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Mapping mining-area biodiversity research and its educational relevance: A bibliometric analysis of selected Asian countries over a decade

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ABSTRACT

This study maps publication growth, disciplinary foundations, geographic contributions, keyword structures, and thematic trajectories in selected Asian countries during 2015–2025. A Scopus query was filtered to English final-stage journal articles associated with the selected Asian countries included in the search strategy (n=118). We conducted performance analysis and science mapping using VOSviewer (network, overlay, density) and bibliometrics (thematic map, trend topics). Publications were sparse until 2018, consolidated in 2019–2021, and accelerated after 2022, peaking in 2025. The field is led by Environmental Sciences (32.5%) and Agricultural /Biological Sciences (14.9%), with Social Sciences (12.9%) providing a growing bridge. Output is highly concentrated in China, followed by Indonesia and India. Core keywords centre on mining, water quality, contamination, heavy metals, ecosystems, and sustainability, while recent work emphasizes land use, soil, environmental monitoring, remote sensing, machine learning, and risk assessment. The findings demonstrate that the retrieved literature is predominantly environmental rather than education-led. Education-related constructs, pedagogical approaches, and learning outcomes are not prominent within the keyword structure. Accordingly, the educational dimension should be interpreted as an underdeveloped research opportunity rather than an established characteristic of the field. Future studies should explicitly integrate pedagogical frameworks and measurable learning outcomes with ecological monitoring in mining-affected contexts.

INTRODUCTION

Mining has become one of the most visible drivers of land-use change across Asia over the last decade. Alongside its economic benefits, the expansion of extractive activities has intensified ecological pressures—habitat loss, fragmentation, soil and water contamination, invasive species spread, and altered ecological functions—often in biodiversity-rich landscapes (Kemp et al., 2026; Lee et al., 2025). In many regions, mining areas are not isolated industrial enclaves; they sit close to schools, universities, and communities that directly experience both the environmental costs and the socio-economic dependencies of extraction (Antoci et al., 2019; Gräser, 2025; Maier et al., 2014). This proximity makes mining landscapes a distinctive setting for biodiversity research and a context with potential relevance for environmental and science learning: real-world problems, contested values, and measurable ecological outcomes provide concrete entry points for environmental education, field-based science instruction, citizen science, and community-engaged pedagogies (Amos, 2025; Sonter et al., 2018; Tupala et al., 2022; Young et al., 2022). Yet, the extent to which scholarship has meaningfully connected biodiversity in mining areas with educational practices in Asia remains unclear—particularly when viewed systematically over time. However, such educational possibilities should not be assumed to constitute a dominant feature of the literature. Their actual visibility must be examined through the occurrence of education-related concepts, pedagogical approaches, and learning outcomes in the retrieved publications.

Research on biodiversity in mining areas has grown substantially, with studies documenting ecological impacts, rehabilitation outcomes, and post-mining restoration strategies across taxa and ecosystems (Fois et al., 2025; Gao et al., 2024; Torres et al., 2024). A parallel body of work in environmental and science education has examined place-based learning, outdoor education, education for sustainable development, and socio-scientific issues (SSI) as approaches to strengthen ecological literacy and civic engagement (Genisa & Angraini, 2023; Hu & Mou, 2025). However, these two streams often develop in partial isolation. Biodiversity studies in mining contexts frequently prioritise ecological indicators and reclamation performance, while education studies tend to focus on schools, curricula, and learning outcomes without sustained engagement with the ecological complexities of extractive landscapes (Buckton et al., 2023; Corazza, 2024). Where links do appear, they are scattered across disciplines and expressed through varied terms—restoration ecology, reclaimed land, mine rehabilitation, fieldwork pedagogy, geoscience education, community outreach, and indigenous or local knowledge—making it difficult to see the overall structure of the field. Consequently, key questions remain unanswered: Has research integrating mining-area biodiversity and education actually accelerated in Asia? Which disciplines anchor the conversation? Which countries shape the research agenda? What concepts dominate keyword networks, and how have they shifted? And which emerging themes are beginning to define the next wave of scholarship?

To address these gaps, this review investigates the intellectual landscape of mining-area biodiversity research with potential educational relevance in selected Asian countries through a decade-long bibliometric analysis. Specifically, the study asks: how publication output has evolved over time and what the growth rate looks like; which subject areas serve as the most common entry points for this topic; which Asian countries lead publication contributions; how keywords are distributed and connected—interpreted through network, overlay, and density visualizations—to reveal conceptual emphases and research clusters; how thematic evolution unfolds across the decade, indicating continuity and shifts in core themes; and what topics are currently trending, signalling emerging priorities and potential future directions. In addition, the study evaluates whether education-related constructs, pedagogical approaches, and learning outcomes are explicitly visible within the bibliometric structure. This distinction is important because the inclusion of education-related search terms does not necessarily demonstrate that education constitutes a dominant intellectual component of the retrieved literature.

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This article contributes in four ways. First, it provides a structured map of research on mining-area biodiversity represented predominantly by ecology, environmental management, geosciences, and related environmental disciplines. This article contributes in four ways. First, it offers a structured map of a cross-disciplinary domain that is frequently fragmented across ecology, environmental management, geosciences, and education research, making the field easier to navigate for both biodiversity scientists and education scholars. Second, by focusing on the selected Asian countries represented by the search strategy, it highlights regional patterns that may be obscured in global reviews—such as country-level leadership, research concentration, and topic trajectories shaped by local mining contexts and educational priorities. Third, the combined use of keyword network patterns, thematic evolution, and trending-topic detection provides a multi-layered understanding: not only what has been studied, but how the conversation has reorganized over time and where it appears to be heading. Finally, the study critically examines the limited visibility of educational terminology in the bibliometric results. Rather than treating mining landscapes as established educational laboratories, the study identifies the explicit integration of pedagogical theories, learning activities, and educational outcomes as a gap requiring further empirical investigation.

METHODS

Research framework

This study applies a bibliometric analysis framework to map and interpret the research landscape linking biodiversity in mining areas and its potential educational relevance in selected Asian countries over the last decade. The framework starts with building a curated publication dataset using a transparent search query, a defined time window, and clear eligibility rules (e.g., relevance to mining-area biodiversity, explicit educational connection, and Asian focus), followed by deduplication and basic data cleaning to standardize author names, affiliations, countries, and keywords. The analysis then proceeds in two complementary layers. First, a performance analysis quantifies the field's development through annual publication trends and growth rates (RQ1), the distribution of subject areas (RQ2), and country-level contributions (RQ3). Second, a science-mapping analysis explores the conceptual structure and dynamics of the literature by examining keyword co-occurrence patterns through network, overlay, and density visualizations (RQ4), tracking thematic evolution across defined time slices to reveal how core themes emerge, persist, or decline (RQ5), and identifying trending topics that signal current research directions (RQ6). Together, these steps provide an evidence-based, reproducible map of productivity, disciplinary anchors, geographic leadership, and thematic trajectories, enabling a coherent synthesis of how this interdisciplinary topic has formed and where it is heading. A further interpretive component evaluates the extent to which education-related constructs, pedagogical approaches, and learning outcomes appear explicitly in the bibliometric results. This analysis prevents the presence of the words "education" or "learning" in the search strategy from being interpreted automatically as evidence of a coherent education-focused research domain.

Research Question (RQ)

To achieve the study objectives, the following research questions were formulated: RQ1. How did the annual publication output of mining-area biodiversity research represented in the dataset develop during 2015–2025? RQ2. Which subject areas constitute the principal disciplinary foundations of the retrieved literature? RQ3. How are publication contributions distributed across the countries represented in the dataset? RQ4. What conceptual structures are revealed by the network, overlay, and density visualizations of keyword co-occurrence? RQ5. What themes occupy motor, basic, niche, and emerging or declining positions in the thematic map? RQ6. Which topics show the strongest recent prominence within the study period? RQ7. To what extent are

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educational constructs, pedagogical approaches, and learning outcomes explicitly represented in the keyword networks and thematic structures?

Search article, inclusion criteria, and analysis

The bibliometric dataset was retrieved from the Scopus database because of its broad coverage of peer-reviewed publications and its rich metadata for mapping scientific trends. The search was performed across all fields using the core string biodiversity AND "mining area" AND learning, then refined using Scopus filters to match the scope of this study. The applied query was: (ALL (biodiversity AND "MINING AREA" AND learning) AND PUBYEAR > 2014 AND PUBYEAR < 2026) AND (education) AND (mining) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (PUBSTAGE, "final")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (AFFILCOUNTRY, "China") OR LIMIT-TO (AFFILCOUNTRY, "Indonesia") OR LIMIT-TO (AFFILCOUNTRY, "India") OR LIMIT-TO (AFFILCOUNTRY, "Malaysia")). Because the affiliation-country filter was limited to China, Indonesia, India, and Malaysia, the dataset should not be interpreted as representing the entire Asian continent. The study therefore refers to selected Asian countries when describing its geographic scope. Other country names may appear in the country analysis because publications can include international co-authors with affiliations outside the four countries used as entry filters. The initial search returned 1,403 records. Screening and eligibility checks were then conducted stepwise following the logic shown in the PRISMA flow diagram. First, non-article document types were removed (e.g., conference papers/reviews, book chapters, reviews, editorials, notes, and data papers), excluding 370 records and leaving 1,033 original articles. Second, "article in press" items were excluded (20 records), leaving 1,013 final-stage articles. Third, non-English items were excluded (32 records), resulting in 981 English articles. Fourth, education-related relevance screening was applied, retaining only papers that met the education criterion (operationalized as containing the term education), leaving 193 records and excluding 788. Finally, the dataset was restricted according to the predefined time window and selected affiliation-country criteria, yielding 118 included articles. Accordingly, the final corpus represents literature retrieved through the specified search configuration rather than a comprehensive census of all mining-area biodiversity publications from Asia.

To ensure consistency and reproducibility, the following inclusion criteria were applied: (1) Topical scope: The article addresses biodiversity in relation to mining areas (including mining landscapes, reclamation sites, post-mining environments, or extractive zones) and contains a clear link to learning/education (formal, non-formal, community-based learning, field-based instruction, environmental education, science education, ESD, citizen science, or similar). (2) Time window: Published within the last decade (2015–2025), aligned with the PUBYEAR limits in the query. (3) Document type: Peer-reviewed journal articles only (DOCTYPE = "ar"), to maintain comparability of scholarly standards and metadata completeness. (4) Publication stage: Final publications only (PUBSTAGE = "final"), excluding articles in press to avoid unstable metadata and citation information. (5) Language: English only, to ensure consistent interpretation and keyword standardization. (6) Geographic focus: Articles were included when the study context and/or author affiliation-country filter aligned with Asia; records not meeting the Asian focus were excluded at the eligibility stage (as reflected in the PRISMA step that removed non-Asian outputs; see Figure 1). Exclusion criteria mirrored the above: non-article outputs, non-final publications, non-English papers, studies unrelated to education/learning, and papers not aligned with the Asian focus and the defined time window.

Before science mapping, author and indexed keywords were reviewed to remove terms that did not represent substantive research concepts. Geographic names, including country names such as "China" and "India," were excluded from thematic interpretation because they describe study location or affiliation rather than conceptual content. Singular and plural forms were merged, spelling variants were standardized, and obvious synonyms were consolidated using a thesaurus file. Generic database terms and non-substantive indexing labels were also removed.

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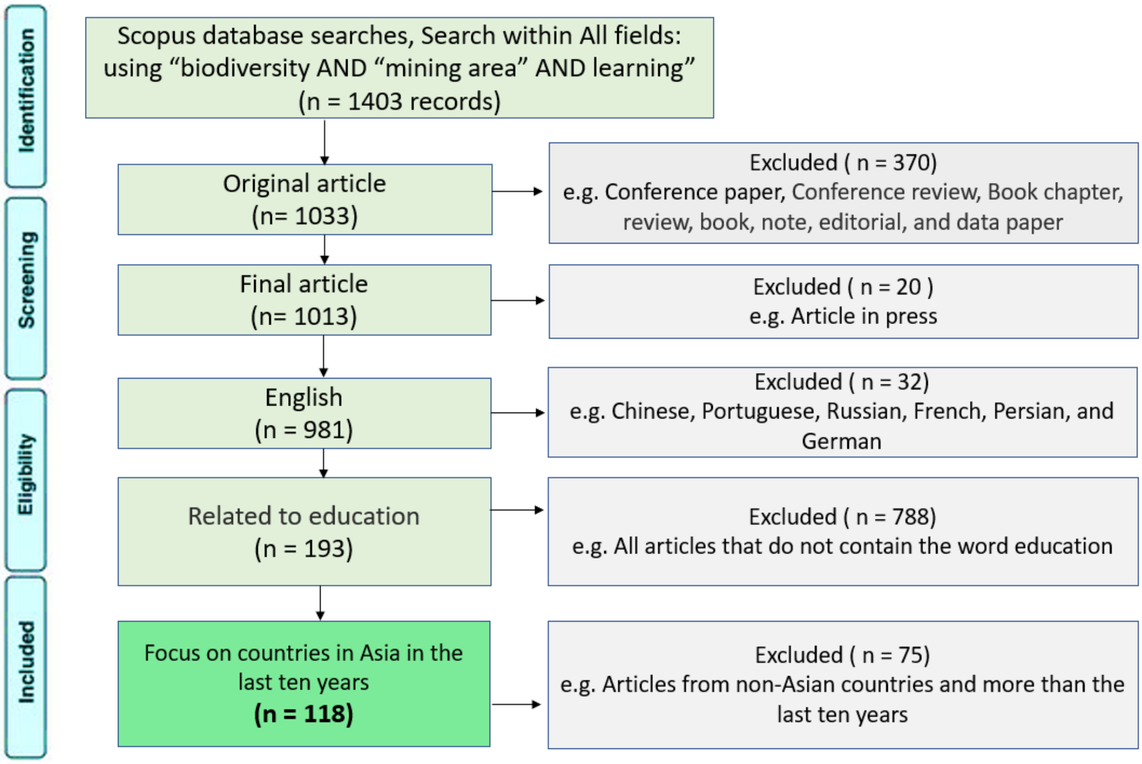
Educational terms were subsequently examined as a distinct interpretive category. The presence, frequency, and network position of terms referring to educational constructs, pedagogy, teaching, learning activities, or learning outcomes were reviewed to address RQ7.

Figure 1
PRISMA flow diagram.



After finalizing the corpus (n = 118), bibliometric analysis was conducted in two complementary layers: performance analysis and science mapping. Performance analysis summarized publication dynamics and productivity patterns, including (i) annual publication counts and growth rates (RQ1), (ii) subject-area distribution (RQ2), and (iii) country contributions based on affiliation metadata (RQ3). Science mapping focused on the conceptual and thematic structure of the field. Author keywords and indexed keywords were cleaned through light normalization (e.g., merging singular/plural forms, harmonizing synonyms, and removing overly generic terms) before analysis. Keyword co-occurrence was then visualized using three perspectives—network, overlay, and density—to identify dominant clusters, emerging terms, and areas of high topical concentration (RQ4). To capture how research themes changed over time, the dataset was divided into time slices across the decade and analyzed for thematic evolution, highlighting themes that persisted, split, merged, or declined (RQ5). Finally, trending topics were identified by examining the most rapidly increasing keywords/themes in recent years within the time window, providing a forward-looking view of where the literature is currently moving (RQ6). This combined approach enables the review to describe not only how much has been published, but also how ideas are connected, how the field has reorganized, and which directions appear most active for future research.

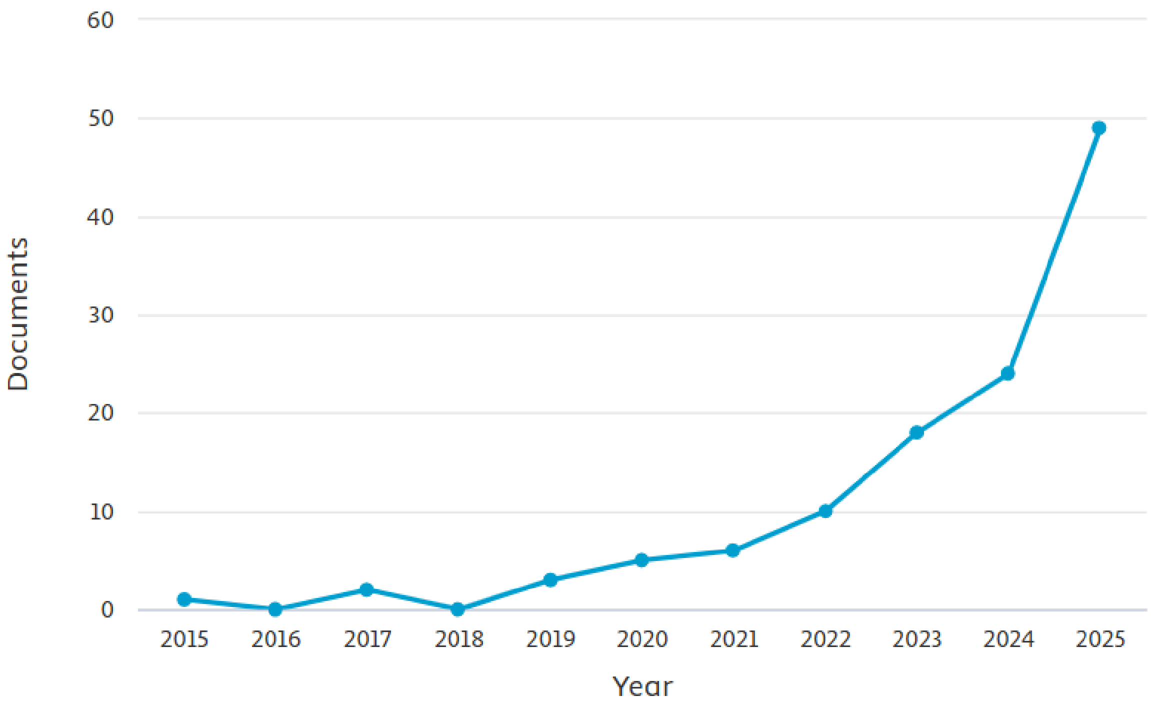
RESULTS AND DISCUSSION

Documents by year

Figure 2 displays the annual publication output across the last decade. This visualization provides a clear overview of growth patterns, helps identify potential turning points, and offers an initial basis for interpreting how the field has progressed from early exploratory work to more sustained and systematic research. The analysis of Figure 1 is presented immediately after the figure to highlight key phases of development and the implications of the observed trend for subsequent bibliometric mapping.

Figure 2

Documents by year.



Based on the annual publication trend (2015–2025), research linking biodiversity in mining areas with educational or learning practices shows a clear progression from an early, fragmented stage to a phase of rapid expansion in recent years. The curve is not merely upward; it suggests an inflection point around 2022–2023, when the field shifts from slow growth to accelerated output.

During 2015–2018, the number of documents remains very low and intermittent (roughly 0–2 papers per year). This pattern is typical of an emerging topic: studies appear sporadically, often as isolated case-based contributions, and the integration between mining-related biodiversity research and education-oriented scholarship is still limited. From 2019 to 2021, publication output becomes more consistent and increases gradually (approximately 3 → 5 → 6 documents per year). This period can be interpreted as early consolidation, when the topic begins to gain traction, terminology becomes more stable, and a small but recognizable research community starts to form.

The most pronounced growth occurs in 2022–2025. Publications rise to around 10 documents in 2022, then climb sharply in 2023 (~18) and 2024 (~24), before surging in 2025 (~49).

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The jump from 2024 to 2025 is the steepest increase, indicating intensified scholarly attention to how mining landscapes—especially reclamation and post-mining environments—can function as ecological sites and learning spaces. Substantively, this acceleration is plausible: the rising prominence of sustainability agendas, restoration and rehabilitation priorities, and the demand for contextual environmental education has encouraged more interdisciplinary work across ecology, environmental management, geosciences, and education. At the same time, the 2025 spike should be interpreted with some caution because bibliometric counts can also be influenced by database updates, indexing dynamics, and publication-stage timing. Overall, however, the pattern strongly suggests that the field has entered a rapid growth phase, with 2022–2025 emerging as a pivotal period shaping both the volume and direction of future research.

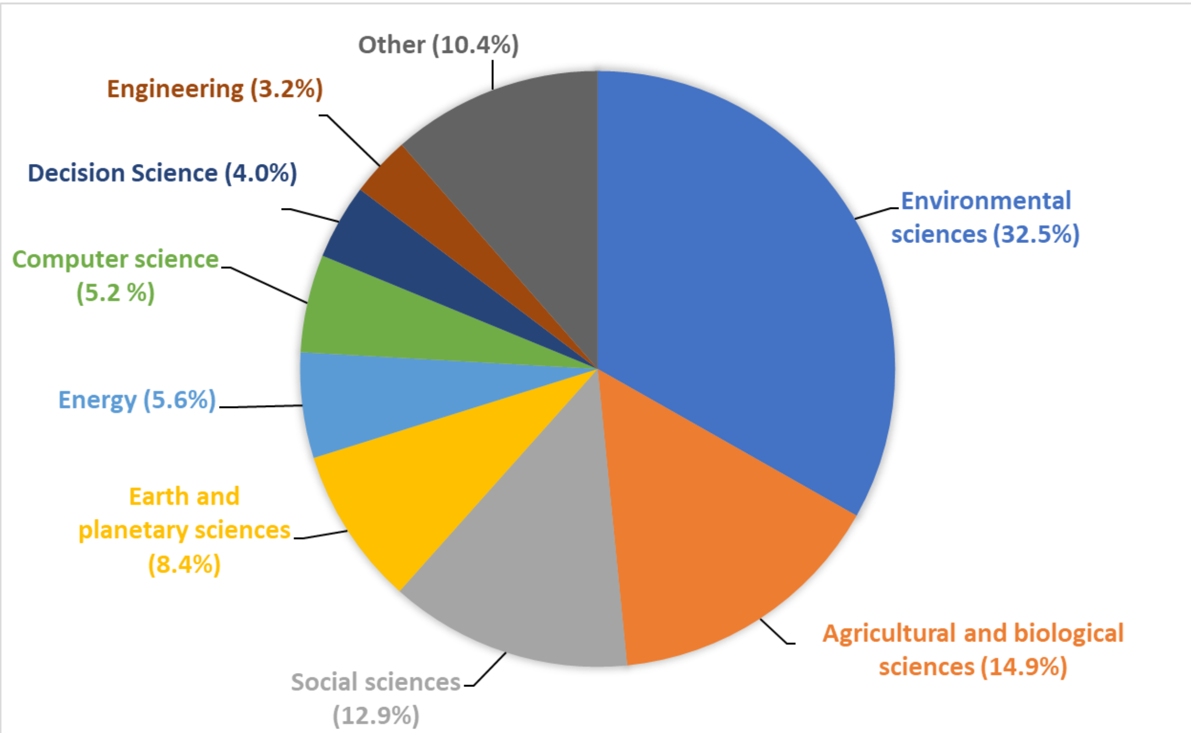
Subject Area

Before moving to keyword structures and thematic trajectories, it is useful to clarify the disciplinary entry points through which this topic has been approached. In bibliometric mapping, subject-area distribution provides an early signal of where a research domain is anchored, which communities contribute most actively, and how strongly the field leans toward ecological science, educational scholarship, or broader socio-technical perspectives. Because studies on biodiversity in mining landscapes can be framed as restoration ecology, environmental management, socio-ecological governance, or place-based learning, understanding the subject-area composition helps explain why certain concepts dominate later network analyses and why some themes evolve faster than others.

Figure 3 presents the subject-area distribution of publications linking biodiversity in mining areas to educational or learning-related practices. This overview highlights the balance between environmental–biological sciences and the social sciences, while also revealing smaller but meaningful contributions from computational and decision-oriented fields.

Figure 3

Documents by subject area.



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The pattern is clearly environment-led. Environmental Sciences represent the largest share (32.5%), indicating that the literature is primarily rooted in ecological assessment, rehabilitation, reclamation, and environmental monitoring of mining landscapes. This dominance suggests that, even when education is present, it is often embedded within environmentally framed problem settings—for example, learning activities tied to biodiversity surveys, restoration programs, or environmental risk communication in mining-affected regions (Amprazis & Papadopoulou, 2025; Pantić et al., 2026; Schlecht et al., 2026).

The second-largest contribution comes from Agricultural and Biological Sciences (14.9%), reinforcing the ecological foundation of the field. This presence is consistent with studies focusing on species diversity, habitat recovery, vegetation succession, and bioindicator-based evaluations of post-mining land. Importantly, this category can also reflect applied, field-oriented research that naturally lends itself to experiential learning, field courses, and community-based monitoring—pathways that may explain why “learning” appears as a recurring connector across disciplines.

Notably, Social Sciences account for a substantial proportion (12.9%). This indicates that the field is not purely biophysical; it increasingly recognizes the human and institutional dimensions of mining landscapes—community engagement, environmental governance, socio-economic impacts, and educational interventions. However, the social-science share remains smaller than the environmental-science share, implying that education-related discussions may still be positioned as a supporting dimension rather than the primary analytical lens in many studies (Bossér & Lindahl, 2019; Halfon, 2026; Kelly et al., 2024; Ouyang et al., 2025; Sass et al., 2025).

The presence of Earth and Planetary Sciences (8.4%) and Energy (5.6%) reflect the geoscientific and resource-development context of mining. These contributions typically align with landform change, geochemistry, environmental hazards, and resource systems—topics that often stimulate educational applications such as geoscience fieldwork, risk literacy, and sustainability education. Their combined share suggests that the field also draws from the “physical systems” perspective, which can broaden educational framing beyond biodiversity alone toward integrated socio-ecological–geological learning contexts.

Smaller but significant shares appear in Computer Science (5.2%) and Decision Science (4.0%). Although modest, these areas are strategically important because they often signal methodological shifts—such as the use of GIS/remote sensing, ecological modelling, machine learning for biodiversity mapping, decision-support systems for restoration planning, or analytics for program evaluation. In educational terms, these approaches can translate into data-driven learning, digital field laboratories, citizen science platforms, and technology-enhanced environmental education, potentially shaping future trending topics (Kerry et al., 2022; Zhu et al., 2025).

Engineering contributes 3.2%, which is expected given engineering’s role in mine reclamation design, remediation technologies, and infrastructure planning. Even at a smaller share, engineering-oriented studies can strongly influence educational practice by providing tangible case studies, design-based learning opportunities, and interdisciplinary training models relevant to sustainable mining and ecological restoration.

Finally, the “Other” category (10.4%) suggests a long tail of disciplines that do not dominate individually but collectively enrich the field—potentially including business/management, health, materials science, arts and humanities, or multidisciplinary outlets. This tail indicates that the topic is spreading beyond its original ecological core, which is often a hallmark of an emerging interdisciplinary domain.

Overall, the subject-area profile shows a field that is ecologically anchored but increasingly interdisciplinary. Environmental and biological sciences provide the conceptual and empirical backbone, while social sciences and geoscience-related fields introduce community, governance, and systems perspectives that make education-oriented integration more visible. This distribution also helps anticipate the next analytical steps: keyword networks and thematic evolution are likely to be dominated by environmental and restoration concepts, with education-related terms

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appearing as cross-cutting connectors that become more pronounced as the social-science and computational components continue to grow.

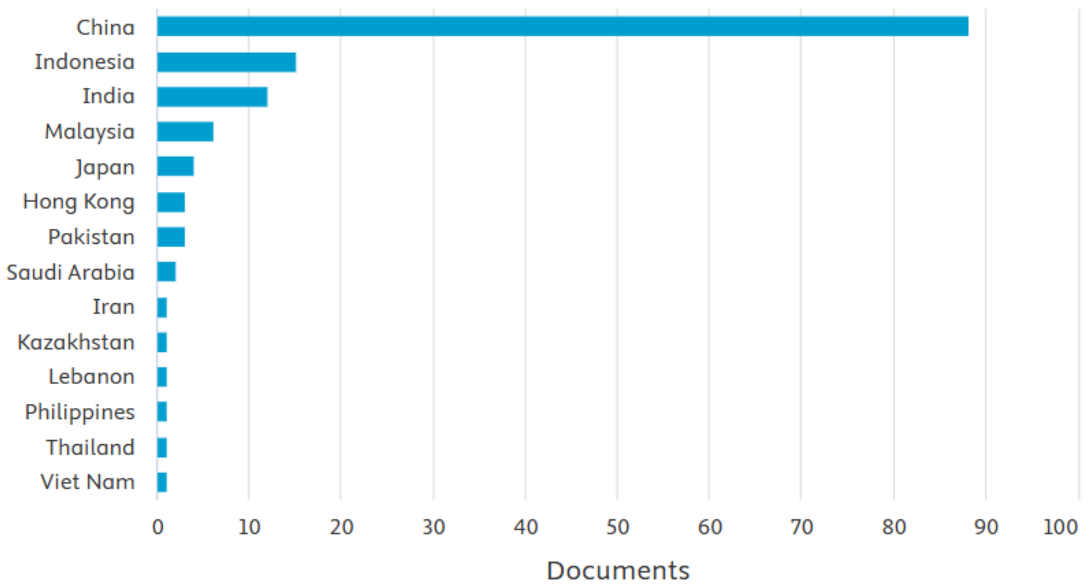
Documents by Country or Territory

Before examining keyword networks and thematic evolution, it is also important to understand where the evidence is being produced geographically. In bibliometric studies, country-level distribution does more than describe productivity; it indicates regional leadership, research capacity, and the socio-environmental contexts that shape scientific attention. Because mining-related biodiversity issues—and the educational responses they trigger—vary widely across Asia, mapping national contributions helps clarify which countries are driving the conversation, where research clusters are concentrated, and where gaps may still exist.

Figure 4 shows the distribution of documents by country for publications linking biodiversity in mining areas to educational or learning-related practices in Asia over the last decade. The figure 4 provides an overview of leading contributors and the extent to which output is concentrated or dispersed across the region.

Figure 4

Documents by country



The country distribution is highly uneven, with China contributing the largest number of publications in the dataset. This result establishes China's numerical dominance within the retrieved corpus; however, the bibliometric analysis does not directly test the economic, institutional, political, or environmental factors responsible for this pattern. The concentration may be associated with differences in research capacity, publication output, mining-related research activity, or Scopus indexing coverage, but these possible explanations require supporting empirical evidence and should not be treated as findings of the present analysis. Because Chinese-affiliated publications constitute a substantial proportion of the dataset, their terminology and research priorities may also exert a strong influence on the aggregate keyword structure.

Indonesia and India form a second tier of contributors, each producing substantially fewer documents than China. The bibliometric results demonstrate their publication contributions but do not establish whether the publications involve field-based learning, community education, conservation education, or other specific educational practices. Consequently, interpretations concerning the use of mining or post-mining landscapes as learning contexts would require

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content analysis of the individual publications and are not inferred from country-level publication counts alone.

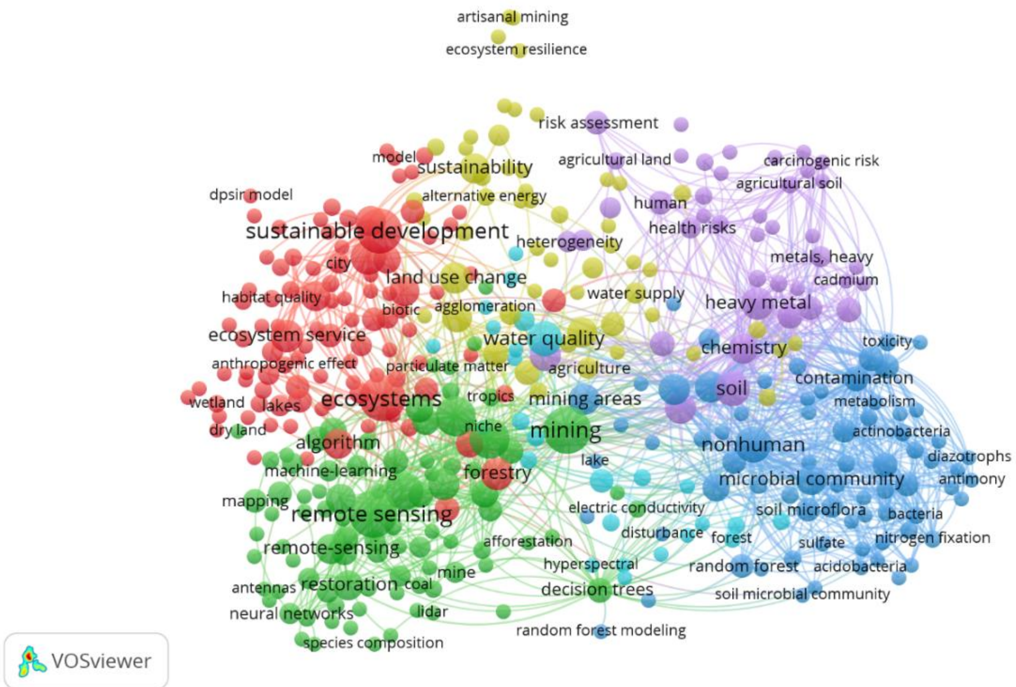
Beyond China, Indonesia, and India, publication output is distributed among Malaysia, Japan, Hong Kong, Pakistan, Saudi Arabia, Iran, Kazakhstan, Lebanon, the Philippines, Thailand, and Viet Nam. Each of these countries or territories contributes a comparatively small number of documents. The distribution therefore indicates that the retrieved corpus is concentrated geographically. However, because the initial search used affiliation filters for only four countries, this pattern should not be interpreted as a complete comparison of research productivity across Asia.

The country distribution indicates that the bibliometric patterns reported in this study are shaped predominantly by publications associated with a small number of national contexts, particularly China. Therefore, the keyword structures and thematic patterns should be interpreted as characteristics of the retrieved dataset rather than as region-wide patterns applicable to all Asian countries. Explanations involving funding levels, language barriers, institutional capacity, or international collaboration were not examined in this study and should be investigated separately (Alemdar, 2025; Jiang et al., 2025; Mohamed, 2025; Mohammadi & Soltanifar, 2025).

Keywords (based on network visualization, overlay visualization, and density visualization)
Keyword co-occurrence analysis is widely used for this purpose because it captures the shared vocabulary of a research community. When visualized in VOSviewer, frequently co-occurring keywords form clusters that represent dominant research conversations, while the size of nodes and the density of links indicate their relative prominence and connectedness.

Figure 5 presents the keyword network visualization generated in VOSviewer. Nodes represent keywords, node size reflects frequency, and lines indicate co-occurrence relationships. Colors denote clusters—groups of keywords that co-appear often, suggesting coherent thematic subfields within the broader topic of biodiversity in mining areas and its relationship to learning/education.

Figure 5
R*elevant keywords based on network visualization (VOSviewer results).*



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The keyword network is organized around highly central terms such as “mining,” “mining areas,” “water quality,” “contamination,” “heavy metal,” and “sustainable development.” These terms demonstrate that the conceptual structure of the retrieved corpus is dominated by environmental assessment, contamination, ecosystem change, and monitoring. In contrast, keywords referring explicitly to educational constructs, pedagogical approaches, teaching strategies, or learning outcomes are absent or peripheral. Therefore, the dataset more strongly represents environmental research with limited educational visibility than a mature body of biology-education scholarship (Cardillo & Basso, 2025; Jiang et al., 2025; Manyani et al., 2024; Siahaan et al., 2025).

Cluster 1 (red): sustainability and ecosystem framing. The red cluster contains terms such as “sustainable development,” “ecosystems,” “ecosystem services,” “habitat quality,” and “land-use change.” Based on their co-occurrence, this cluster represents a substantive focus on ecosystem conditions, landscape transformation, and sustainability-related environmental management (Lis & Mackiewicz, 2023; Shabbir & Salman, 2025). Educational applications cannot be concluded directly from this cluster because education-related terms are not prominent within it. Any connection to sustainability education or environmental literacy should therefore be treated as a possible direction for future research rather than as a bibliometric finding.

Cluster 2 (green): monitoring, mapping, and restoration technologies. The green cluster includes “remote sensing,” “mapping,” “machine learning,” “neural networks,” “LiDAR,” and terms related to restoration and land recovery. The co-occurrence of these terms indicates a strong methodological orientation toward spatial analysis, environmental change detection, habitat characterization, and rehabilitation monitoring (Baskent et al., 2024; Rahmila et al., 2026; Salata & Yiannakou, 2023).

The bibliometric map does not demonstrate that these technologies have been used in student or community learning. Their application in inquiry-based learning, citizen science, or data-driven environmental education is therefore proposed only as a future research possibility (Grandin et al., 2025; Zhao et al., 2024).

Cluster 3 (blue): soil–microbial ecology and contamination pathways. The blue cluster centers on microbial community, soil microflora, bacteria, actinobacteria, nitrogen fixation, and related biogeochemical terms. This cluster reflects a more biological and process-based view of post-mining ecosystems, focusing on how mining disturbances reshape soil health and microbial biodiversity—often a key indicator of ecosystem recovery. Conceptually, this cluster is important because it frames biodiversity beyond visible flora and fauna, emphasizing functional biodiversity and ecosystem processes. The cluster itself provides evidence of a specialized research focus on soil and microbial processes. Potential applications in laboratory or field-based education were not directly represented by the mapped keywords and therefore require separate pedagogical investigation (Correia & Lopes, 2023; Robinson et al., 2024).

Cluster 4 (purple): heavy metals and human-health risk. The purple cluster includes “heavy metal,” “cadmium,” “toxicity,” “health risk,” and “risk assessment.” Its strong connections with contamination and chemistry terms indicate a substantive focus on pollutant exposure and environmental or human-health risk assessment. Terms associated with socio-scientific issues, scientific literacy, risk reasoning, or educational decision-making do not appear prominently in the mapped cluster. Consequently, linking this cluster to SSI-based teaching would constitute a proposed educational application rather than a result of the bibliometric analysis (Jimenez et al., 2024).

Bridging concepts and what the network suggests about the field. Keywords such as water quality, contamination, and mining appear as bridges across clusters, connecting ecological sustainability narratives (red), monitoring technologies (green), biological recovery processes (blue), and toxicity/health-risk assessments (purple). This pattern indicates that the field is cohering around a shared environmental problem space—mining disturbance and its ecological and health consequences—while deploying diverse methods and scales of analysis.

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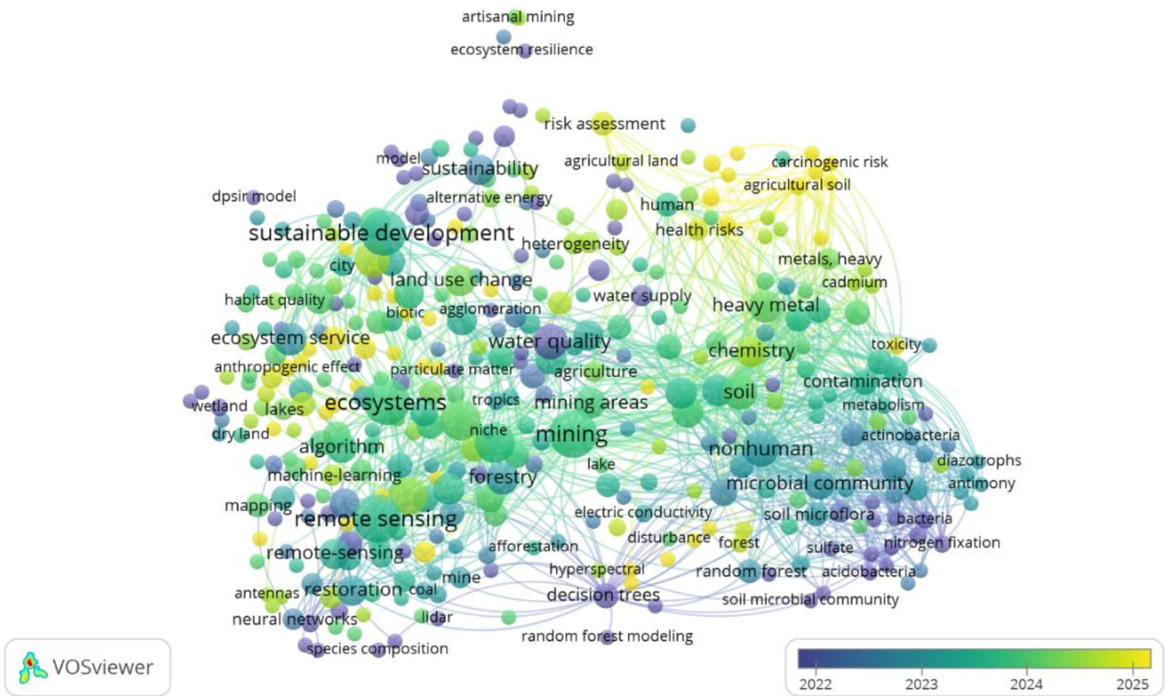
Education-related terms are not visually dominant in the network despite the inclusion of education and learning terms in the search strategy. This result may indicate either that educational elements occur only incidentally in many publications or that the search configuration retrieved environmentally oriented studies in which education is not a substantive analytical focus. Because the present analysis is based primarily on bibliographic metadata and keywords, it cannot determine whether education is embedded in the full text of individual articles. Accordingly, the limited visibility of education should be reported as a limitation of the corpus and as justification for more targeted content analysis.

The overlay visualization helps clarify when particular keywords gained prominence. Unlike the network map—which emphasizes clustering and co-occurrence structure—the overlay view adds a temporal layer by coloring keywords according to their average publication year. In this way, the map highlights which concepts represent long-standing foundations of the field and which topics have appeared more recently, offering a clear bridge between descriptive trends and forward-looking interpretations.

Figure 6 shows the overlay visualization of relevant keywords generated in VOSviewer. Nodes represent keywords, node size reflects frequency, links indicate co-occurrence, and colors indicate temporal prominence (older terms on the earlier end of the scale and newer terms on the later end).

Figure 6

Relevant keywords based on overlay visualization (VOSviewer results)



A clear pattern emerges: foundational terms related to mining impacts and environmental quality remain central, while newer keywords increasingly reflect risk-oriented, data-driven, and sustainability-integrated approaches. In the center of the map, enduring hub terms such as "mining," "mining areas," "water quality," "contamination," and "heavy metal" continue to connect multiple thematic pathways. Their persistent centrality suggests that, across the decade, the field has been anchored in understanding how mining alters environmental conditions and biodiversity-related indicators, especially through aquatic and soil pathways.

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The overlay gradient indicates that more recent publications (toward the later end of the scale) increasingly emphasize risk assessment and human–environment interfaces. Terms such as "risk assessment," "health risks," "carcinogenic risk," "toxicity," and specific pollutants like "cadmium" and "metals, heavy" appear comparatively "newer," suggesting a shift toward more explicit evaluation of exposure pathways and the implications of mining contamination for communities and ecosystems. This trajectory aligns with a broader global move toward actionable evidence—where biodiversity and environmental measurements are interpreted not only ecologically, but also in terms of societal vulnerability and policy-relevant risk (Huynh et al., 2025; Jimenez et al., 2024).

At the same time, the overlay also shows a growing methodological modernization. Keywords associated with computational and monitoring approaches—such as "machine learning," "random forest," "decision trees," "remote sensing," "mapping," and related modelling terms—tend to appear in more recent colors compared with older ecological descriptors. This suggests that the field is moving beyond descriptive assessments toward predictive and spatially explicit analytics, supported by increasing access to remote-sensing products, open environmental datasets, and practical machine-learning toolkits. The methodological shift toward predictive and spatially explicit analysis is evident in the mapped literature. However, the overlay visualization does not establish that these techniques have been incorporated into educational activities. Their use in data-rich learning designs remains a potential research direction.

Another visible trend is the strengthening of sustainability framing in more recent years. Keywords such as "sustainability," "sustainable development," and "land-use change" appear as connective concepts that link ecological assessment to broader development narratives. This pattern indicates that mining-area biodiversity is increasingly examined within broader sustainability and land-use frameworks. Nevertheless, terms referring to systems thinking, socio-scientific reasoning, or education for sustainable development are not prominent in the map; thus, these pedagogical connections should not be presented as findings of the bibliometric analysis (Siahaan et al., 2025).

Importantly, while "learning/education" is part of the selection logic for the dataset, the overlay visualization suggests that education-related elements are often interwoven with application domains—risk communication, monitoring, restoration, and sustainability—rather than dominating the keyword space on their own. This again points to a central bibliometric insight: the education linkage in this literature is frequently expressed through contextualized practice (field learning, community engagement, training, citizen science, and applied sustainability education) rather than through explicitly education-theory keywords. For the review, this is a valuable interpretation: it implies that the most promising future work may lie in making these educational constructs more explicit and analytically robust while staying grounded in the dominant environmental and methodological trends highlighted by the overlay.

The density visualization provides a compact way to identify the most intensively studied areas in the literature. Unlike the network map (which emphasizes connections) and the overlay map (which emphasizes time), the density view highlights where keyword frequency and co-occurrence concentrate most strongly. In VOSviewer, warmer colors (yellow) indicate high-density zones—topics that appear often and co-occur with many other terms—while cooler colors (green to blue) indicate lower density and more specialized or emerging niches.

Figure 7 presents the density visualization of relevant keywords. The figure reveals the conceptual "hotspots" that structure research on biodiversity in mining areas and its relationship to educational or learning-oriented practices. The most prominent hotspot is centered on "mining" and closely connected environmental-quality terms, showing that the literature is heavily organized around mining-driven environmental change as the core problem space. Around this central hub, several high-density zones appear, indicating three dominant thematic concentrations.

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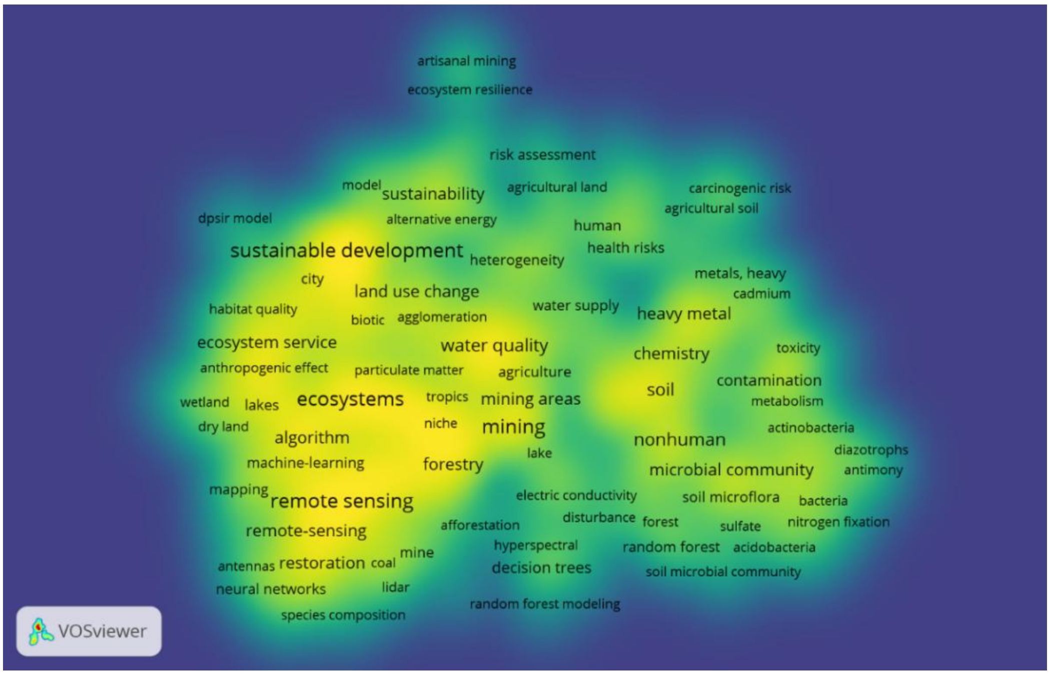
Figure 7

Relevant keywords based on density visualization (VOSviewer results).



First, a strong density area surrounds water-related and contamination indicators, especially "water quality," "contamination," "soil," "chemistry," and "heavy metal." This suggests that the primary empirical backbone of the field is built on measurable environmental parameters—often used as proxies for ecological degradation and as benchmarks for reclamation performance. The prominence of these terms indicates that biodiversity discussions are frequently operationalized through environmental stressors and pathways (e.g., pollutant loads, soil and water chemistry), rather than through biodiversity alone as an abstract concept.

Second, another high-density region is associated with ecosystem and sustainability framing, including "ecosystems," "ecosystem service," "sustainable development," "land use change," and related terms. This cluster indicates that mining-area biodiversity research is commonly positioned within broader sustainability narratives, emphasizing trade-offs, ecosystem functioning, and long-term landscape management. The ecosystem and sustainability hotspot is conceptually relevant to environmental education, but the density map itself does not provide evidence of learning designs, systems-thinking outcomes, socio-scientific reasoning, or community-engagement activities.

Third, a dense methodological zone appears around "remote sensing," "mapping," "machine learning," and associated analytical terms. Although this region may be slightly less intense than the contamination and ecosystem cores, it is still clearly visible, indicating that technology-enabled monitoring has become a mainstream approach for assessing post-mining landscapes. This methodological concentration may provide resources for future educational applications, including geospatial or data-based learning. Such applications, however, were not demonstrated by the keyword density results.

Beyond the hotspots, several terms appear in lower-density regions but remain thematically important. The area featuring microbial ecology—including "microbial community," "soil microflora," "bacteria," and related taxa—suggests a more specialized research stream focusing on functional biodiversity and soil health recovery. Likewise, the terms "risk assessment," "health risks," and "carcinogenic risk" form a recognizable, but comparatively less dense, zone that emphasizes human-health pathways and exposure-related concerns. These lower-density zones

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may represent either more specialized subfields or themes that are newer and still expanding, which aligns with the temporal patterns suggested by the overlay visualization (Ockleford et al., 2017; Vagelas & Leontopoulos, 2023).

Overall, the density map indicates that the literature is concentrated around an integrated triad: (1) mining-driven environmental impacts (especially soil and water contamination), (2) sustainability and ecosystem-level framing, and (3) technology-enabled monitoring and analysis. At the same time, the visualization also reinforces an important interpretive point: education-related constructs are not among the highest-density terms, implying that educational elements are often present as contextual applications—field-based learning, community training, citizen science, and sustainability education—rather than as the dominant conceptual vocabulary of the papers. This finding strengthens the rationale for future work that articulates educational theories and learning outcomes more explicitly, while leveraging the mature environmental and methodological cores that the density map clearly reveals.

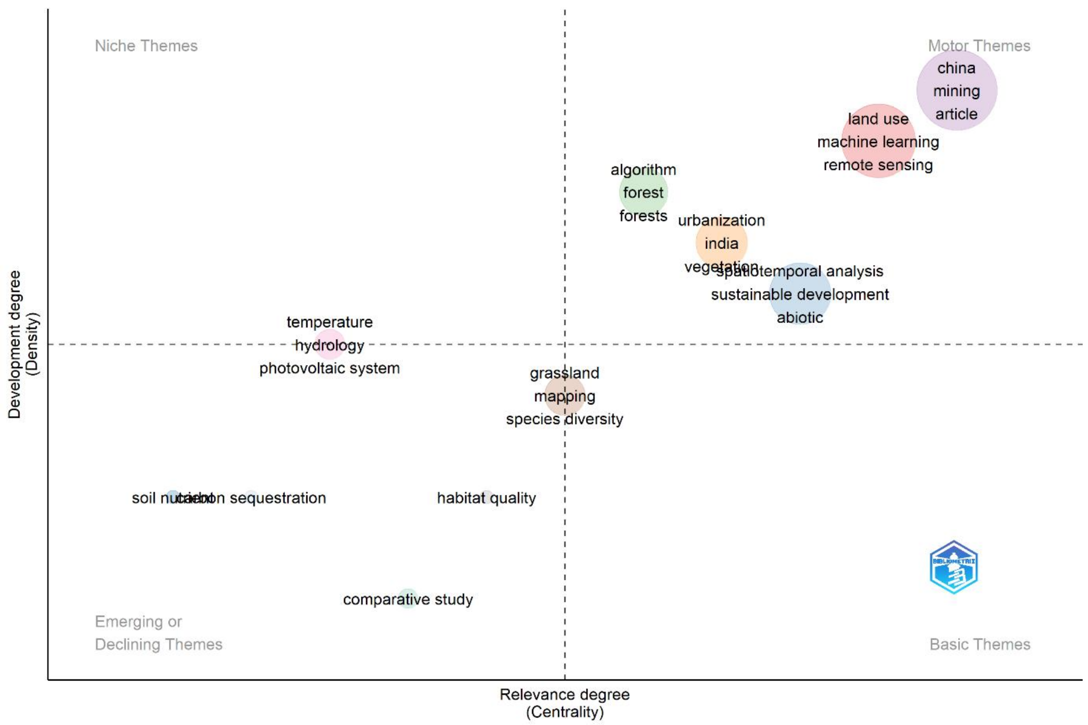
Thematic evolution

It is useful to examine how themes are positioned in terms of their importance and maturity within the field. Thematic mapping—often produced through the bibliometrix package in R/RStudio—plots clusters of keywords based on two dimensions: centrality (relevance/importance to the overall research network) and density (internal development/maturity of the theme). This approach helps distinguish between themes that currently drive the field, themes that serve as foundational building blocks, specialized but well-developed niches, and emerging (or declining) topics that have not yet become central.

Figure 8 presents the thematic map for publications linking biodiversity in mining areas to educational or learning-related practices in Asia. The horizontal axis represents relevance degree (centrality), while the vertical axis represents development degree (density). The four quadrants—Motor Themes, Basic Themes, Niche Themes, and Emerging/Declining Themes—offer a structured way to interpret the thematic evolution of this literature.

Figure 8

Thematic evolution (Rstudio results)



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Motor themes: well-developed and highly central. The upper-right quadrant (Motor Themes) contains the most influential and mature themes. In this map, the dominant motor cluster is anchored by “China” and “mining,” closely linked with “land use,” “remote sensing,” and “machine learning.” This configuration suggests that the most developed and field-driving research stream is currently shaped by (i) a strong geographic concentration of output, and (ii) a methodological emphasis on spatial and computational approaches to characterize mining landscapes and their ecological consequences. In other words, the field’s “engine” is not only about mining impacts per se, but about how those impacts are assessed—through land-use analysis, remote sensing, and machine-learning-enabled monitoring. This also aligns with the sharp publication growth observed in recent years, where digital environmental analytics have become increasingly accessible and scalable.

Before constructing the thematic map, geographic labels such as “India” and “China” should be removed through the thesaurus-based data-cleaning process because they identify locations rather than substantive research themes. Following this cleaning, the relevant motor theme is interpreted through the remaining conceptual terms, particularly “urbanization” and “vegetation.” Their co-occurrence represents research on vegetation change in landscapes affected by broader development and land-transformation pressures.

Basic themes: central but less developed. The lower-right quadrant (Basic Themes) represents topics that are important across the field but may be less internally developed as coherent, specialized clusters. In this map, terms such as “sustainable development,” “spatiotemporal analysis,” “abiotic,” and related general descriptors lie toward the right side but closer to the horizontal midline, suggesting they function as cross-cutting foundations rather than tightly bounded subfields. These are the concepts that many studies draw upon—framing mining-area biodiversity in sustainability terms and using spatiotemporal approaches—yet they may be expressed in broad ways that connect multiple topics rather than forming a single consolidated research niche.

Niche themes: specialized and well developed but peripheral. The upper-left quadrant (Niche Themes) includes themes with high density but low centrality—well-developed within themselves, but less connected to the main research network. Here, “temperature,” “hydrology,” and “photovoltaic system” appear as niche clusters. This indicates a specialized set of studies that engage mining landscapes through particular environmental-process lenses (e.g., hydrological dynamics, thermal conditions) or energy-related land uses. These topics may be methodologically rigorous but remain peripheral to the dominant, mining–remote-sensing–sustainability core.

Emerging or declining themes: low density and low centrality. The lower-left quadrant captures themes that are either newly emerging (not yet developed) or declining (losing momentum). Terms such as “soil nutrients,” “carbon sequestration,” “comparative study,” and “habitat quality” appear in this region. Interpreting this quadrant requires care: for example, habitat quality is a conceptually important idea, but its position may indicate that it is being used inconsistently across studies or dispersed across multiple thematic clusters rather than forming a mature, cohesive theme. Likewise, carbon sequestration and soil nutrients may represent promising intersections with restoration and climate mitigation, but they have not yet become central drivers of the mining–biodiversity–learning literature within the current dataset.

Themes near the center: bridging concepts. Several terms—such as “species diversity,” “mapping,” and “grassland”—appear near the center of the plot, indicating bridging themes that connect different parts of the literature but do not (yet) show high internal cohesion. These may function as “connector” topics linking biodiversity measures to spatial approaches and land-cover contexts.

Taken together, Figure 8 suggests that the field’s thematic development is currently propelled by a highly central, method-driven core—mining and land-use change assessed through remote sensing and machine learning, with strong output concentration in China and additional contributions linked to broader land transformation contexts (e.g., India–urbanization–vegetation)

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(Chen et al., 2025; Gandharum et al., 2025; Purnomo & Redha, 2025; Zhang et al., 2021). Meanwhile, sustainability framing operates as a widely shared foundation, and several ecology- and restoration-relevant topics (habitat quality, soil nutrients, carbon sequestration) appear as less mature or less integrated themes—pointing to clear opportunities for future work (Eelager et al., 2025; Giuliani et al., 2024; Varshney et al., 2022). For studies explicitly linking mining-area biodiversity to educational practice, this thematic structure also implies that education is most often connected through applied contexts (monitoring, mapping, sustainability problem-solving) rather than through consolidated education-theory-driven clusters, reinforcing the need for stronger conceptual integration in future interdisciplinary research.

1. Trend topics

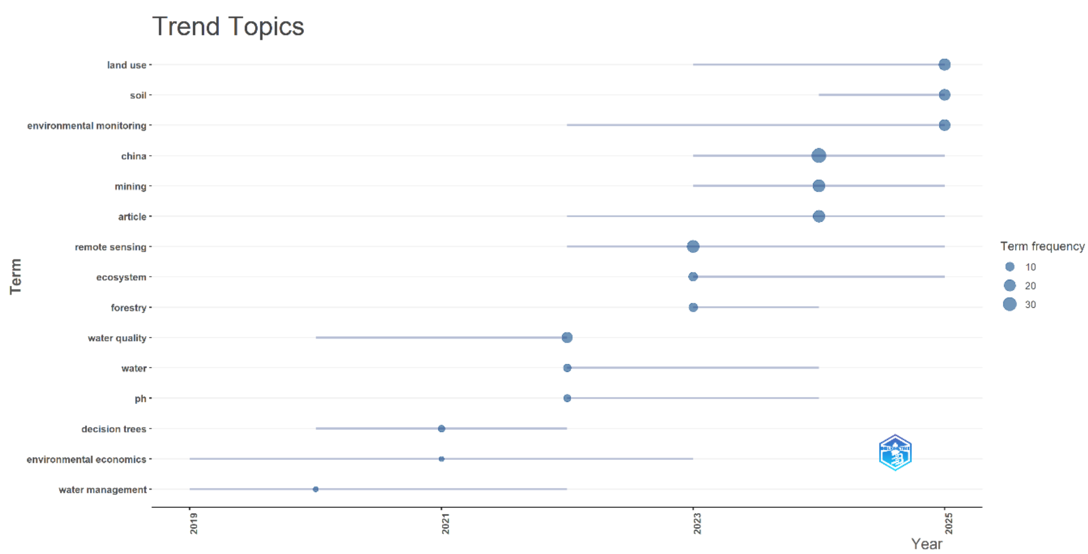
While the thematic map explains how themes are positioned in terms of maturity and centrality, the trend-topics analysis focuses more directly on recency and growth: it highlights keywords that become prominent in specific years and shows how long they remain active in the literature. In bibliometric terms, this visualization offers a practical way to capture the field's research front—the concepts that are most visible in the newest wave of publications and most likely to shape near-future directions.

Figure 9 presents the trend topics generated in RStudio (bibliometrix). Each term is shown across the years in which it is most active, and bubble size indicates relative frequency. This figure therefore helps distinguish between long-running topics with sustained attention and newer terms that rise quickly in the most recent period.

A clear shift toward landscape-scale analysis and monitoring is visible in the most recent years. Terms such as "land use" and "soil" appear prominently toward the far-right end of the timeline (near 2024–2025), suggesting that recent studies increasingly frame mining-area biodiversity through land transformation and soil-related indicators—both of which are central to rehabilitation success and ecological recovery. Closely aligned with this is "environmental monitoring," which also becomes prominent in the later period, indicating a growing emphasis on systematic measurement, surveillance of environmental quality, and evidence-based evaluation of post-mining conditions (Liu et al., 2023; Ren et al., 2026).

Figure 9

Trend topics (Rstudio results)



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Another strong and sustained trend is the continued prominence of "remote sensing", which emerges earlier (around 2022–2023) and remains active into the later period. This pattern reinforces what is seen in the subject-area and thematic-map results: the research front is increasingly shaped by technology-enabled assessment—satellite imagery, spatial analysis, and scalable monitoring of mining landscapes. The presence of "decision trees" (earlier, around 2021–2022) suggests that specific machine-learning or data-mining techniques have also entered the field, likely as part of efforts to classify land-cover change, predict contamination patterns, or model ecological indicators from large datasets.

Several terms reflect the enduring environmental-quality core of the literature. Keywords such as "water quality," "water," and "pH" appear as earlier-to-mid trends, with activity extending across multiple years. This indicates that aquatic and physico-chemical indicators remain a stable backbone of mining-related biodiversity research. The fact that these topics persist while newer monitoring and land-use terms rise suggests a field that is evolving by layering new methods and broader spatial framings onto established environmental metrics, rather than replacing them.

The trend map also includes terms such as "ecosystem," "forestry," and "mining," which occupy the middle-to-late years and show continued relevance. Their presence implies that, alongside methodological advances, the field continues to frame mining impacts through ecosystem-level narratives and land-cover contexts (including forested landscapes and reclamation trajectories). In addition, the appearance of "environmental economics" and "water management"—more visible in earlier years—indicates a policy and management-oriented stream that has been present but may not be the dominant driver of the most recent surge compared with remote sensing and monitoring topics.

An important interpretive note is that country-related and generic terms (e.g., "China" and "article") appear as trend topics. "China" likely reflects the strong concentration of output identified in the country analysis, meaning that the newest wave of publications remains heavily shaped by research produced in, or affiliated with, China. Meanwhile, "article" is not conceptually meaningful by itself and may reflect indexing artifacts or how terms were extracted; it should be treated cautiously and not interpreted as a substantive theme.

Overall, Figure 9 suggests that the current research front is characterized by the convergence of three priorities: (1) land-use and soil-focused framing of post-mining landscapes, (2) technology-enabled environmental monitoring—especially remote sensing—and (3) the continued centrality of water-quality indicators as a persistent empirical foundation. For the educational linkage of this field, these trends imply growing opportunities for learning designs based on authentic monitoring tasks: students and communities can engage with remote-sensing data, interpret land-use change, analyze soil and water indicators, and connect these observations to biodiversity recovery and sustainability decision-making in mining-affected regions (Bielecka et al., 2025; Brevik et al., 2022; Ekka et al., 2026; Ikuemonisan et al., 2025; Sarkar et al., 2025).

LIMITATIONS

This study has several limitations. First, the affiliation-country filters were limited to China, Indonesia, India, and Malaysia. Consequently, the corpus does not represent all Asian countries, even though publications involving international co-authors introduced additional country names into the country analysis. Second, Scopus was used as the sole database, which may exclude relevant literature indexed elsewhere or published in languages other than English. Third, the inclusion of the terms "education" and "learning" in the search strategy did not ensure that education constituted a central topic in every retrieved publication. The dominance of environmental keywords suggests that some records may refer to learning in computational, machine-learning, organizational, or incidental contexts rather than formal or non-formal education. Fourth, the study relies mainly on metadata and keyword-based mapping; therefore, it cannot determine the actual pedagogical content, learning activities, or educational outcomes

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reported in the full texts. Future reviews should combine bibliometric analysis with systematic content analysis and use a more education-specific search strategy.

CONCLUSION

Overall, the bibliometric evidence indicates that research on mining-area biodiversity represented in the selected-country dataset has expanded rapidly, particularly since 2022. Publication output remained sporadic in 2015–2018, stabilized in 2019–2021, and then accelerated sharply after 2022, culminating in a pronounced surge in 2025—suggesting a decisive shift toward more systematic and interdisciplinary inquiry, even while acknowledging possible database and indexing effects. Across subject areas, the field is clearly anchored in Environmental Sciences and Agricultural/Biological Sciences, with meaningful contributions from Social Sciences, geosciences, and computational fields, reflecting an increasingly hybrid agenda that combines ecological assessment, rehabilitation, and socio-environmental considerations. Geographically, output is highly concentrated, particularly in publications associated with China. Because the search strategy used selected affiliation-country filters, this distribution should not be generalized as a complete representation of publication productivity throughout Asia. Keyword maps reinforce this structure: the conceptual core is organized around mining impacts, water and soil contamination, heavy metals, and sustainability framing, while recent years increasingly emphasize risk assessment and data-driven monitoring through remote sensing and machine learning. Educational constructs, pedagogical approaches, and measurable learning outcomes are not prominent in the keyword network, thematic map, or trend-topic analysis. Therefore, the retrieved dataset more accurately represents environmentally oriented mining-area biodiversity research with limited educational visibility than a consolidated research domain linking biodiversity and educational practice. This discrepancy between the original educational framing and the bibliometric evidence constitutes an important finding as well as a limitation of the study.

Because educational concepts were weakly represented in the bibliometric results, future research should test rather than assume the educational value of mining and post-mining environments. Studies should explicitly formulate educational objectives, employ recognized pedagogical frameworks, and measure learning outcomes alongside ecological variables. First, researchers could integrate established educational constructs—such as environmental literacy, place-based learning, socio-scientific issues (SSI), citizen science pedagogy, and education for sustainable development (ESD)—and evaluate learning outcomes alongside ecological indicators in post-mining and reclamation settings. However, these constructs should be incorporated into the research design and measurement instruments rather than inferred retrospectively from environmentally focused publications. Second, remote sensing, machine learning, participatory mapping, and soil or water monitoring may be examined as learning tools. Future studies could test whether student-led environmental data collection and analysis improve systems thinking, evidence evaluation, risk reasoning, or environmental decision-making. Third, comparative research is needed in a wider range of Asian settings. Such research should employ search strategies that comprehensively include relevant Asian countries rather than relying on a limited set of affiliation-country filters. Finally, longitudinal and mixed-method studies could evaluate whether mining and reclamation areas can function effectively as learning environments. Evidence should include clearly defined participants, pedagogical interventions, assessment instruments, ecological learning materials, and measurable cognitive, affective, behavioral, or community-level outcomes.

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