted transferability across geological settings. Many studies rely on synthetic or project-specific datasets rather than large, standardized field databases. Building well-documented datasets that link geology, design parameters, installation records, monitoring data, and observed performance is essential before AI models can be used confidently in routine practice [15,16,22,44]. Explainable AI should also be prioritized to address practitioner concerns about black-box predictions.

4.1.4 Materials, corrosion resistance, and installation technology

Material innovation targets corrosion resistance, bond strength, and fatigue performance [28–31]. Fiber-reinforced polymer (FRP) bolts offer excellent corrosion resistance for permanent support in aggressive environments, though higher cost and lower stiffness than steel limit wider uptake. Coating technologies-hot-dip galvanizing, epoxy coating, and fusion-bonded epoxy-extend steel bolt service life while preserving mechanical properties and installation efficiency.

Grouting technology advances aim to improve bond quality and installation reliability [45–48]. Self-drilling systems that combine drilling and grouting operations reduce installation time and improve grout quality by eliminating the need for a separate grouting step. Fast-setting grout formulations enable immediate load transfer, critical for rapid excavation cycles in mining and tunneling applications. Quality-control challenges persist, though, with inadequate grout coverage and voids remaining common causes of premature bolt failure [21,46,49]. Advanced energy-absorbing bolt configurations further enhance performance under dynamic loading [50–53].

Resin-anchored systems provide rapid load development and high bond strength, making them particularly suitable for immediate support requirements [48,54–56]. Capsule-based systems offer consistent installation quality but require proper drill hole diameter control and careful attention to installation procedures to achieve design capacity.

4.2 Methodological distribution and implementation

Analysis of the coded primary methods confirms that the evidence base is dominated by conventional rock bolt research rather than fully developed AI-driven design workflows. To avoid double counting, each article was assigned one primary-method category, while secondary tags were retained for qualitative interpretation. Under this coding rule, numerical modeling accounted for approximately 58% of the reviewed articles (91/157), experimental and laboratory/field testing for approximately 28% (44/157), and monitoring-system studies for approximately 14% (22/157). AI-, optimization-, and BIM-related contributions were present mainly as cross-cutting secondary tags rather than as a large independent methodological group. This distribution supports the paper's revised argument: digital transformation in rock bolt support is emerging from a mature base of computational mechanics, monitoring, and materials research, not replacing it. Figure 9 visualizes this primary-method distribution.

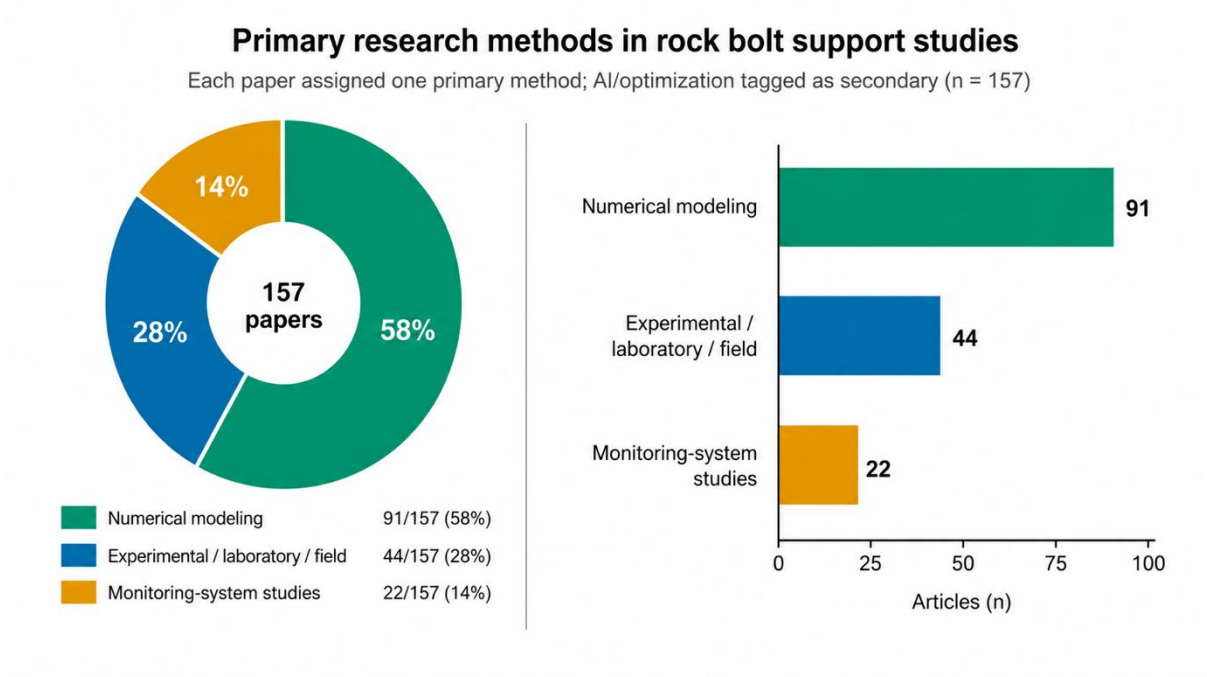


Figure 9. Distribution of primary research methods across the 157 reviewed articles. Each article was assigned one primary method; AI, optimization, and BIM appear mainly as cross-cutting secondary tags rather than as a large independent methodological group. Numerical modeling accounts for 58% (91/157), experimental and laboratory or field testing for 28% (44/157), and monitoring-system studies for 14% (22/157).

Numerical modeling studies formed the largest methodological group, predominantly using FLAC3D, ABAQUS, Phase2, DEM, FDEM, DDA, or hybrid approaches. The most reproducible studies reported constitutive assumptions, boundary conditions, excavation sequences, bolt/grout interface behavior, mesh or particle-size settings, calibration data, and field or laboratory validation. However, systematic uncertainty quantification, sensitivity analysis, and open reporting of model inputs remain inconsistent. For SCI-level reproducibility, future numerical studies should disclose the minimum parameter set needed to rebuild the model: geometry, rock-mass classification and mechanical parameters, joint properties, support element properties, installation sequence, loading conditions, convergence criteria, calibration targets, and validation metrics.

Experimental investigations included laboratory pull-out tests, shear tests, dynamic loading tests, grouting/material characterization, corrosion tests, and field load tests. These studies are essential because they provide the empirical constraints needed to calibrate and validate numerical and AI-assisted models. Reporting quality, though, varies. A reproducible experimental report should state specimen geometry, rock or analogue material properties, bolt type and dimensions, grout/resin formulation, curing conditions, installation torque or pretension, loading protocol, sensor type and sampling rate, failure criterion, and statistical treatment of repeated tests.

Monitoring-system studies included distributed optical fiber sensing, FBG sensors, load cells, displacement monitoring, ambient-vibration monitoring, wireless acquisition, and automated stability-control systems [24–27]. These studies provide the data infrastructure needed for digital twins and AI-supported decision-making, but most remain open-loop monitoring applications rather than closed-loop generative design

systems. For stronger reproducibility, monitoring studies should report sensor layout, sampling frequency, calibration procedure, data-cleaning rules, missing-data handling, synchronization with excavation stages, and criteria used to trigger engineering interpretation or intervention.

4.3 Challenges and research gaps

Despite progress, several persistent challenges limit the effectiveness and reliability of rock bolt support systems:

Design uncertainty remains a fundamental challenge, arising from incomplete characterization of geological conditions, variability in material properties, and simplifying assumptions in analytical and numerical models [9,13,57,58]. Current practice largely relies on deterministic designs with implicit safety factors, providing limited quantitative assessment of failure probability or system reliability. Probabilistic design approaches incorporating uncertainty quantification, including analyses of wedge failures and combined support systems, could improve risk management but require substantial data and computational resources beyond the capabilities of most practitioners [9,57].

Installation quality control strongly affects field performance but receives insufficient attention in design and construction phases [21,30,46,49]. Studies document frequent issues including inadequate hole cleaning, incomplete grout coverage, improper mixing, and insufficient installation torque. These defects can substantially reduce load capacity and compromise intended safety margins. Developing robust quality assurance protocols and real-time installation monitoring systems is critical for improving reliability.

Long-term performance under corrosive environments, cyclic loading, and time-dependent rock behavior remains poorly understood [7,28,29,31]. Most research focuses on short-term performance immediately after installation, with limited data on degradation mechanisms and service life under various exposure conditions. This knowledge gap complicates design of permanent support systems and assessment of maintenance requirements for existing installations.

Integration challenges limit adoption of advanced technologies including AI-assisted design optimization, real-time monitoring systems, digital twins, and BIM-based documentation [15–17,40]. Interoperability between software platforms, lack of standardized data formats, limited field datasets, and insufficient training opportunities create barriers to implementation. Uncertainty about return on investment also discourages adoption, particularly in smaller projects where traditional design methods remain cost-competitive.

5. Future research directions and recommendations

The evidence synthesis suggests future work should treat AI, generative design, and optimization as emerging research directions that must be grounded in validated numerical models, reliable monitoring data, installation-quality records, and practical design constraints. Several strategic directions are recommended for advancing rock bolt support systems toward intelligent, automated, and sustainable workflows:

5.1 AI and machine learning integration

Predictive failure analysis: Developing ML models capable of predicting bolt failure modes and load capacity based on geological parameters, installation-quality indicators, numerical simulations, and monitoring data remains a high-priority research direction

[16,22,33,43]. These models should be validated across multiple sites and reported with uncertainty metrics rather than presented only as proof-of-concept case studies.

Automated design optimization: Integrating multi-objective optimization algorithms with numerical modeling platforms could support automated selection of bolt spacing, length, diameter, inclination, and installation sequence [17,18,32,33]. At present, such workflows should be described as AI-assisted or optimization-assisted design, because fully validated generative design systems for rock bolt layouts remain limited.

Real-time decision support: Combining monitoring data with predictive models through digital-twin frameworks could enable dynamic updating of support-system performance as excavation progresses [17,24,27,40]. Anomaly detection algorithms can identify deviations from expected behavior, but implementation requires robust sensor networks, data governance, communication infrastructure, and clearly defined engineering decision protocols.

5.2 Digital twin and BIM integration

Lifecycle management: BIM-based documentation of rock bolt installations should capture design parameters, as-built conditions, installation quality records, and monitoring data in a centralized, accessible format [16,17,33,40]. This large database supports maintenance planning, performance assessment, and lessons learned for future projects. Standardized data schemas and interoperability protocols are central to enabling information exchange between different software platforms and project stakeholders.

Real-time monitoring integration: Connecting field sensors directly to BIM models enables real-time visualization of support system behavior, facilitating rapid detection of anomalies and informed decision-making [17,26,27,40]. Digital twin frameworks combining BIM geometry with numerical models and monitoring data can simulate "what-if" scenarios, assess impacts of design changes, and optimize intervention strategies before implementation.

Automated layout generation: Developing parametric design tools within BIM platforms could assist generation and comparison of rock bolt layouts based on geological models, excavation geometry, support rules, and performance requirements [17,18,22,33]. Future studies should validate these workflows against field performance and construction constraints before presenting them as generative design solutions.

5.3 Advanced materials and sustainability

Sustainable materials development: Research on environmentally friendly bolt materials, including bio-based composites and recycled materials, could reduce environmental impact while maintaining structural performance [30,31,59,60]. Life cycle assessment (LCA) methodologies should be applied to compare environmental footprints of different bolt systems, informing material selection for projects with sustainability objectives.

Corrosion-resistant systems: Continued innovation in corrosion protection through advanced coatings, cathodic protection, and corrosion-resistant alloys will extend service life and reduce maintenance requirements [28–30,61]. Field validation studies documenting long-term performance under various exposure conditions are central to establishing design guidelines and service life prediction models.

Recyclability and reuse: Developing bolting systems designed for disassembly and reuse in temporary support applications could reduce material consumption and waste generation. Research is needed on connection details, installation procedures, and quality assurance protocols for reusable systems [21,30,55].

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5.4 Standardization and industry adoption

Design guidelines: Updating design codes and standards to incorporate recent advances in numerical modeling, monitoring technology, and AI-driven optimization would accelerate industry adoption of good practice [19–21,33]. Performance-based design approaches that specify required outcomes rather than prescriptive solutions could encourage innovation while ensuring adequate safety margins.

Quality assurance protocols: Establishing standardized procedures for installation quality control, including acceptance criteria and inspection methods, would improve field performance reliability [21,40,46,49]. Digital documentation using mobile devices and automated data management systems can reduce record-keeping burden while improving traceability.

Training and education: Developing structured training programs covering modern design methodologies, installation good practice, and monitoring data interpretation will build workforce capacity to implement advanced technologies [20,21,33]. Online platforms, virtual reality simulations, and hands-on workshops should be employed to maximize accessibility and effectiveness.

5.5 Interdisciplinary research priorities

Cross-domain knowledge transfer: Adapting generative design and optimization methodologies from prefabricated construction to rock support applications offers real opportunities. Parametric design tools, automated layout optimization, and BIM-based documentation approaches developed for modular construction are directly applicable to rock bolt systems with appropriate modifications for geotechnical boundary conditions [17,18,22,44].

Human-AI collaboration: Research on effective interfaces between AI systems and human decision-makers is central to successful technology deployment. Studies should examine cognitive processes, decision-making frameworks, and trust development to optimize human-AI collaboration in design and construction management [15–17,44].

Economic analysis: Comprehensive cost-benefit analyses comparing traditional design approaches with advanced AI-driven methodologies are needed to quantify return on investment and identify applications where benefits justify additional implementation costs [18,22,33,62]. Such analyses should account for reduced design time, improved safety outcomes, lower maintenance requirements, and potential for cost optimization.

5.6 Limitations of the review

This review has several limitations. It is confined to Web of Science-indexed English-language journal articles and may omit relevant conference proceedings, technical reports, design standards, non-English studies, and papers indexed only in Scopus, Google Scholar, CNKI, or specialist engineering databases. Bibliometric maps are sensitive to keyword quality, thesaurus cleaning, citation-window effects, and threshold choices; they are therefore read as descriptive evidence of research structure, not direct evidence of engineering effectiveness. The review does not run a meta-analysis because the included studies differ in geological setting, support configuration, loading condition, modeling assumptions, monitoring technology, and performance metrics. AI and generative-design applications remain sparse and often project-specific, so conclusions about these technologies are deliberately framed as emerging opportunities needing multi-site field validation. Future reviews can address these gaps by expanding databases, adding non-English literature where relevant, and publishing open screening and coding datasets.

6. Conclusions

This systematic review of 157 Web of Science-indexed journal articles shows that rock bolt support research is undergoing digital transformation—but the transformation is incremental, not complete. The strongest evidence still sits in numerical modeling, laboratory and field testing, monitoring, materials, corrosion resistance, and installation-quality studies. AI, optimization, BIM, and digital-twin applications are important emerging directions, yet they are not mature enough to present as routine field-validated generative design practice.

Four key research themes emerge: (1) numerical modeling and stability analysis, establishing computational methods as standard practice for design and analysis; (2) monitoring and performance evaluation, with fiber optic systems giving new insight into bolt behavior; (3) design optimization and intelligent decision-making, marking a transition toward data-driven methodologies; and (4) innovation in materials and installation technology, improving durability and construction efficiency.

Despite significant progress, several challenges persist: design uncertainty from incomplete site characterization, installation quality control deficiencies, limited understanding of long-term performance, and integration barriers limiting adoption of advanced technologies. These challenges indicate clear directions for future research and development efforts.

The convergence of AI, digital twins, and BIM presents important opportunities when it is grounded in validated mechanics, reliable monitoring data, and transparent engineering constraints. Current machine-learning studies can assist bolt detection, failure-risk classification, load-capacity prediction, compliance checking, and parameter optimization. Digital-twin frameworks can connect BIM geometry, numerical models, sensor networks, quality-control records, and lifecycle documentation. However, generative or parametric layout tools should be described as prospective or optimization-assisted unless they have been validated through field performance, construction feasibility, and uncertainty analysis.

For practitioners, the near-term value of digital integration is likely to come from improved monitoring interpretation, transparent decision support, quality-control documentation, and optimization-assisted design rather than fully autonomous AI-generated support systems. Technology developers should therefore prioritize interoperability, explainability, and integration with existing engineering workflows.

Future research should prioritize developing large databases of field performance to enable robust machine learning applications, creating standardized protocols for technology integration, and conducting economic analyses demonstrating value propositions of advanced methodologies. Cross-domain knowledge transfer from other industries, particularly building construction where BIM and generative design are more mature, can speed progress.

The main contribution of this revised review is a reproducible and evidence-calibrated synthesis of rock bolt support research through the lens of digital transformation. Its conclusion is not that AI-driven generative design is already mature in rock bolt support, but that numerical modeling, monitoring, optimization, and material/installation research collectively provide the foundation on which future AI-assisted, BIM-linked, and digital-twin-enabled support systems can be developed. To reach that stage, the field requires auditable field-performance databases, standardized monitoring and installation-quality schemas, explainable predictive models, uncertainty-aware optimization, and validation across multiple geological and construction contexts.

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Conflict of Interest

The authors declare no conflicts of interest.

Generative AI Declarations

During the preparation of this revision, the authors used OpenAI Codex to assist with manuscript restructuring, reference-formatting checks, and language editing in response to editorial comments. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Ethics Approval and Consent to Participate

Not applicable. This literature-based systematic review did not involve human participants, animal subjects, or primary personal data.

Availability of Data and Materials

The data supporting this review, including the search strategy, screening log, coding sheet, keyword thesaurus, and VOSviewer map and network files, are available from the corresponding author on reasonable request. Raw Web of Science records are subject to database licensing restrictions.

Abbreviations

AI	Artificial intelligence
BEM	Boundary element method
BIM	Building information modeling
DEM	Discrete element method
FBG	Fiber Bragg grating
FEM	Finite element method
LCA	Life cycle assessment
ML	Machine learning
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
WoS	Web of Science

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