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A Bibliometric and Quantitative Review of Renewable Energy–Powered Mine Dewatering Systems: Trends, Performance, and Gaps

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Abstract

Renewable energy integration into mine dewatering systems has gained increasing attention amid rising energy costs, decarbonization pressures, and hydrological variability in mining operations. However, existing studies remain fragmented across hydrogeological modeling, hybrid energy optimization, and environmental assessment, limiting cross-study comparability and system-level integration. This study conducts a structured bibliometric and quantitative synthesis to examine the evolution of research, collaboration patterns, thematic concentration, and methodological gaps in renewable energy–based mine dewatering systems between 2015 and 2025. A PRISMA-based dataset of 43 eligible publications was analyzed using co-authorship networks, keyword co-occurrence mapping, temporal overlay visualization, and composite bibliometric scoring. The results reveal a transition from hydrogeology-focused research toward hybrid renewable integration and energy storage–oriented systems. Publication activity increases significantly after 2020, with a peak in citation impact around that time. Energy storage, renewable integration, and groundwater management emerge as dominant research hotspots, while system-level optimization, stochastic hydrological modeling, real-time control, and long-term validation remain underdeveloped. Quantitative evidence indicates energy savings of approximately 12–25% and carbon emission reductions of 20–40%, although these remain constrained by heterogeneous baselines and deterministic modeling approaches. This study proposes a conceptual analytical framework integrating bibliometric structural analysis, temporal performance evaluation, and gap-driven synthesis to support uncertainty-aware and system-level evaluation of renewable-based mine dewatering systems. The findings guide scalable, integrated dewatering strategies across diverse mining contexts.

1. Introduction

The transition toward low-carbon industrial systems has intensified the need to decarbonize energy-intensive sectors, including mining operations. Mining sites frequently operate in remote locations where energy supply reliability and fuel logistics significantly influence operational continuity and cost structure. At the same time, regulatory pressure and sustainability commitments are accelerating the integration of alternative power configurations such as hybrid storage, underground pumped hydropower, and hydrogen-assisted pumping infrastructure within mining environments [1–3]. In parallel with this energy transition, groundwater control and dewatering remain critical operational requirements for maintaining slope stability, preventing flooding, and ensuring safe extraction processes. The intersection of energy supply transformation and mine water management thus represents a strategically important domain within the broader industrial water–energy nexus [4, 5], particularly as the integration of renewables and operational uncertainties increasingly demand coordinated, system-level optimization approaches.

Mine dewatering operations are inherently sensitive to hydrological variability. Groundwater inflow, rainfall intensity, seasonal fluctuations, and aquifer characteristics significantly influence pumping demand, system sizing, and operational risk [6, 7]. Several studies have investigated hybrid PV–diesel integration, the deployment of pumped storage in abandoned mines, and geothermal energy recovery from mine water discharge to reduce fossil fuel dependency while maintaining reliability [8–10]. However, these studies are often conducted as site-specific feasibility assessments or techno-economic optimization exercises, focusing on component-level improvements rather than system-wide coordination under uncertain inflow conditions. As a result, reported efficiency gains are difficult to compare across studies due to heterogeneous system boundaries and evaluation metrics.

Previous research has increasingly explored the integration of renewable energy systems into water infrastructure, particularly in irrigation, desalination, and municipal water supply contexts. From both technical and operational perspectives, several studies have investigated intelligent monitoring systems, predictive maintenance frameworks, and energy management strategies to enhance pump reliability, microgrid coordination, and load balancing in energy-intensive water systems [11–13]. These contributions emphasize system optimization, component-level efficiency improvements, and adaptive control strategies under relatively stable demand conditions. Techno-economic and bibliometric analyses further demonstrate the competitiveness of solar photovoltaic (PV), wind, and hybrid renewable configurations compared to diesel-based systems, highlighting significant reductions in operational expenditure and lifecycle emissions [14, 15]. However, these studies generally assume predictable demand profiles and do not explicitly account for the highly variable and safety-critical conditions characteristic of mining dewatering systems.

These studies document technological evolution from conventional chemical neutralization methods toward adsorption-based systems, hybrid treatment technologies, and resource recovery approaches aligned with circular economy principles [14, 16–23]. Bibliometric mapping analyses further reveal accelerated publication growth and geographic concentration of research output in regions such as China, the United States, and South Africa, as well as emerging thematic clusters related to nanomaterials, sustainability metrics, and valorization strategies. Despite these advancements, AMD-oriented research predominantly addresses treatment efficiency, contaminant removal mechanisms, and material innovation, while largely overlooking the energy supply dimension that underpins pumping and dewatering operations in active mining environments.

2. Materials and Methods

This section describes the methodological framework used to examine research on renewable energy–based mine dewatering. Bibliometric analysis helps map intellectual structures, thematic trends, and collaboration patterns in scientific domains [24]. Our analytical approach proceeds as follows: systematic literature identification, followed by bibliometric mapping, quantitative performance evaluation, and, finally, structured gap synthesis. This sequence forms a coherent workflow. A PRISMA-based selection procedure ensures a transparent and reproducible dataset [25]. Bibliometric mapping then identifies relational structures and thematic concentrations [24]. The methodology proceeds as follows: first, a structured gap synthesis stage is used to consolidate recurring methodological inconsistencies; this is followed by adherence to modern systematic synthesis principles, including transparency, replicability, and cross-dimensional evaluation [26]. This multi-layered methodology ensures analytical transparency, reproducibility, and alignment between data extraction, performance evaluation, and conceptual interpretation. The following subsections describe each methodological stage in detail.

2.1. Study Design and Analytical Framework

This study uses a structured bibliometric and quantitative synthesis design. It systematically examines research development, performance trends, and knowledge gaps in the literature on renewable energy–based mine dewatering. Bibliometric methods are widely applied to map scientific structures, thematic evolution, and knowledge domains across interdisciplinary research fields [24, 27]. The methodological workflow includes systematic screening, network-based mapping, quantitative normalization, and structured gap synthesis. These steps create a coherent analytical sequence. This approach aligns with hybrid bibliometric–systematic reviews, which are increasingly used in recent research synthesis studies [26].

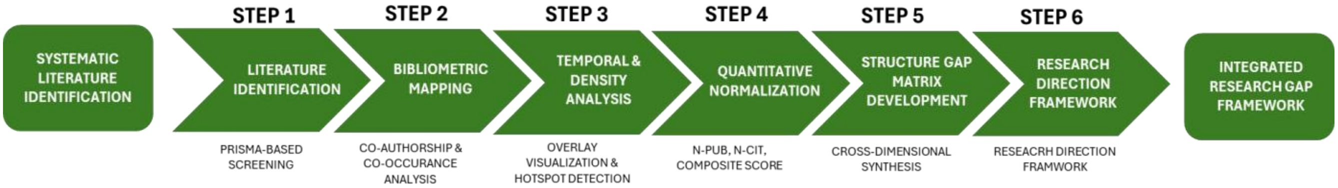

Figure 1. Conceptual workflow.

As shown in Figure 1, the analytical process consists of six sequential stages: (1) systematic literature identification and PRISMA-based dataset construction, ensuring transparency, replicability, and record tracking [25]; (2) dataset filtering; (3) bibliometric mapping, using co-authorship and keyword co-occurrence analysis to reveal collaborative structures and thematic links [24]; (4) temporal overlay analyses; (5) density analysis to identify patterns of research evolution and thematic focus; and (6) adherence to established bibliometric visualization practices [26, 27].

First, we normalize quantitative performance indicators using composite scoring to evaluate publication influence and thematic prominence across diverse study contexts [24]. Second, we synthesize the normalized outputs using a structured gap-matrix process that identifies methodological and contextual limitations in accordance with systematic synthesis principles of transparency and reproducibility. Third, we consolidate these findings into an integrated research gap framework to guide future research. This multi-layered approach sequentially aligns dataset construction, analytical rigor, and conceptual interpretation, providing a systematic foundation for the bibliometric and gap analyses in the following sections.

2.2. Data Source and Search Strategy

The bibliometric dataset was created using Scopus as the main source. Scopus covers peer-reviewed journals across energy, mining, and environmental fields. It is often used in bibliometric studies due to its structured metadata and broad interdisciplinary indexing [24, 27]. The search included only English-language journal articles to ensure consistent quality and citation metrics. This is common in bibliometric mapping studies [24].

A structured search query was developed. Systematic search design principles for bibliometric and systematic reviews were followed [28]. The search string used keywords related to renewable energy technologies and mining-related water management. Example terms include “renewable energy”, “solar PV”, “hybrid system”, “mine drainage”, “groundwater”, and “pumping”. Boolean operators (AND/OR) ensured thematic precision and minimized irrelevant results. This approach aligns with best practices for database queries.

The Scopus query was defined as TITLE-ABS-KEY (("renewable energy" OR "solar PV" OR "photovoltaic" OR "hybrid system" OR "hybrid energy") AND ("mine dewatering" OR "mine drainage" OR "groundwater pumping" OR "mine water management") AND ("pumping" OR "water system" OR "dewatering system")). The query captured studies on renewable energy systems, mine water management, and pumping. The search focused on English-language journal articles. This approach maintains quality, comparability of indicators, and consistency in citation metrics, following common bibliometric mapping studies [24].

The initial search returned 2,800 records. Preliminary refinement used domain-specific filters to include studies about renewable-based pumping, mine water management, or hybrid energy integration in mining. Subsequent filtering included restrictions on publication year (2015–2025), language (English), and document type (journal articles). The 2015–2025 timeframe was chosen to capture recent developments in renewable energy systems. This period followed PV cost reductions and more competitive renewable energy systems [29], leading to increased adoption in practical applications [30]. The screening and eligibility steps followed a PRISMA framework. This ensured transparent documentation of the criteria [25]. After applying the criteria, the dataset contained 43 eligible publications for analysis.

From these eligible studies, a subset with explicit quantitative performance indicators was selected. Example metrics include energy efficiency, emission reductions, cost savings, and renewable penetration. A performance-based extraction logic ensured these metrics were comparable across studies. This approach followed hybrid bibliometric–quantitative synthesis methods [26]. The process produced 15 studies for the final performance evaluation.

2.3. Study Selection and Screening Process

The study selection process followed a PRISMA-based procedure to ensure transparency and reproducibility [25]. Figure 2 shows the screening workflow, which has four stages: identification, screening, eligibility assessment, and inclusion.

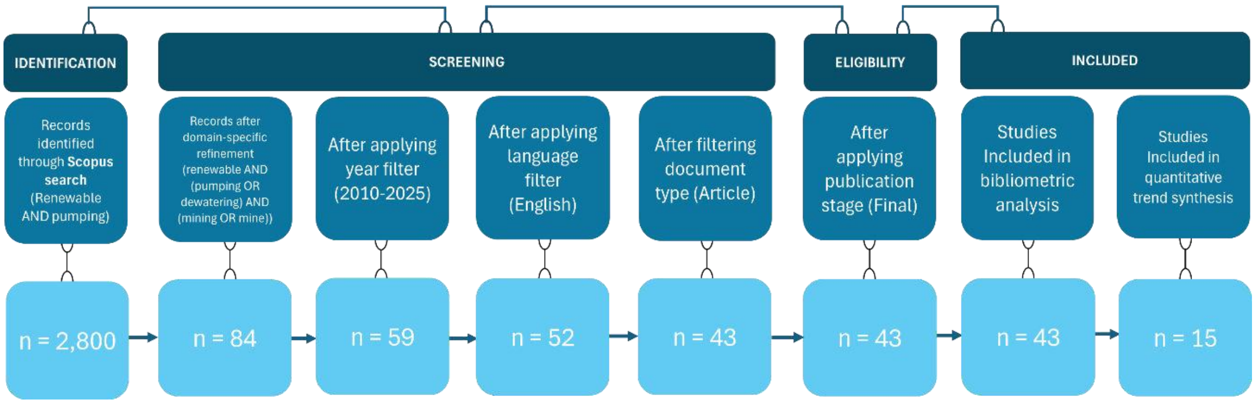

Figure 2. Prisma flow diagram of the study selection process.

During the identification phase, an initial Scopus search yielded 2,800 records on renewable energy integration and pumping. Preliminary refinement used domain-specific criteria to keep only works on renewable-based pumping, mine water management, or hybrid energy in mining contexts. This reduced the dataset to 84 records.

This domain-specific refinement used both keyword filtering and manual screening. Records were first filtered for mining and pumping terms in their title and abstract. Then, manual screening was conducted to assess for relevance to mine dewatering. Studies on irrigation, municipal water, or non-mining uses were excluded. Water treatment-only and laboratory-scale or conceptual studies were also excluded. This process ensured records matched the scope set in the objectives.

In the screening stage, temporal filtering restricted the dataset to publications from 2015 to 2025, yielding 59 records. Language filtering (English only) reduced this further to 52. Document type filtering retained only journal articles, leaving 43 for eligibility assessment. In the eligibility stage, full-text screening checked thematic relevance and methodological consistency with the research objectives. Studies were excluded if they focused solely on hydrogeological modeling without energy integration, on renewable energy applications unrelated to pumping systems, or on conceptual discussions lacking quantitative or analytical contributions. After evaluation, 43 studies remained for bibliometric analysis.

Finally, for the synthesis stage, studies with measurable performance indicators, such as energy efficiency, renewable energy rates, emission reductions, or cost savings, were selected. This resulted in 15 studies for the final performance evaluation.

2.4. Bibliometric and Network Analysis

Bibliometric analysis was conducted to examine the structural and conceptual organization of the research field. Bibliometric mapping is widely used to uncover intellectual structures, collaboration networks, and thematic evolution across scientific domains [24, 27]. The final dataset was processed using VOSviewer (version 1.6.20), a widely used software for constructing and visualizing bibliometric networks, to generate relational network maps and thematic clusters. VOSviewer is commonly used to construct and visualize bibliometric networks due to its robust handling of co-authorship, co-occurrence, and citation-based linkages.

Three analytical approaches were applied. First, co-authorship analysis was performed at the author, organizational, and country levels to identify collaboration patterns and influential research actors. Network nodes represent contributors, while link strength reflects collaborative intensity measured by total link strength (TLS), a metric frequently adopted in bibliometric network studies to quantify relational connectivity [24].

Second, keyword co-occurrence analysis was conducted to determine dominant research themes and conceptual relationships. Author keywords were used as the unit of analysis, and a minimum occurrence threshold was applied to ensure cluster stability and reduce noise, consistent with established bibliometric clustering procedures [27]. Only keywords that met this threshold were included in the network construction and clustering processes. The VOSviewer clustering algorithm was applied with default settings to group related keywords into thematic categories based on association strength, thereby enabling the identification of core thematic domains within the dataset.

Third, overlay and density visualizations were employed to examine temporal evolution and research hotspots. The overlay visualization identifies emerging topics based on the average publication year, while density mapping highlights areas of high thematic concentration. These visualization techniques are commonly used to explore thematic dynamics and patterns of knowledge concentration in bibliometric studies [24, 26]. Collectively, these analyses provide insight into collaboration structures, thematic development, and knowledge concentration within renewable-based mine dewatering research.

2.5. Quantitative Performance and Composite Scoring

To evaluate the relative influence and thematic prominence of the selected studies, a quantitative normalization and composite scoring approach was employed. Composite bibliometric indicators are commonly used to synthesize multidimensional metrics into an interpretable performance index, enabling cross-study comparison across heterogeneous scales [24, 27]. Three bibliometric indicators were selected: the number of publications (N_Pub), the total citation count (N_Cit), and the total link strength (TLS). These indicators represent publication productivity, citation impact, and collaborative network connectivity, respectively, and are frequently adopted in bibliometric performance assessments [24]. Because the raw values of these indicators vary across scales, min–max normalization was applied to standardize each variable within a comparable range between 0 and 1, as shown in Equation (1):

$$N_x = \frac{x - x_{min}}{x_{max} - x_{min}} \tag{1}$$

where x represents the observed value of each indicator, and x_{min} and x_{max} denote the minimum and maximum values within the dataset. The normalization was applied to all indicators before aggregation to ensure comparability across heterogeneous scales. Following normalization, a composite performance score (OS) was calculated to synthesize the multidimensional bibliometric impact, as shown in Equation (2):

$$OS = \frac{N_{Pub} + N_{Cit} + N_{TLS}}{3} \tag{2}$$

This formulation ensures consistency between the selected indicators and the level of analysis, while preserving interpretability within each analytical framework.

In addition to the study-level and keyword-level composite scores, a modified composite index was defined for temporal trend analysis. Since annual performance evaluation focuses on publication output and citation dynamics over time, network-based indicators such as total link strength (TLS) were excluded due to their limited stability and interpretability at the yearly level. Accordingly, the temporal overall score (denoted as OS_t was calculated using normalized publication (N_Pub) and normalized citation (N_Cit) as shown in Equation (3):

$$OS_t = \frac{N_{Pub} + N_{Cit}}{2} \tag{3}$$

This formulation ensures that temporal performance trends are evaluated using indicators that are directly comparable across years, while avoiding bias introduced by network-dependent metrics such as TLS.

For the study-level composite score (OS), an equal-weight aggregation scheme was initially adopted as a neutral baseline to provide a balanced representation of productivity, citation influence, and collaborative connectivity. While equal weighting is commonly applied in exploratory composite indicators, it is recognized that N_Pub, N_Cit, and TLS capture distinct conceptual dimensions and are not strictly equivalent.

To address this limitation and enhance methodological robustness, a sensitivity analysis was conducted using alternative weighting scenarios. Sensitivity analysis has been widely applied in composite indicator development to evaluate the robustness of weighting and aggregation assumptions, particularly given the multidimensional and non-equivalent nature of underlying indicators [31]. In bibliometric and composite performance evaluations, variations in weighting schemes may influence ranking outcomes, necessitating robustness checks to ensure the reliability and interpretability of the results [32]. These scenarios were designed to reflect different emphases on productivity, citation impact, and collaboration strength, as presented in Table 1.

The robustness of the composite scoring framework was evaluated by comparing ranking consistency across the alternative weighting schemes. The analysis indicates that the relative ranking patterns remain largely stable, with only minor positional variations observed among lower-ranked entities. This consistency suggests that the composite performance evaluation is not overly sensitive to specific weighting assumptions and provides a reliable basis for comparative analysis. The resulting ranking robustness is further analyzed and discussed in Section 3.

2.6. Gap Matrix Development and Synthesis Approach

Following the bibliometric mapping and quantitative evaluation stages, a structured gap abstraction process was conducted to identify recurring methodological and

Table 1. Sensitivity analysis of weighting configurations for composite performance scoring.

Scenario	N_Pub	N_Cit	TLS	Interpretation
S1 (Baseline)	0.33	0.33	0.33	Neutral baseline (equal weighting)
S2 (Citation-emphasis)	0.25	0.5	0.25	Emphasizes scientific impact
S3 (Collaboration-emphasis)	0.25	0.25	0.5	Emphasizes network connectivity
S4 (Productivity-emphasis)	0.5	0.25	0.25	Emphasizes research output
S5 (Impact-productivity balance)	0.4	0.4	0.2	Balanced emphasis on output and impact
S6 (Impact-collaboration balance)	0.2	0.4	0.4	Balanced emphasis on impact and collaboration

Table 2. Robustness of ranking results under alternative weighting schemes.

Entity	Rank							Interpretation
	S1	S2	S3	S4	S5	S6	Range	
Study/Country/Author A	1	1	2	1	1	2	1–2	Highly stable
Study/Country/Author B	2	3	1	2	2	1	1–3	Stable
Study/Country/ Author C	3	2	3	4	3	3	2–4	Moderately stable
Study/Country/ Author D	4	4	4	3	4	4	3–4	Stable
Study/Country/ Author E	5	5	5	5	5	5	5	Highly stable

contextual limitations across the reviewed literature. Rather than merely summarizing reported findings, the analysis focused on detecting systematic inconsistencies in system boundary definition, hydrological modeling assumptions, dispatch strategies, depth validation, and contextual scalability. Structured gap identification in review-based research requires transparent coding procedures and cross-study comparability to avoid subjective interpretation [25]. Each study included in the quantitative synthesis was critically examined to assess: (i) the definition of analytical boundaries (component-level vs. system-level evaluation), (ii) treatment of hydrological variability (deterministic vs. stochastic modeling), (iii) level of operational integration (static sizing vs. dynamic dispatch modeling), and (iv) degree of empirical validation (simulation-only vs. field-supported assessment). These dimensions were iteratively coded and compared to identify cross-cutting structural weaknesses, consistent with structured evidence synthesis methodologies that emphasize replicability and systematic abstraction [24, 26].

The coding process was conducted collaboratively by the research team using the predefined analytical framework. To ensure reliability and reduce subjectivity, a subset of studies was independently reviewed by a second researcher. Discrepancies in coding outcomes were discussed and resolved through consensus. This iterative validation process enhanced inter-coder consistency and ensured that classification decisions were systematically aligned with the defined analytical dimensions. The identified limitations were subsequently consolidated into higher-level research gap dimensions through cross-dimensional synthesis. This abstraction process enabled the development of a structured gap matrix linking each structural gap to its potential consequences and corresponding implications for future research. The resulting gap matrix is presented as a structured analytical framework that supports the systematic interpretation and prioritization of research gaps (see Section 3). The use of matrix-based synthesis in systematic reviews facilitates transparent categorization and traceability of findings across heterogeneous studies [27]. By explicitly structuring the gap identification process, the resulting framework moves beyond descriptive review and establishes a coherent analytical foundation for formulating research direction. This approach ensures that the gap synthesis remains grounded in empirical evidence derived from the reviewed studies and directly aligned with the integrated evaluation framework proposed in this research.

3. Results and Discussion

Section 3 presents the results of the bibliometric analysis. Findings are structured to reveal dataset characteristics, the research field's intellectual structure, and emerging thematic patterns. This section combines quantitative indicators and network-based visualizations to systematically interpret publication trends, collaboration structures, and the evolving research focus.

3.1. Robustness Analysis of Composite Scoring

To test the robustness of the composite scoring framework, we conducted a sensitivity analysis using alternative weightings that emphasize productivity (N_Pub), citation impact (N_Cit), and collaborative connectivity (TLS). These scenarios assess whether changes in weighting significantly affect rankings. The analysis results are shown in Table 2, which lists entity rankings under different weighting schemes (S1–S6). Rankings are highly consistent across scenarios, indicating that the composite scoring framework remains stable despite changes in the weighting scheme. Rank variations are minimal (usually 1–2 positions), indicating limited sensitivity. Several entities consistently remain at the top, suggesting robust influence across perspectives.

Minor ranking variations occur for entities with uneven performance across the three indicators. For example, studies with high citation impact but low collaboration intensity are sensitive to citation-emphasized scenarios, whereas those with strong network connectivity perform better under collaboration-weighted configurations. These variations reflect the multidimensionality of bibliometric performance, not instability in the scoring framework.

Overall, the sensitivity analysis confirms that the composite indicator provides a reliable, robust foundation for comparative evaluation and flexibility to accommodate diverse analytical priorities. This robustness strengthens the validity of subsequent bibliometric and gap analysis results.

3.2. Overview of Publications and Dataset Characteristics

This overview describes the dataset's publication trends, geographic distribution, and disciplinary composition, giving essential context before network and thematic analyses follow.

To further examine the research field's intellectual structure, a keyword co-occurrence analysis was conducted in VOSviewer using author keywords. Keyword clusters were generated algorithmically by the VOSviewer clustering algorithm, grouping terms by co-occurrence strength. A minimum occurrence threshold ensured cluster stability and reduced noise, in line with bibliometric practices.

Beyond descriptive metrics, the keyword co-occurrence analysis reveals a structured thematic distribution comprising four dominant clusters. These clusters were not manually defined but emerged from the underlying network structure generated algorithmically through VOSviewer based on keyword co-occurrence relationships.

The first cluster comprises studies on hybrid renewable integration and energy transition in active mining systems, including hydrogen-based systems, intelligent hybrid energy management, pumping optimization, and circular economy transformation [1–3, 33–42]. These works emphasize system-level decarbonization, hybrid PV–hydrogen integration, and adaptive operational control in mining contexts.

The second cluster focuses on underground pumped storage hydropower and integrated renewable–storage configurations in abandoned or repurposed mines [8, 9, 38, 43–46]. These studies primarily address storage sizing, hydraulic interaction modeling, transient simulation, and the positioning of mines as distributed energy storage assets within broader energy networks.

A third group centers on hydrogeological modeling, groundwater dynamics, and dewatering-related system analysis [6, 7, 47–49]. While essential for inflow prediction, subsidence assessment, and operational safety, energy system optimization is often treated implicitly, revealing partial integration between hydrological modeling and renewable energy planning.

The fourth cluster encompasses geothermal utilization, thermal recovery, water treatment technologies, environmental performance assessment, and water–energy nexus studies [4, 5, 10, 50–65]. These contributions expand the scope beyond electrical pumping toward broader sustainability applications, including heat recovery, membrane processes, beneficiation chemistry, and carbon footprint analysis. Following the algorithmic clustering process, each cluster was subsequently interpreted and labeled based on the dominant keywords and thematic coherence within the group.

The four-cluster structure shows research diversifies across electrical, thermal, storage, and environmental fields. Integration between hydrological uncertainty, dynamic energy dispatch, and system optimization remains uneven. This heterogeneity provides key context for interpreting publication and citation trends.

Figure 3 displays annual publication and citation data from 2015 to 2025. Publications generally increase, with a post-2020 rise that mirror growing academic interest in the energy transition and mining sustainability. Citation trends, however, diverge from publication volume. Some years have high citation counts despite few publications, reflecting influential studies that shape research directions. Impact depends on the significance of the contribution, not just its quantity.

The dataset reflects geographic diversity. Figure 4 shows publication distribution by country. China leads, followed by Germany, Poland, and the US, reflecting their research strengths in energy systems, mining engineering, and environmental management. Other notable contributors include Canada, South Africa, and the UK, underscoring the field’s global relevance, with mining and energy operations key.

The disciplinary distribution of the selected publications is shown in Figure 5. Research output is predominantly concentrated in the fields of Energy and Engineering, followed by Earth and Planetary Sciences and

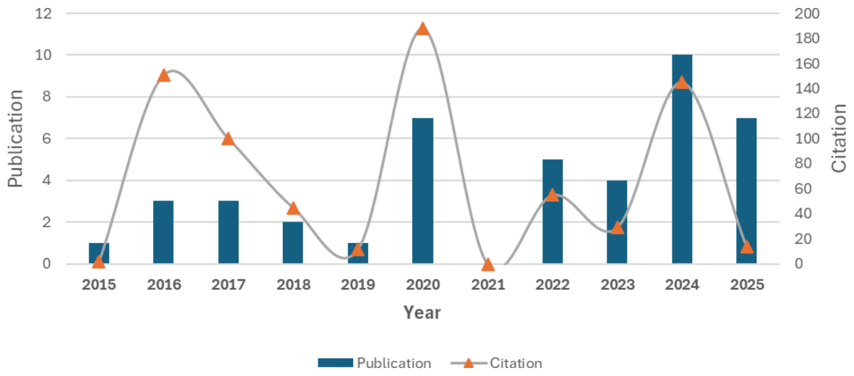

Figure 3. Annual distribution of publications and citations in the study domain (2015–2025).

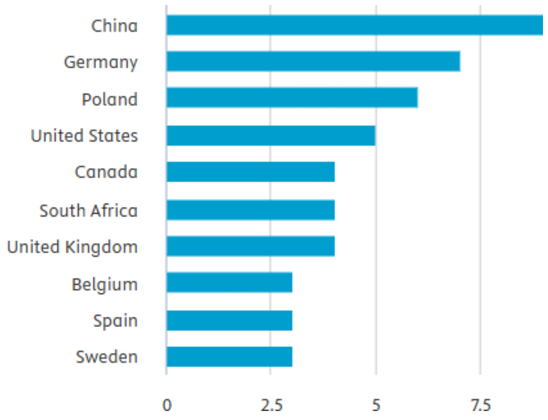

Figure 4. Distribution of publications by country/territory.

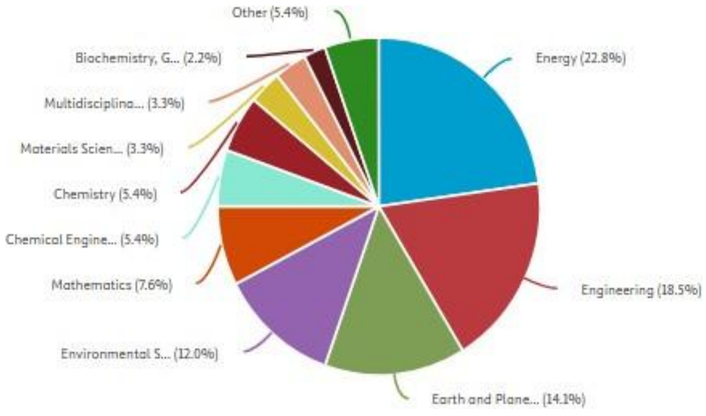

Figure 5. Distribution of publications by subject area.

Environmental Sciences. This distribution underscores the inherently multidisciplinary nature of the research domain, which integrates technical, environmental, and systems-oriented perspectives. The presence of additional subject areas such as Chemistry, Materials Science, and Mathematics further suggests that the literature extends beyond applied engineering solutions, incorporating modeling, optimization, and analytical methods to address complex energy and resource management challenges.

While the preceding subsection provides an overview of the dataset's temporal, geographical, and disciplinary characteristics, these descriptive insights do not yet capture the field's underlying intellectual structure. To address this gap and build on the previous findings, the following subsection extends the analysis through a keyword co-occurrence and thematic clustering approach.

3.3. International Collaboration and Keyword Network Structure

Following the exploration of descriptive and thematic characteristics, this subsection examines the relational structure of the research field by analyzing international collaboration patterns and the conceptual interconnections among dominant research themes.

Figure 6. International country-level collaboration network based on co-authorship analysis.

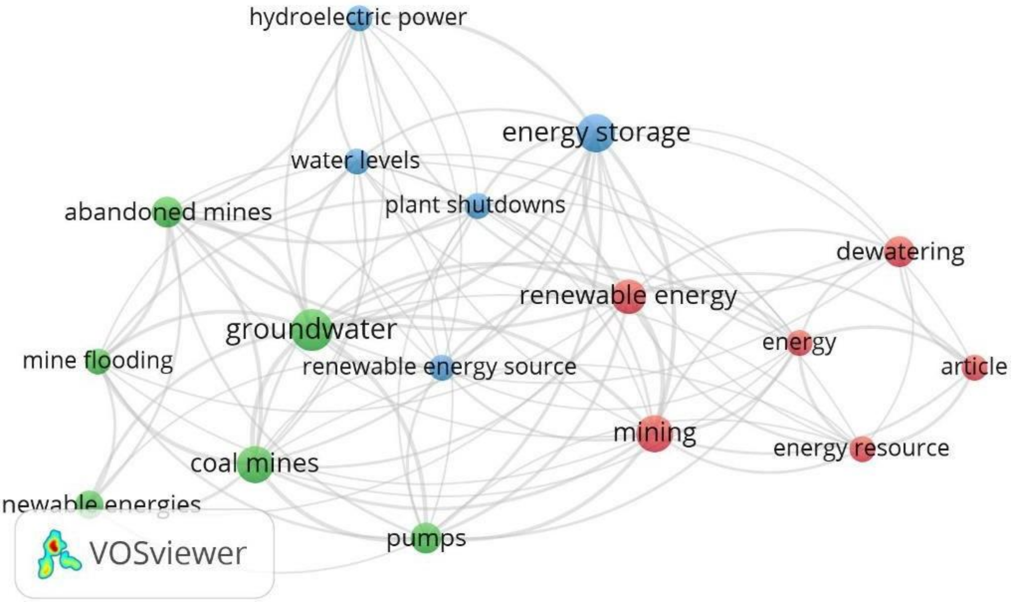

Figure 7. Keyword co-occurrence network of renewable-based dewatering research.

Moving beyond descriptive statistics, the analysis focuses on how research actors and knowledge domains are structurally linked within the bibliometric dataset.

Figure 6 presents the international country-level collaboration network based on co-authorship analysis. The network reveals a relatively linear, uneven collaboration structure, with a limited number of countries serving as central connectors. China and Poland form a tightly linked collaboration cluster, indicating strong bilateral research activity, while Germany and the United States function as intermediary hubs connecting multiple regions. Sweden appears as a bridge between Western research clusters and Eastern European contributions, whereas South Africa is positioned more peripherally, suggesting selective or project-specific collaboration. Overall, the network structure indicates that research on renewable energy–based dewatering systems remains geographically concentrated, with limited multilateral collaboration across regions.

Building on the actor-level collaboration patterns, Figure 7 illustrates the keyword co-occurrence network, highlighting the conceptual structure of the research field. The network identifies renewable energy, groundwater, mining, and dewatering as central nodes, reflecting the literature’s core technical focus. Closely related terms, such as energy storage, pumps, coal mines, and water levels, indicate an operational emphasis on system integration and water management in mining contexts. In contrast, terms related to broader system optimization and digital control appear less central, suggesting that these themes are still emerging rather than fully integrated into the dominant research discourse.

Taken together, the collaboration and keyword networks indicate a field that is technically cohesive yet institutionally and geographically fragmented. Although core concepts are strongly interconnected, collaboration pathways remain limited, suggesting opportunities for broader international and interdisciplinary integration, particularly in advancing system-level optimization and innovation-driven research.

However, these structural networks do not capture the evolution of thematic relationships over time. To address this limitation, the following subsection presents a chronological analysis of shifts in scholarly focus and the emergence of new priorities in renewable–energy–based dewatering research.

3.4. Temporal Evolution of Research Themes

This subsection examines the temporal evolution of research themes within the selected bibliometric dataset, capturing how scholarly attention has shifted in response to technological advances, operational challenges, and

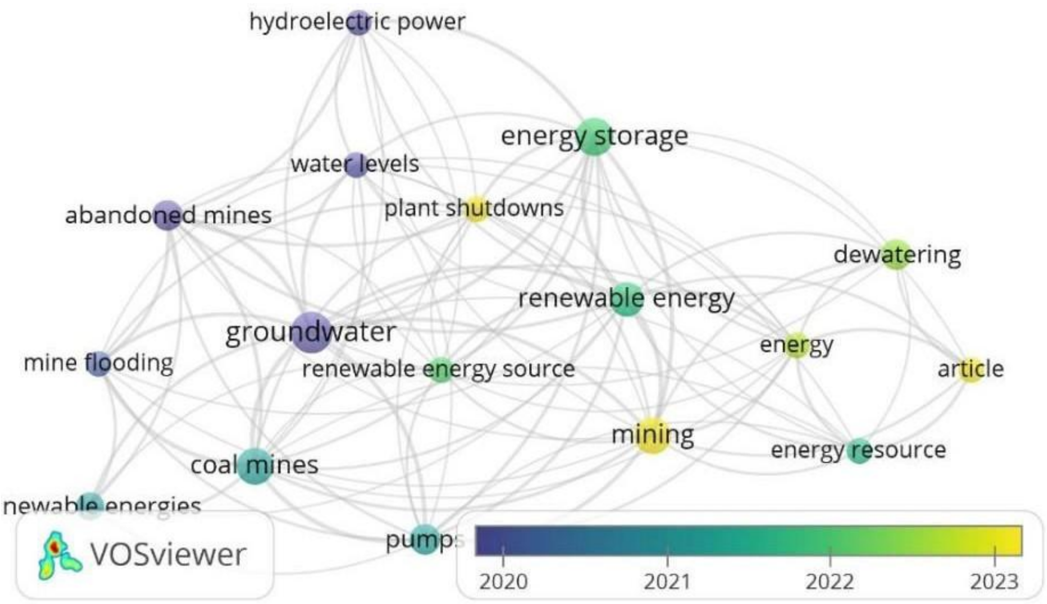

Figure 8. Overlay visualization of keyword co-occurrence based on average publication year.

broader energy transition agendas in mining-related dewatering systems. By applying time-overlay visualization, the analysis extends previous network structures by introducing a chronological perspective on thematic development and emergence.

Figure 8 presents an overlay visualization of keyword co-occurrence, in which node color indicates the average publication year for each keyword. Earlier themes appear in darker blue tones, while more recent topics are shown in green to yellow. The visualization reveals a clear temporal progression in the research landscape. Studies published before 2020 primarily focused on hydrogeological and operational fundamentals, including groundwater, coal mines, mine flooding, water levels, and hydroelectric power. These themes reflect an initial emphasis on managing water-related risks and energy demands under site-specific safety and operational constraints.

From approximately 2020 onward, a gradual shift toward energy-oriented system integration becomes evident. Keywords such as renewable energy sources, pumps, and energy storage emerge as transitional themes, bridging traditional dewatering practices with the deployment of renewable energy. This period corresponds to growing interest in hybrid energy systems, in which renewable generation and storage technologies are explored to enhance the reliability and efficiency of pumping operations.

In the most recent phase (2022–2024), the thematic focus increasingly converges on system-level and sustainability-driven concepts. Prominent keywords such as renewable energy, dewatering, energy resources, and mining appear in lighter color tones, indicating their association with more recent publications. The central positioning and strong connectivity of these terms suggest that current research efforts prioritize integrated energy–water management frameworks, techno-economic optimization, and decarbonization strategies tailored to mining dewatering applications. Notably, the emergence of energy storage as a highly connected and temporally recent keyword underscores its growing role in addressing intermittency and enhancing operational resilience in renewable-powered dewatering systems.

Overall, the temporal analysis indicates a clear evolution from problem-driven, site-specific dewatering studies toward more holistic, systems-oriented research paradigms. While foundational hydrogeological concerns remain relevant, recent literature increasingly frames dewatering within the broader context of the energy transition, with an emphasis on optimization, integration, and long-term sustainability rather than on isolated operational performance.

Although the temporal overlay highlights how research themes have evolved chronologically, it does not explicitly indicate which topics currently constitute the core research hotspots or where critical knowledge gaps persist. To address this limitation, the following subsection synthesizes patterns of thematic density to identify dominant research concentrations and underexplored areas warranting further investigation.

3.5 Research Hotspots and Knowledge Gaps

This subsection identifies dominant research hotspots and critical knowledge gaps in the literature on

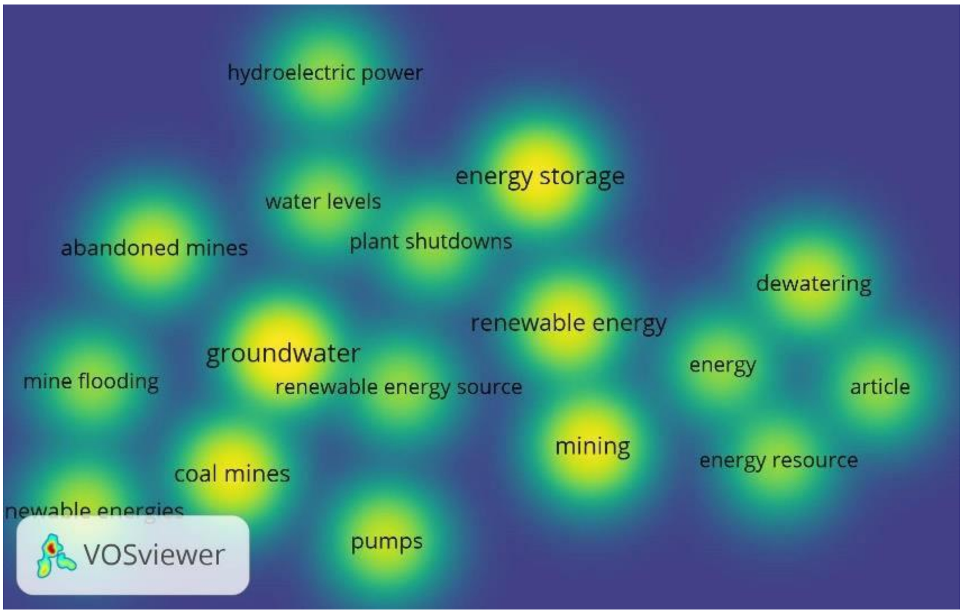

Figure 9. Density visualization of keyword co-occurrence highlighting research hotspots and knowledge gaps in renewable energy–based dewatering systems.

Table 3. Quantitative ranking of dominant author keywords based on occurrence and network strength.

Author Keyword	Occ.	TLS	N-Occ	N-TLS	OSa	Cluster
Energy Storage	9	13	1	1	1	4
Renewable Energy	5	11	0.556	0.846	0.7	2
Mining	2	8	0.222	0.615	0.42	2
Mine Water	3	6	0.333	0.462	0.4	1
Hydropower	2	7	0.222	0.538	0.38	3
Numerical Modelling	2	7	0.222	0.538	0.38	3
Abandoned Mines	3	5	0.333	0.385	0.36	1
Heat Pump	2	6	0.222	0.462	0.34	1
Groundwater	2	5	0.222	0.385	0.3	3
Renewable Energy Sources	3	3	0.333	0.231	0.28	4
Dewatering	2	3	0.222	0.231	0.23	2
Geothermal Energy	2	3	0.222	0.231	0.23	1
Simulation	2	1	0.222	0.077	0.15	1
Mine Drainage	2	0	0.222	0	0.11	5

Note: Occ = Occurrence; TLS = total link strength; N-Occ/TLS = normalized values (max = 1.000); OSa = composite index calculated from normalized occurrence (N-Occ) and normalized total link strength (N-TLS).

renewable energy–based dewatering systems by examining patterns of thematic density. The density visualization highlights areas of high research concentration, as well as topics that remain underexplored or fragmented.

Figure 9 presents the density visualization of keyword co-occurrence, where higher color intensity indicates research hotspots. Core themes such as groundwater, mining, renewable energy, energy storage, and dewatering emerge as dominant research areas, reflecting sustained scholarly attention to hydrogeological challenges and the integration of renewable energy technologies in mining operations. These hotspots indicate a well-established technical foundation focused on improving operational efficiency and reducing environmental impacts.

Table 3 summarizes the distribution and relative importance of author keywords within the selected bibliometric dataset, based on their occurrence frequency (Occ.) and total link strength (TLS). The occurrence value reflects how frequently a keyword appears across the dataset, while TLS indicates the strength of its co-occurrence relationships within the keyword network. The normalized indicators (N-Occ and N-TLS) are aggregated into a composite overall score (OS_a) to represent the relative prominence and connectivity of each keyword within the research landscape. It is important to note that this keyword-level analysis differs from study-level performance evaluation, which uses indicators such as N_Pub, N_Cit, and TLS, as described in Section 2.5. Higher OS values indicate

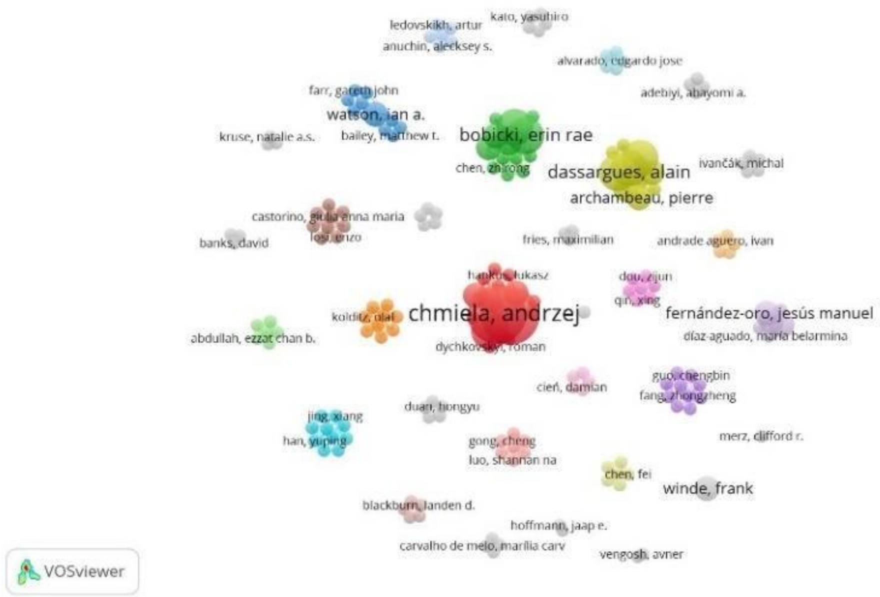

Figure 10. An author co-authorship network highlighting influential researchers and collaboration clusters.

keywords that are both frequently studied and strongly connected within the thematic network.

However, several important knowledge gaps remain evident. Keywords related to system-level optimization, real-time control, economic performance indicators, and long-term field validation appear less prominent and weakly connected. This suggests that existing studies are largely conceptual or simulation-based, with limited emphasis on comprehensive quantitative evaluation and practical deployment. Addressing these gaps is essential to advance renewable energy–based dewatering systems from feasibility-oriented research toward scalable, data-driven, and economically optimized solutions applicable across diverse mining contexts.

While the hotspot and gap analyses highlight thematic concentration and underexplored areas, a comprehensive understanding of knowledge development also requires examining the actors and institutional structures that drive these research activities. Accordingly, the following subsection analyses collaboration patterns at the author, organizational, and country levels to reveal how research capacity and influence are distributed across the scientific community.

3.6 Author, Organization, and Country Collaboration Analysis

This subsection examines collaboration structures at multiple analytical levels, encompassing individual authors, research organizations, and countries. By progressively moving from micro-level author networks to meso-level institutional linkages and macro-level international collaborations, the analysis provides a comprehensive view of how knowledge production and dissemination are shaped within renewable energy–based mine dewatering research.

Figure 10 presents the author-level co-authorship network, revealing a highly centralized collaboration structure dominated by a small number of prolific researchers. Several authors emerge as key hubs with high total link strength, forming dense intra-cluster collaborations, while most contributors are positioned in small, weakly connected groups. This pattern suggests that knowledge production in the field is concentrated within a few influential research teams, with relatively limited cross-cluster interaction. Such structural concentration may constrain the diffusion of novel ideas and interdisciplinary approaches across the broader research community.

Figure 11 shows the organizational co-authorship network, highlighting a pronounced centralization around a small number of dominant institutions. These organizations function as primary knowledge hubs, maintaining strong internal collaboration intensity while exhibiting relatively sparse inter-institutional connections. The observed structure indicates that research activities are largely shaped by institutional silos, where collaboration remains localized rather than globally interconnected, potentially limiting the scalability and transferability of research outcomes.

Building on individual-level collaboration patterns, the analysis is extended to the organizational level to examine how institutional affiliations structure research partnerships. Table 4 presents the top five organizations with the highest overall score (OS) in the analyzed

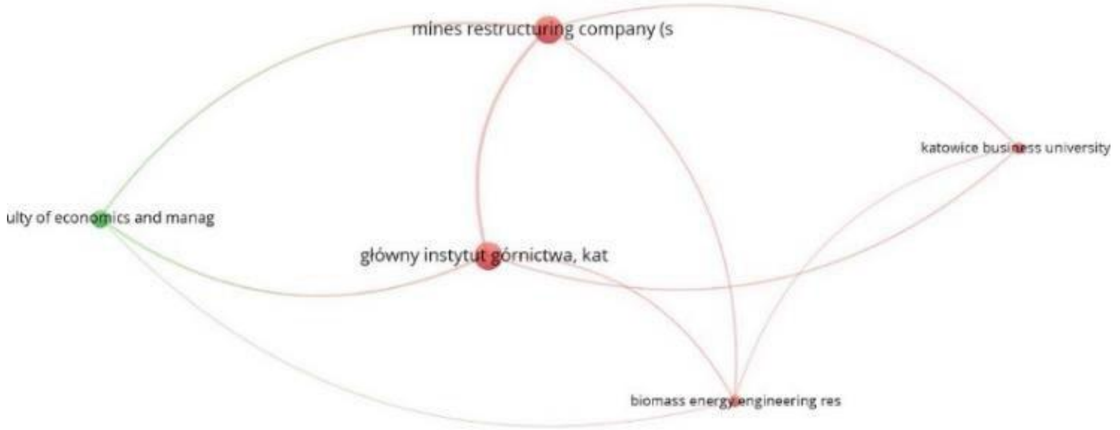

Figure 11. Organizational collaboration network showing dominant institutions and inter-institutional linkages.

Table 4. Leading organizations by composite bibliometric performance (overall score).

Organization	Pub	Cit.	TLS	N-Pub	N-Cit	N-TLS	OS	Cluster
Glowny Instytut Gornictwa	5	19	12	1	0.19	1	0.73	1
Mines Restructuring Company	5	19	12	1	0.19	1	0.73	1
The Coal Authority, Mansfield, Nottinghamshire	2	100	0	0.4	1	0	0.467	5
Faculty of Economics and Management, Opole University of Technology	3	19	7	0.6	0.19	0.583	0.458	1
Hydraulics in Environmental and Civil Engineering (HECE), Université de Liège	2	70	3	0.4	0.7	0.25	0.45	2

Note: Pub = publications; Cit = citations; TLS = total link strength; N-Pub/Cit/TLS = normalized values (max = 1.000); OS = Overall Score (composite index).

Figure 12. Country-level co-authorship collaboration overlay showing international research linkages over time.

bibliometric dataset. The ranking integrates publication output (Pub), citation impact (Cit.), total link strength (TLS), and their normalized counterparts to reflect both academic productivity and collaborative embeddedness within the research network. The results indicate that institutions with similar publication volumes may exhibit substantially different collaboration intensities and citation profiles, highlighting diverse institutional roles in shaping research on renewable energy–based mine dewatering.

Figure 12 illustrates the country-level collaboration network based on international co-authorship relations. The network reveals an uneven distribution of research collaborations, with a limited number of countries serving as central nodes in the global research landscape. Although cross-national links are present, they tend to be bilateral and concentrated among established research economies. This selective collaboration pattern suggests that broader international engagement—particularly with underrepresented regions—remains an opportunity to enhance contextual diversity and global knowledge exchange.

Overall, the collaboration analysis demonstrates that, while the research field benefits from concentrated expertise and institutional continuity, it remains structurally fragmented across authors, organizations, and countries. This fragmentation limits the formation of robust multilateral collaboration networks, potentially constraining knowledge diffusion and interdisciplinary integration. Expanding cross-cluster and cross-regional collaboration is therefore critical to enhancing innovation capacity and addressing complex system-level challenges that transcend national and institutional boundaries.

Building upon the identified structural patterns of collaboration, the analysis now transitions from relational network dynamics to quantitative performance evaluation. The following subsection examines measurable performance indicators in renewable energy–based dewatering systems, focusing on metrics related to technological effectiveness, operational efficiency, and system-level feasibility reported in the literature.

Table 5. Annual temporal performance of renewable energy–based mine dewatering research (2015–2025).

Year	Pub.	Cit.	N-Pub	N-Cit	OSt
2025	7	14	0.7	0.074	0.387
2024	10	145	1	0.771	0.886
2023	4	29	0.4	0.154	0.277
2022	5	55	0.5	0.293	0.396
2021	0	0	0	0	0
2020	7	188	0.7	1	0.85
2019	1	12	0.1	0.064	0.082
2018	2	45	0.2	0.239	0.22
2017	3	100	0.3	0.532	0.416
2016	3	151	0.3	0.803	0.552
2015	1	2	0.1	0.011	0.055

Note: Pub = publications; Cit = citations; N-Pub and N-Cit = normalised values (max = 1.000); OS_t = temporal composite index calculated from N-Pub and N-Cit

3.7 Quantitative Performance Trends in Renewable Energy-Based Dewatering Systems

To complement the structural and thematic analyses presented in the preceding subsections, this subsection examines quantitative performance trends across publication years. By integrating normalized bibliometric indicators, the analysis aims to identify periods of heightened scholarly impact and assess how research productivity and influence have evolved within renewable energy–based mine dewatering studies.

Table 5 summarizes the annual quantitative performance of the research field using two key indicators: the number of publications (Pub) and total citations (Cit), as well as a temporal composite score (OS_t). Normalized publication (N-Pub) and citation (N-Cit) values were calculated using min–max normalization to ensure comparability across years. The temporal composite score (OS_t) is a combined index of research productivity and citation impact over time, excluding network-based indicators, which are not interpretable at the annual level.

The results reveal distinct temporal patterns in research performance. The OS_t values provide a normalized representation of temporal research performance, enabling consistent comparison across years despite variations in publication volume and citation accumulation. The zero-value observation in 2021 is attributed to data retrieval constraints related to database indexing and keyword filtering, rather than a true absence of research activity. Such anomalies are not uncommon in bibliometric analyses and are therefore treated as methodological artifacts that do not alter the interpretation of the overall trend.

Although recent years, such as 2024 and 2025, exhibit higher publication counts, peak overall performance is observed in years with disproportionately high citation intensity relative to publication volume, particularly 2020. This indicates that scholarly impact in this domain is not solely driven by output quantity but is strongly influenced by high-impact contributions that shape subsequent research directions. Conversely, years with moderate publication activity but low citation uptake demonstrate limited influence, underscoring the uneven maturation of research themes over time.

Overall, the quantitative trends suggest a transition from sporadic, impact-driven contributions toward more sustained and diversified research output in recent years. However, the variability in OS_t across time highlights the need for future studies to balance publication growth with substantive innovation and empirical validation.

Taken together, the findings presented in Sections 3.1–3.7 provide structured and evidence-based responses to the research questions. Specifically, the bibliometric and network analyses address RQ1 by revealing the field's dominant research structures, collaboration patterns, and thematic evolution. Meanwhile, the gap synthesis presented in Section 3.8 addresses RQ2–RQ4 by identifying critical methodological and contextual limitations and outlining key directions for future research.

3.8 Research Gaps and Implications for Future Studies

While Table 6 provides consolidated evidence of measurable improvements in energy efficiency, emission reduction, and renewable integration across renewable-based mine dewatering studies, a critical examination reveals substantial limitations in methodological consistency, contextual representativeness, and operational realism.

First, the reported efficiency gains are difficult to compare across studies due to heterogeneous baselines and system boundaries. Some studies benchmark against diesel-only systems or grid-assisted configurations, while others assess subsystem-level

Table 6. Quantitative efficiency impacts of renewable energy–based mine dewatering studies.

Category	Dominant Objective	Typical Method	Quantified Impact Range	Key Limitation Identified	Ref.
Hybrid & pumping optimization (mining context)	Energy and OPEX reduction in dewatering operations	Robust/hybrid optimization, pump modernization, operational optimization	12–25% reduction in energy use and drainage OPEX	Deterministic inflow assumptions; subsystem-level evaluation; limited long-term validation	[2, 37, 40, 41]
Energy system integration	Storage sizing, system stability, load management	Hybrid optimization, system dynamics, load management	Improved storage efficiency and peak load reduction	Static sizing bias; limited real-time dispatch integration	[6, 43, 45]
Power electronics efficiency	Component-level energy loss reduction	Power electronics design optimization	5–8% switching loss reduction	Component-level boundary; not integrated with the full dewatering system	[42]
Geothermal & thermal recovery	Heat extraction and low-grade heat utilization	Thermal modelling, energy potential analysis	Increased heat extraction/utilization efficiency	Weak integration with active mine pumping systems	[55, 65]
Water management & carbon impact	Freshwater reduction and carbon footprint mitigation	Feasibility analysis, carbon footprint analysis	20–40% carbon reduction; freshwater demand reduction	Limited coupling with dynamic energy dispatch modelling	[10, 58]
Environmental & energy recovery extensions	Land-use efficiency and renewable generation potential	Environmental assessment, energy conversion analysis	Improved environmental performance; renewable potential increase	Fragmented linkage between environmental metrics and operational energy optimization	[48, 56, 57]

performance (e.g., pump efficiency or switching losses) without evaluating full dewatering system dynamics. Consequently, percentage reductions in energy use or OPEX are not directly transferable across cases. The absence of standardized evaluation metrics—such as harmonized levelized cost of energy (LCOE), reliability indices, and carbon accounting boundaries—limits cross-study comparability and meta-analytical synthesis. This limitation is clearly reflected in Table 6, where reported performance improvements are drawn from studies that employ inconsistent system boundaries and evaluation baselines.

Second, the literature is methodologically dominated by static sizing optimization and deterministic modeling approaches. Although hybrid optimization and system dynamics methods are occasionally employed, hydrological variability—particularly uncertainty in stochastic rainfall and groundwater inflow—remains insufficiently addressed. Most models assume deterministic inflow patterns, which may overestimate the stability of performance under extreme climatic conditions. Furthermore, dispatch strategies are often simplified and lack dynamic, real-time operational control architectures that integrate monitoring, prediction, and adaptive energy management. As shown in Table 6, most studies rely on deterministic assumptions and static optimization approaches, highlighting the lack of stochastic hydrological integration and dynamic dispatch modeling.

Third, validation depth remains limited. A substantial proportion of studies rely on simulation-based feasibility analyses without long-term field validation or incorporating operational constraints such as pump duty cycling, maintenance downtime, diesel logistics variability, and curtailment scenarios. This gap reduces confidence in large-scale deployment and system replicability. This limitation is further evidenced in Table 6, where most studies report simulation-based results with limited field validation or consideration of real operational constraints.

From a contextual perspective, the literature exhibits significant geographic and operational heterogeneity. Studies are often site-specific, with limited discussion of scalability across multi-pit operations or mines in high-rainfall environments (e.g., tropical environments). Additionally, research on active mine dewatering, energy recovery from flooded or abandoned mines, and water reuse systems remains fragmented rather than integrated into a unified water–energy framework.

These limitations underscore the need for a more integrated evaluation framework that standardizes performance boundaries across energy, cost, reliability, and environmental indicators and incorporates stochastic hydrological variability into system sizing and dispatch optimization. Such a framework should further integrate real-time operational control architectures with techno-economic modeling to enhance scalability and transferability across diverse, heterogeneous mining contexts.

Importantly, these gaps are not isolated but systematically interconnected, indicating that improvements in renewable-based mine dewatering systems require simultaneous advancement across modeling assumptions, system integration, and operational validation. It is also important to emphasize that the present study does not empirically model or simulate these dimensions. Rather, the following research questions emerge as structured implications derived from the systematic gap analysis conducted across the reviewed literature and are positioned as future-oriented research directions grounded in bibliometric synthesis.

Based on the recurring structural and methodological gaps identified, the following research questions are proposed:

- RQ1: How can renewable-based mine dewatering systems be evaluated using a standardized and comparable multidimensional performance framework integrating energy, cost, reliability, and environmental metrics?
- RQ2: How does stochastic hydrological variability influence optimal system sizing and dispatch strategies compared to deterministic assumptions?
- RQ3: What operational control architecture is required to sustain efficiency gains under real-world constraints in active mining environments?
- RQ4: How can renewable-powered mine dewatering systems be structured to enhance scalability and contextual transferability across diverse mine settings?

To further clarify how these methodological and contextual inconsistencies manifest across the reviewed studies, Table 6 reorganizes the literature into structured analytical categories, explicitly linking quantified performance impacts with their underlying methodological limitations. Rather than merely summarizing efficiency gains, Table 6 establishes a structured empirical foundation that connects performance outcomes to their methodological constraints, thereby enabling a systematic transition from descriptive evidence to gap-driven synthesis.

Table 6 identifies category-specific limitations across individual studies. These limitations consistently converge into broader structural gaps that affect the comparability, robustness, and scalability of renewable-based mine dewatering systems. To synthesize these patterns at a higher analytical level, Table 7 consolidates the identified limitations into cross-cutting research gap dimensions. Each dimension is linked to its methodological consequence and corresponding implication for future research, thereby providing a structured pathway from observed limitations to actionable research directions.

Collectively, these findings indicate that the field is transitioning from component-level optimization toward more integrated, system-oriented approaches. However, this transition remains incomplete, as many studies continue to rely on simplified assumptions and narrowly defined system boundaries, limiting their ability to capture real-world system dynamics. As a result, a unified framework that simultaneously addresses hydrological uncertainty, operational control, and techno-economic scalability remains insufficiently developed.

The gap synthesis presented in Table 7 highlights that existing limitations are structurally interconnected rather than independent. In particular, the widespread use of static sizing approaches and simplified dispatch strategies suggests that many reported efficiency gains may be systematically overestimated due to the limited representation of dynamic inflow variability and real-world operational constraints. This interconnected nature of gaps underscores the need for integrative modeling approaches that bridge hydrological variability, control strategy optimization, and system-level validation.

Moreover, contextual gaps, including the lack of site-specific case studies and the fragmented treatment of water–energy interactions, indicate that existing research often addresses isolated system components rather than the integrated dewatering–energy nexus. This fragmentation reduces scalability and limits the generalizability of findings across diverse mining environments, particularly in high-variability climates where hydrological uncertainty significantly influences system stability. The combined presence of methodological and contextual gaps suggests that future research should move beyond incremental efficiency improvements toward integrated, uncertainty-aware system frameworks. Such frameworks must simultaneously standardize performance boundaries, incorporate stochastic hydrological modeling, integrate real-time operational control, and ensure techno-economic scalability across heterogeneous mining contexts.

Table 7. Research gap synthesis derived from the literature review.

Gap Dimension	Identified Gap	Consequence	Implications for Future Research
Baseline Standardisation	Lack of consistent benchmarking approaches	Reduced comparability across studies	Develop a standardised evaluation framework
System Boundary Definition	Predominance of subsystem-level analysis	Risk of over- or underestimating system efficiency	Adopt integrated, system-wide boundary definitions
Hydrological Modelling	Reliance on deterministic inflow assumptions	Overestimation of system stability	Incorporate stochastic rainfall and inflow modelling
Dispatch Strategy	Use of static or simplified dispatch methods	Limited representation of real operational conditions	Develop dynamic, real-time energy management systems (EMS)
Validation Depth	Heavy reliance on simulation-based studies	Low confidence in real-world applicability	Conduct field-based validation and long-term monitoring
Scalability	Focus on site-specific case studies	Limited transferability of findings	Develop scalable, multi-site frameworks
Integration Gap	Fragmented treatment of water–energy interactions	Loss of potential system synergies	Develop unified water–energy optimization models

Therefore, the synthesis of evidence and identified gaps underscores the necessity of developing a comprehensive evaluation and optimization framework that bridges the water–energy interface under realistic operational conditions. This forms the conceptual foundation for the research direction proposed in the following sections.

3.9. Discussion

These findings are consistent with previous studies highlighting the increasing integration of renewable energy and storage systems in mining operations. However, unlike prior research that primarily focuses on component-level optimization, this study emphasizes the importance of system-level coordination and uncertainty-aware modeling.

The results of this bibliometric and synthesis study indicate an emerging shift in the analytical perspective of renewable-based mine dewatering research—from isolated efficiency improvements toward a more integrated consideration of hydrology, energy supply, and operational coordination. Rather than treating hybrid photovoltaic (PV)–diesel integration purely as a techno-economic enhancement, the reviewed literature increasingly frames dewatering as a rainfall-responsive energy system whose performance depends on the synchronization of uncertainty modeling, dispatch coordination, and system boundary definition. These interpretations are grounded in the quantitative, network-based, and gap-analysis results, which collectively provide a structured basis for the analytical conclusions. This broader framing reveals implications that extend beyond the quantitative results typically emphasized in prior research.

First, the synthesis reframes hybrid dewatering not merely as a fuel-reduction strategy but as a risk management instrument. Conventional evaluations often prioritize renewable fraction or cost reduction, implicitly assuming stable operating conditions. In rainfall-sensitive mining environments, operational risk is often driven more by hydrological variability than by energy inefficiency alone. The gap synthesis reveals that stochastic rainfall considerations are rarely embedded within existing evaluation frameworks, suggesting that resilience under extreme inflow scenarios remains a critical yet under-addressed performance dimension. In this context, diesel backup capacity should not be interpreted as a limitation of renewable penetration but as a strategic safeguard against low-probability, high-impact events. This reliability-oriented perspective challenges the prevailing optimization bias toward maximizing renewable penetration and instead emphasizes resilience-weighted sustainability.

Second, the reviewed literature suggests that the definition of the system boundary fundamentally shapes perceived performance outcomes. When dewatering is evaluated as a standalone energy load, excess renewable generation during dry periods may appear inefficient. However, when the analytical boundary is expanded to include auxiliary mining loads, monitoring systems, and broader operational energy demand, surplus PV generation emerges as a strategic resource. This expanded boundary perspective implies that renewable-based dewatering should be integrated within a comprehensive mine energy ecosystem rather than assessed in isolation. Such integration may enhance asset utilization, improve lifecycle economic returns, and strengthen the strategic case for renewable investment. This fragmentation in the definition of the system boundary is also reflected in the thematic clustering structure, where hydrogeological modeling and energy system optimization appear partially disconnected, indicating limited cross-domain integration.

Third, this study highlights the governance dimension embedded within hybrid energy deployment. While much of the existing literature focuses on component optimization and cost metrics, fewer studies address decision thresholds related to acceptable flooding risk, emission-reduction targets, or exposure to fuel price volatility. The synthesis further indicates that evaluation frameworks that link energy performance, cost efficiency, hydrological resilience, and operational adaptability remain conceptually underdeveloped—particularly regarding managerial risk tolerance and strategic priorities. Optimal system design, therefore, becomes context-dependent, reflecting institutional objectives rather than purely technical efficiency criteria.

Collectively, these insights suggest that renewable-based mine dewatering should be understood as a system-integration challenge under uncertainty rather than a straightforward technology substitution problem. The contribution of this study lies in systematically mapping the field's evolution and identifying the need for uncertainty-aware system coordination beyond component-level hybridization. By highlighting limitations in baseline comparability, hydrological modeling, dispatch responsiveness, and scalability, this study contributes to a more coherent, decision-oriented framework for evaluating sustainable dewatering strategies. These patterns are consistently observed across temporal performance trends, thematic clustering, and structured gap synthesis, reinforcing the need for integrated, uncertainty-aware evaluation frameworks.

This study is subject to several limitations. First, the analysis relies on bibliometric data and published literature, which may introduce bias toward highly cited studies and well-established research domains, thereby potentially underrepresenting emerging or less visible contributions. Second, the synthesis is based on secondary data and does not involve direct empirical modeling or field validation; therefore, the findings should be interpreted as structured insights rather than operational performance verification. Third, variations in data indexing, keyword selection, and database coverage may affect the dataset's completeness, particularly for recent publications.

Despite these limitations, the study provides a systematic and integrative perspective on the structural evolution and methodological gaps in renewable-based mine dewatering research, offering a robust foundation for future research and model development.

This study contributes to the literature by integrating bibliometric analysis with system-level gap synthesis, enabling a comprehensive understanding of both the structural evolution and methodological limitations of renewable-based mine dewatering research. Unlike prior studies that primarily focus on isolated technical improvements or component-level optimization, this work presents a unified analytical framework that connects collaboration patterns, thematic evolution, quantitative performance trends, and cross-cutting research gaps. This integrative perspective advances the field beyond descriptive analysis toward a more coherent, decision-oriented approach for evaluating sustainable, uncertainty-aware dewatering systems.

Looking forward, future research should explore the integration of this framework into real-time operational environments, particularly through adaptive dispatch mechanisms linked to rainfall forecasting and digital monitoring systems [66, 67]. The importance of structured energy auditing, performance benchmarking, and integrated energy management, demonstrated in small-scale industrial applications and ICT-based monitoring systems [68–70] suggests that similar performance-driven evaluation architectures could be embedded within mine dewatering operations. Multi-site validation across diverse rainfall regimes would further clarify the limits of transferability and boundary conditions.

In addition, advances in hybrid photovoltaic-thermal system optimisation and performance experimentation indicate the relevance of integrating component-level efficiency modelling with system-level dispatch coordination [71, 72]. Furthermore, incorporating carbon-pricing scenarios [73], modelling fuel supply volatility, and conducting long-term degradation analysis could expand the framework into a strategic planning tool for decarbonization pathways in mining operations [74]. Although much of the literature is situated within rainfall-sensitive mining contexts, the conceptual implications derived from this synthesis remain applicable to other industrial water management systems where energy reliability and hydrological uncertainty intersect.

4. Conclusions

This study examined the evolution, performance trends, and research gaps in renewable energy–based mine dewatering using an integrated bibliometric and synthesis framework. The field has shifted from site-specific hydrogeological studies toward hybrid energy integration and storage-focused optimization, with rapid growth after 2020 and increasing system-level impact. While reported energy savings (12–25%) and emission reductions (20–40%) demonstrate clear benefits, cross-study comparability is limited by inconsistent baselines, system boundaries, and reliance on deterministic models. Key limitations include static system sizing, limited operational realism, and insufficient long-term validation, which constrain scalability and transferability. To address these issues, this study proposes a framework combining bibliometric mapping, temporal analysis, and gap-driven synthesis to support transparent benchmarking and decision-making. Future work should focus on stochastic hydrological modeling, adaptive real-time energy management, field-based validation, multi-site analysis, and integrated water–energy modeling to enhance system resilience and scalability.

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References

1. Chmiela, A., Barszczowska, B., Fernandez, P. R., Lutyński, M., Liu, R., Zhang, L., Howaniec, N., Hankus, Ł., and Smoliński, A. (2025). Integrating Green Hydrogen Storage into Mine Water Pumping Stations in the Context of Energy Transition, *Scientific Reports*, Vol. 15, No. 1, 17624. doi:10.1038/s41598-025-02295-2.
2. Wang, D., Li, Y., Gong, C., Li, T., Wang, F., Luo, S., and Li, J. (2025). Distributionally Robust Hybrid Energy Management in Smart Mining Using Process-Coupled Primal-Dual Mirror Descent, *Scientific Reports*, Vol. 15, No. 1, 26121. doi:10.1038/s41598-025-11013-x.
3. Magdziarczyk, M., Chmiela, A., Su, W., and Smolinski, A. (2024). Green Transformation of Mining towards Energy Self-Sufficiency in a Circular Economy—A Case Study, *Energies*, Vol. 17, No. 15, 3771. doi:10.3390/en17153771.
4. Winde, F. (2023). Innovative Closure Concepts around the Water-Energy-Nexus in Mining--a Case Study from South Africa., *Mining Report*, Vol. 159, No. 4.
5. Winde, F. (2020). Turning Water Pollution Sources Into Assets: Exploring Innovative Options Of Using Abandoned Mines For Generating And Storing Renewable Energy, *Geography, Environment, Sustainability*, Vol. 13, No. 2, 6–16. doi:10.24057/2071-9388-2020-03.
6. Mohammadi, M. ahmad. (2025). A System Dynamics Simulating Model of Groundwater Level Changes and Its Impacts on Land Uplift, *Mining, Metallurgy & Exploration*, Vol. 42, No. 1, 83–98. doi:10.1007/s42461-024-01170-4.
7. Zago, M. M., Fries, M., and Ramires, J. E. F. (2020). Groundwater Infiltration in a Gold Mine–A Geoelectrical Investigation Model as an Aid to Dewatering Process Determination, *Journal of Applied Geophysics*, Vol. 172, 103909. doi:10.1016/j.jappgeo.2019.103909.
8. Pujades, E., Orban, P., Archambeau, P., Kitsikoudis, V., Erpicum, S., and Dassargues, A. (2020). Underground Pumped-Storage Hydropower (UPSH) at the Martelange Mine (Belgium): Interactions with Groundwater Flow, *Energies*, Vol. 13, No. 9, 2353. doi:10.3390/en13092353.
9. Kitsikoudis, V., Archambeau, P., Dewals, B., Pujades, E., Orban, P., Dassargues, A., Pirotton, M., and Erpicum, S. (2020). Underground Pumped-Storage Hydropower (UPSH) at the Martelange Mine (Belgium): Underground Reservoir Hydraulics, *Energies*, Vol. 13, No. 14, 3512. doi:10.3390/en13143512.
10. Menéndez, J., Ordónez, A., Fernández-Oro, J. M., Loredo, J., and Díaz-Aguado, M. B. (2020). Feasibility Analysis of Using Mine Water from Abandoned Coal Mines in Spain for Heating and Cooling of Buildings, *Renewable Energy*, Vol. 146, 1166–1176. doi:10.1016/j.renene.2019.07.054.
11. Werbinska-Wojciechowska, S., and Rogowski, R. (2025). Proactive Maintenance of Pump Systems Operating in the Mining Industry—A Systematic Review, *Sensors*, Vol. 25, No. 8, 2365. doi:10.3390/s25082365.
12. Pereira, G., Gonzalez, A., and Rios, R. (2020). Systematic Literature Review of Water-Energy Nexus: An Overview of the Field and Analysis of the Top 50 Influential Papers, *2020 IEEE Congreso Bienal de Argentina (ARGENCON)*, IEEE, 1–8. doi:10.1109/ARGENCON49523.2020.9505528.
13. García Vera, Y. E., Dufo-López, R., and Bernal-Agustín, J. L. (2019). Energy Management in Microgrids with Renewable Energy Sources: A Literature Review, *Applied Sciences*, Vol. 9, No. 18, 3854. doi:10.3390/app9183854.
14. Essallami, N., and Khouya, A. (2025). Sustainable Desalination and Renewable Energy Integration: A Bibliometric Analysis and Review, *2025 International Conference on Circuit, Systems and Communication (ICCSC)*, IEEE, 1–5. doi:10.1109/ICCSC66714.2025.11135028.
15. Emmanuel Chigozie Ani, Oladiran Kayode Olajiga, Zamathula Queen Sikhakane, and Tosin Michael Olatunde. (2024). Renewable Energy Integration for Water Supply: A Comparative Review of African and U.S. Initiatives, *Engineering Science & Technology Journal*, Vol. 5, No. 3, 1086–1096. doi:10.51594/estj.v5i3.972.
16. Zahoor, A., Mao, G., Jia, X., Xiao, X., and Chen, J. L. (2022). Global Research Progress on Mining Wastewater Treatment: A Bibliometric Analysis, *Environmental Science: Advances*, Vol. 1, No. 2, 92–109. doi:10.1039/D2VA00002D.
17. Li, Z., Sun, F., Jiang, W., Li, X., Jiang, J., Jin, F., Lu, J., and Yang, F. (2024). Bibliometric Analysis of Trends and Research Progress in Acid Mine Drainage Remediation from 1990 to 2023, *Water*, Vol. 16, No. 13, 1826. doi:10.3390/w16131826.
18. Ngerem, E. C., Sanusi, I. A., Dalu, T., and Suinyuy, T. N. (2026). Sustainable Acid Mine Drainage Wastewater Remediation: A Comprehensive Review and Bibliometric Analysis, *Environmental Science: Advances*, Vol. 5, No. 3, 681–710. doi:10.1039/D5VA00266D.
19. Dube, V., Phiri, Z., Kuvarega, A. T., Mamba, B. B., and de Kock, L.-A. (2024). Exploring Acid Mine Drainage Treatment through Adsorption: A Bibliometric Analysis, *Environmental Science and Pollution Research*, Vol. 31, No. 50, 59659–59680. doi:10.1007/s11356-024-35047-2.

20. Mogashane, T. M., Maree, J. P., Mokoena, L., and Tshilongo, J. (2025). Research Activities on Acid Mine Drainage Treatment in South Africa (1998–2025): Trends, Challenges, Bibliometric Analysis and Future Directions, *Water*, Vol. 17, No. 15, 2286. doi:10.3390/w17152286.

21. Zhang, M., Huang, C., Ni, J., and Yue, S. (2023). Global Trends and Future Prospects of Acid Mine Drainage Research, *Environmental Science and Pollution Research*, Vol. 30, No. 50, 109233–109249. doi:10.1007/s11356-023-30059-w.

22. Wibowo, Y. G., Safitri, H., Malik, I. B. I., Sudibyo, and Priyanto, S. (2022). Alternative Low-Cost Treatment for Real Acid Mine Drainage: Performance, Bioaccumulation, Translocation, Economic, Post-Harvest, and Bibliometric Analyses, *Sustainability*, Vol. 14, No. 22, 15404. doi:10.3390/su142215404.

23. Otunola, B. O., and Mhangara, P. (2024). Global Advancements in the Management and Treatment of Acid Mine Drainage, *Applied Water Science*, Vol. 14, No. 9, 204. doi:10.1007/s13201-024-02259-3.

24. Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., and Lim, W. M. (2021). How to Conduct a Bibliometric Analysis: An Overview and Guidelines, *Journal of Business Research*, Vol. 133, 285–296. doi:10.1016/j.jbusres.2021.04.070.

25. Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., McGuinness, L. A., Stewart, L. A., Thomas, J., Tricco, A. C., Welch, V. A., Whiting, P., and Moher, D. (2021). The PRISMA 2020 Statement: An Updated Guideline for Reporting Systematic Reviews, *BMJ*, n71. doi:10.1136/bmj.n71.

26. Suri, N. A., Festiyed, Azhar, M., Yerimadesi, Ahda, Y., and Heffi Alberida. (2025). Measuring What Matters: A Systematic Review and VOSviewer-Based Bibliometric Approach to Digital Literacy Assessment Instruments, Competency Dimensions and Challenges in Education, *Research in Learning Technology*, Vol. 33. doi:10.25304/rlt.v33.3413.

27. Passas, I. (2024). Bibliometric Analysis: The Main Steps, *Encyclopedia*, Vol. 4, No. 2, 1014–1025. doi:10.3390/encyclopedia4020065.

28. Gusenbauer, M., and Gauster, S. P. (2025). How to Search for Literature in Systematic Reviews and Meta-Analyses: A Comprehensive Step-by-Step Guide, *Technological Forecasting and Social Change*, Vol. 212, 123833. doi:10.1016/j.techfore.2024.123833.

29. Agency, I. R. E. (2023). *Renewable power generation costs in 2022*International Renewable Energy Agency (IRENA).

30. Come Zebra, E. I., van der Windt, H. J., Nhumaio, G., and Faaij, A. P. C. (2021). A Review of Hybrid Renewable Energy Systems in Mini-Grids for off-Grid Electrification in Developing Countries, *Renewable and Sustainable Energy Reviews*, Vol. 144, 111036. doi:10.1016/j.rser.2021.111036.

31. Kelemen, A., Szabó, Z. K., Bozóki, S., Szádoczki, Z., and Hartvig, Á. D. (2024). A Sensitivity Analysis of Composite Indicators: Min/Max Thresholds, *Environmental and Sustainability Indicators*, Vol. 23, 100453. doi:10.1016/j.indic.2024.100453.

32. Remizov, A., Memon, S. A., and Sadykova, S. (2025). A Novel Methodology for Identifying the Top 1% Scientists Using a Composite Performance Index, *Publications*, Vol. 13, No. 4, 55. doi:10.3390/publications13040055.

33. Riedemann, J., Reyes, E., Sarasiri, N., Pena, R., and Andrade, I. (2024). Renewable Source-Based Water Pumping Electrification in Mines: Current Technologies and Future Trends, *IEEE Electrification Magazine*, Vol. 12, No. 1, 38–44. doi:10.1109/MELE.2023.3348349.

34. O. Ikitde, U., A. Adebiyi, A., E. Davidson, I., and S. Akinyemi, A. (2023). Enhanced Electric Power Adaptability Using Hybrid Pumped-Hydro Technology with Wind and Photovoltaic Integration, *Energy Engineering*, Vol. 120, No. 9, 1939–1961. doi:10.32604/ee.2023.027574.

35. Mikita, M., Kolcun, M., Špes, M., Vojtek, M., and Ivančák, M. (2017). Impact of Electrical Power Load Time Management at Sizing and Cost of Hybrid Renewable Power System, *Polish Journal of Management Studies*, Vol. 15, No. 1, 154–162. doi:10.17512/pjms.2017.15.1.15.

36. Chmiela, A., Barszczowska, B., Krause, E., Kulawik, A., and Smolinski, A. (2025). Green Energy Production Using a Hydro-Generator in an Underground Mine Water Pumping Station – Case Study, *Journal of Sustainable Mining*, Vol. 24, No. 3, 450–460. doi:10.46873/2300-3960.1463.

37. Wang, M., Kang, J., Liu, W., Li, M., Su, J., Fang, Z., Li, X., Shang, L., Zhang, F., and Guo, C. (2024). Design and Study of Mine Silo Drainage Method Based on Fuzzy Control and Avoiding Peak Filling Valley Strategy, *Scientific Reports*, Vol. 14, No. 1, 9300. doi:10.1038/s41598-024-60228-x.

38. Ren, Y., Sun, K., Zhang, K., Han, Y., Zhang, H., Wang, M., Jing, X., Mo, J., Zou, W., and Xing, X. (2024). Optimization of the Capacity Configuration of an Abandoned Mine Pumped Storage/Wind/Photovoltaic Integrated System, *Applied Energy*, Vol. 374, 124089. doi:10.1016/j.apenergy.2024.124089.

39. Shimizu, Y., Sugihara, M., Fujinaga, K., Nakamura, K., and Kato, Y. (2024). Air-Lift Pumping System for Hybrid Mining of Rare-Earth Elements-Rich Mud and Polymetallic Nodules around Minamitorishima Island, *Journal of Marine Science and Engineering*, Vol. 12, No. 9, 1470. doi:10.3390/jmse12091470.

40. Chmiela, A., Wrona, P., Magdziarczyk, M., Liu, R., Zhang, L., and Smolinski, A. (2024). Hydrogen Storage and Combustion for Blackout Protection of Mine Water Pumping Stations, *Energies*, Vol. 17, No. 10, 2357. doi:10.3390/en17102357.

41. Magdziarczyk, M., Chmiela, A., Dychkovskyi, R., and Smoliński, A. (2024). The Cost Reduction Analysis of Green Hydrogen Production from Coal Mine Underground Water for Circular Economy, *Energies*, Vol. 17, No. 10, 2289. doi:10.3390/en17102289.

42. Zolotov, A. R., Ledovskikh, A. A., Zhukov, A. N., Zharkov, A. A., Kazemirova, Y. K., and Anuchin, A. S. (2024). Development and Implementation of Algorithms for an Intelligent IGBT Gate Driver Using a Low-Cost Microcontroller, *Applied Sciences*, Vol. 14, No. 10, 4247. doi:10.3390/app14104247.

43. Castorino, G. A. M., Dahlquist, E., Kyprianidis, K., Losi, E., Manservigi, L., Pinelli, M., Renuke, A., Spina, P. R., and Venturini, M. (2025). Optimization of Sizing and Operation of Pumped Hydro Storage Plants under Current and Future Economic Scenarios, *Journal of Energy Storage*, Vol. 119, 116130. doi:10.1016/j.est.2025.116130.

44. Menéndez, J., Fernández-Oro, J. M., Galdo, M., and Loredo, J. (2020). Transient Simulation of Underground Pumped Storage Hydropower Plants Operating in Pumping Mode, *Energies*, Vol. 13, No. 7, 1781. doi:10.3390/en13071781.

45. Machalek, D., Young, A., Blackburn, L., Rogers, P., and Powell, K. M. (2020). Mine Operations as a Smart Grid Resource: Leveraging Excess Process Storage Capacity to Better Enable Renewable Energy Sources, *Minerals Engineering*, Vol. 145, 106103. doi:10.1016/j.mineng.2019.106103.

46. Bodeux, S., Pujades, E., Orban, P., Brouyère, S., and Dassargues, A. (2017). Interactions between Groundwater and the Cavity of an Old Slate Mine Used as Lower Reservoir of an UPSH (Underground Pumped Storage Hydroelectricity): A Modelling Approach, *Engineering Geology*, Vol. 217, 71–80. doi:10.1016/j.enggeo.2016.12.007.

47. d'Obyrn, K., Kamiński, P., Cień, D., Jendrysik, S., and Prostański, D. (2024). Hydrogeological and Mining Considerations in the Design of a Pumping Station in a Shaft of a Closed Black Coal Mine, *Energies*, Vol. 17, No. 13, 3297. doi:10.3390/en17133297.

48. Magalhães, C. C. de C., Melo, M. C. de, Guiguer, N., and Paula, R. S. de. (2022). The Cauê Aquifer on the Eastern Limb of the Moeda Syncline: Characterization, Impacts, and Flow in the Western Iron Quadrangle (Quadrilátero Ferrífero), MG, Brazil,

Brazilian Journal of Geology, Vol. 52, No. 4. doi:10.1590/2317-4889202220220005.

49. Schulz, S., Walther, M., Michelsen, N., Rausch, R., Dirks, H., Al-Saud, M., Merz, R., Kolditz, O., and Schüth, C. (2017). Improving Large-Scale Groundwater Models by Considering Fossil Gradients, *Advances in Water Resources*, Vol. 103, 32–43. doi:10.1016/j.advwatres.2017.02.010.

50. Molaei, N., Forster, J., Shoaib, M., Wani, O., Khan, S., and Bobicki, E. (2022). Efficacy of Sustainable Polymers to Mitigate the Negative Effects of Anisotropic Clay Minerals in Flotation and Dewatering Operations, *Cleaner Engineering and Technology*, Vol. 8, 100470. doi:10.1016/j.clet.2022.100470.

51. Molaei, N., Chehreh Chelgani, S., and Bobicki, E. R. (2022). A Comparison Study between Bioflocculants and PAM for Dewatering of Ultrafine Phyllosilicate Clay Minerals, *Applied Clay Science*, Vol. 218, 106409. doi:10.1016/j.clay.2022.106409.

52. Merz, C. R. (2019). Physicochemical and Colligative Investigation of α (Shrimp Shell)- and β (Squid Pen)-Chitosan Membranes: Concentration-Gradient-Driven Water Flux and Ion Transport for Salinity Gradient Power and Separation Process Operations, *ACS Omega*, Vol. 4, No. 25, 21027–21040. doi:10.1021/acsomega.9b02357.

53. Agudosi, E. S., Salleh, M. A. M., Abdullah, E. C., Mubarak, N. M., Khalid, M., and Azni, A. A. (2018). Characterization of Crystallized Struvite on Wastewater Treatment Equipment: Prospects for Crystal Fertilizer Production, *Desalination and Water Treatment*, Vol. 113, 205–212. doi:10.5004/dwt.2018.22281.

54. Hoffmann, J. E., and Dall, E. P. (2018). Integrating Desalination with Concentrating Solar Thermal Power: A Namibian Case Study, *Renewable Energy*, Vol. 115, 423–432. doi:10.1016/j.renene.2017.08.060.

55. Farr, G., Sadasivam, S., Manju, Watson, I. A., Thomas, H. R., and Tucker, D. (2016). Low Enthalpy Heat Recovery Potential from Coal Mine Discharges in the South Wales Coalfield, *International Journal of Coal Geology*, Vol. 164, 92–103. doi:10.1016/j.coal.2016.05.008.

56. Bailey, M. T., Gandy, C. J., Watson, I. A., Wyatt, L. M., and Jarvis, A. P. (2016). Heat Recovery Potential of Mine Water Treatment Systems in Great Britain, *International Journal of Coal Geology*, Vol. 164, 77–84. doi:10.1016/j.coal.2016.03.007.

57. Burnside, N. M., Banks, D., and Boyce, A. J. (2016). Sustainability of Thermal Energy Production at the Flooded Mine Workings of the Former Caphouse Colliery, Yorkshire, United Kingdom, *International Journal of Coal Geology*, Vol. 164, 85–91. doi:10.1016/j.coal.2016.03.006.

58. Macy, T. R., Kruse, N. A., and Stuart, B. J. (2015). Carbon Footprint Analysis of Source Water for Hydraulic Fracturing: A Case Study of Mine Water Versus Freshwater, *Mine Water and the Environment*, Vol. 34, No. 1, 20–30. doi:10.1007/s10230-014-0291-7.

59. Zhang, Z.-A., Tang, M., Yang, J., Yang, Q.-Y., Dai, C.-C., and Chen, F. (2025). Highly Efficient Production of Prodigiosin from Corn Stover Hydrolysate in Serratia Marcescens Mutant RZ 21-6C Generated by Atmospheric and Room-temperature Plasma Mutagenesis, *Bioprocess and Biosystems Engineering*, Vol. 48, No. 5, 799–816. doi:10.1007/s00449-025-03144-2.

60. Williams, G. D. Z., and Vengosh, A. (2025). Quality of Wastewater from Lithium-Brine Mining, *Environmental Science & Technology Letters*, Vol. 12, No. 2, 151–157. doi:10.1021/acs.estlett.4c01124.

61. Duan, H., Ma, D., Zou, L., Xie, S., and Liu, Y. (2024). Co-Exploitation of Coal and Geothermal Energy through Water-Conducting Structures: Improving Extraction Efficiency of Geothermal Well, *Renewable Energy*, Vol. 228, 120666. doi:10.1016/j.renene.2024.120666.

62. Fontananova, E., Grosso, V., Pantuso, E., Donato, L., and Di Profio, G. (2023). Energy Duty in Direct Contact Membrane Distillation of Hypersaline Brines Operating at the Water-Energy Nexus, *Journal of Membrane Science*, Vol. 676, 121585. doi:10.1016/j.memsci.2023.121585.

63. Khan, S., Shoaib, M., Molaei, N., Wani, O. B., Chen, Z., Vuong, T. V, Roth, E. W., Fiddes, L. K., Kuzmenko, I., Master, E. R., and Bobicki, E. R. (2023). Cellulose Nanocrystals' Role in Critical Mineral Beneficiation: Dual Aggregate-Dispersant Behavior Supports Environmentally Benign Nickel Processing, *ACS Sustainable Chemistry & Engineering*, Vol. 11, No. 4, 1294–1304. doi:10.1021/acssuschemeng.2c05923.

64. Alvarado, E. J., Raymond, J., Therrien, R., Comeau, F.-A., and Carreau, M. (2022). Geothermal Energy Potential of Active Northern Underground Mines: Designing a System Relying on Mine Water, *Mine Water and the Environment*, Vol. 41, No. 4, 1055–1081. doi:10.1007/s10230-022-00900-8.

65. Zhang, J., Liu, Y., Qin, X., Dou, Z., Meng, Q., Xu, X., and Lv, J. (2022). Optimization Design and Drag Reduction Characteristics of Bionic Borehole Heat Exchanger, *Frontiers in Energy Research*, Vol. 10. doi:10.3389/fenrg.2022.1024623.

66. Wang, Z., Li, Y., Wu, F., Shi, L., Ding, R., and He, S. (2026). Real-Time Dispatch of Cascade Hydropower-Photovoltaic Complementary System with Hybrid Pumped-Storage Based on Wasserstein Distributionally Robust Optimization, *Renewable Energy*, Vol. 257, 124801. doi:10.1016/j.renene.2025.124801.

67. Zhao, Y., Shi, J., Wang, D., Jiang, H., and Zhang, X. (2025). An Adaptive Load Forecasting Model in Microgrids: A Cloud-Edge Orchestrated Approach Tailored for Accuracy, Real-Time Response, and Privacy Needs, *International Journal of Electrical Power & Energy Systems*, Vol. 165, 110490. doi:10.1016/j.ijepes.2025.110490.

68. Yandri, E., Suherman, S., Lomi, A., Setyobudi, R. H., Ariati, R., Pramudito, P., Ronald, R., Ardiani, Y., Burlakovs, J., Zahoor, M., Shah, L. A., Fauzi, A., Tonda, R., and Iswahyudi, I. (2024). Sustainable Energy Efficiency in Aluminium Parts Industries Utilizing Waste Heat and Equivalent Volume with Energy Management Control System, *Proceedings of the Estonian Academy of Sciences*, Vol. 73, No. 1, 29–42. doi:10.3176/proc.2024.1.04.

69. Rao, C. K., Sahoo, S. K., and Yanine, F. F. (2026). A Review of IoT Enabled Intelligent Smart Energy Management for Photovoltaic Power Forecasting and Generation, *Unconventional Resources*, Vol. 9, 100279. doi:10.1016/j.uncres.2025.100279.

70. Shepovalova, O. V., Belenov, A. T., and Chirkov, S. V. (2020). Review of Photovoltaic Water Pumping System Research, *Energy Reports*, Vol. 6, 306–324. doi:10.1016/j.egyr.2020.08.053.

71. Barbu, M., Siroux, M., and Darie, G. (2023). Performance Analysis and Comparison of an Experimental Hybrid PV, PVT and Solar Thermal System Installed in a Preschool in Bucharest, Romania, *Energies*, Vol. 16, No. 14, 5321. doi:10.3390/en16145321.

72. Yandri, E. (2019). Development and Experiment on the Performance of Polymeric Hybrid Photovoltaic Thermal (PVT) Collector with Halogen Solar Simulator, *Solar Energy Materials and Solar Cells*, Vol. 201, 110066. doi:10.1016/j.solmat.2019.110066.

73. Tokac, B., Zhang, Q., and Sari, Y. A. (2025). Environmental and Economic Comparison of Diesel and Electric Trucks in Open-Pit Mining Operations, *Journal of Cleaner Production*, Vol. 507, 145540. doi:10.1016/j.jclepro.2025.145540.

74. Ellabban, O., and Alassi, A. (2021). Optimal Hybrid Microgrid Sizing Framework for the Mining Industry with Three Case Studies from Australia, *IET Renewable Power Generation*, Vol. 15, No. 2, 409–423. doi:10.1049/rpg2.12038.