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GIS Education for Spatial Thinking and Environmental Literacy: A Bibliometric-Systematic Review

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ABSTRACT

The growing integration of Geographic Information Systems (GIS) and geospatial technologies into education has created new opportunities for developing spatial thinking, environmental literacy, and sustainability competencies. However, research on GIS-based learning remains fragmented across geography education, environmental education, spatial thinking, and geospatial technology studies, limiting a comprehensive understanding of its intellectual structure and educational implications. This study examines the development, thematic evolution, and educational contributions of GIS-based spatial learning through a bibliometric-systematic review approach. Data were collected from the Scopus database using a structured search strategy covering the period 2020 to 2026. A total of 167 publications met the bibliometric inclusion criteria, while 72 studies were selected for thematic synthesis following the PRISMA 2020 framework. Bibliometric analysis was conducted using VOSviewer to examine publication trends, scientific productivity, keyword networks, and thematic clusters, while thematic synthesis was employed to identify major educational themes and emerging research directions. The findings reveal a significant increase in GIS-based educational research, particularly after 2023. Science mapping identified four dominant knowledge clusters related to geography education, spatial thinking, environmental sustainability, and educational technology. Thematic synthesis further revealed five major themes: GIS-based spatial learning, spatial thinking development, environmental literacy and sustainability education, remote sensing and geospatial environmental learning, and action-oriented learning. Notably, action-oriented learning emerged as the most prominent direction, indicating a shift from technology-centered approaches toward participatory, inquiry-based, and problem-solving pedagogies. This study proposes an integrative conceptual framework linking geospatial technologies, spatial thinking, environmental literacy, action-oriented learning, and sustainability competencies, with implications for educational innovation, curriculum development, and future action research in geography, science, and environmental education.

Keywords: Geographic Information Systems (GIS); Spatial Thinking; Environmental Literacy; Sustainability Education; Action Research

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INTRODUCTION

Geospatial technologies have become increasingly important in contemporary education because they provide opportunities for learners to visualize, analyze, and interpret complex environmental phenomena through spatial data. Geographic Information Systems (GIS), remote sensing, Web-GIS, and digital mapping tools are no longer viewed solely as technical instruments for spatial analysis but are increasingly recognized as powerful educational technologies that support inquiry-based learning, problem-solving, and environmental decision-making. Recent studies indicate that GIS-supported learning environments enhance students' engagement, spatial reasoning, critical thinking, and environmental understanding by enabling learners to interact directly with authentic geospatial information (Manakane et al., 2023; Somantri et al., 2024).

The growing adoption of GIS in education is closely associated with broader educational transformations emphasizing twenty-first-century competencies, including spatial thinking, digital literacy, environmental literacy, and sustainability awareness. Spatial thinking has emerged as a fundamental competence in geography and environmental education because it enables learners to understand location, distribution, scale, spatial interaction, and environmental change. Research consistently demonstrates that GIS-based learning contributes significantly to students' ability to interpret spatial relationships, analyze environmental processes, and solve real-world geographic problems (Dewi et al., 2025; Memmase et al., 2025). Consequently, GIS is increasingly integrated into school and higher education curricula as a means of strengthening geospatial competence and supporting evidence-based learning.

Simultaneously, environmental education has experienced a significant shift toward sustainability-oriented and problem-based approaches. Contemporary environmental challenges such as climate change, biodiversity loss, ecosystem degradation, coastal vulnerability, and natural hazards require learners to develop systems thinking and data-informed decision-making skills. GIS and remote sensing technologies provide valuable opportunities for connecting environmental concepts with real-world evidence by allowing students to explore environmental datasets, identify spatial patterns, and investigate local sustainability issues. Previous studies have shown that GIS-supported environmental learning contributes to environmental awareness, sustainability competencies, and responsible citizenship (Husamah et al., 2025; Nikhanbayeva et al., 2026).

Within this context, geography education has become one of the primary domains for GIS implementation. Geography educators increasingly employ GIS, digital mapping, Web-GIS, and remote sensing tools to facilitate inquiry-based learning, project-based learning, and collaborative environmental investigations. These approaches allow students to move beyond passive knowledge acquisition and engage actively in constructing geographic understanding through data exploration and spatial analysis. Such developments have strengthened the role of GIS as both a pedagogical tool and a medium for fostering spatial literacy and environmental problem-solving competencies.

Recent literature also indicates growing convergence between geospatial technologies and emerging educational priorities such as sustainable development, climate change education, environmental literacy, and action-oriented learning. The integration of GIS with inquiry learning, problem-based learning, field-based learning, and project-based learning enables students to investigate authentic environmental problems while developing higher-order thinking skills. This convergence reflects broader efforts to align educational innovation with the goals of Education for Sustainable Development (ESD) and environmental citizenship.

Although GIS-based learning has attracted increasing scholarly attention, the existing literature remains fragmented across several domains, including geography education, environmental education, spatial thinking, geospatial technologies, and sustainability studies. Many studies focus on the effectiveness of GIS in improving spatial reasoning, whereas others emphasize environmental literacy, climate change education, or digital learning innovations. As a result, there is limited synthesis regarding the overall intellectual structure, thematic evolution, and emerging research directions of GIS-based spatial learning and environmental education.

Furthermore, several environmental and sustainability-related contexts remain relatively underexplored within GIS-supported educational research. Geospatial technologies offer substantial potential for transforming authentic environmental issues into meaningful learning experiences through spatial analysis, visualization, and inquiry-based investigation. However, the extent to which these themes are represented within the broader GIS-based educational literature remains unclear.

From an educational perspective, these developments are highly relevant to action-oriented learning and action research. Action research emphasizes cyclical processes of planning, implementation, observation, reflection, and improvement aimed at enhancing educational practice. GIS-supported learning environments align closely with these principles because they encourage learners to investigate authentic problems, analyze evidence, propose solutions, and reflect on outcomes. Consequently, GIS-based learning has considerable potential to support action-oriented educational innovation in science education, geography education, and environmental education.

To address these gaps, bibliometric and systematic review approaches have become increasingly valuable for synthesizing rapidly expanding bodies of literature. Bibliometric analysis enables researchers to identify publication trends, influential authors, dominant keywords, thematic clusters, and emerging research directions (Donthu et al., 2021). When combined with systematic thematic synthesis, bibliometric approaches provide deeper insights into the conceptual structure of a field and its practical implications for educational research and practice (Aria & Cuccurullo, 2017).

Despite the growing number of review studies on GIS implementation and geospatial education, previous reviews have generally focused on specific aspects such as the effectiveness of GIS-based instruction, spatial thinking development, or the adoption of geospatial technologies in particular educational settings. Existing reviews have rarely integrated bibliometric science mapping with systematic thematic synthesis to provide a comprehensive understanding of the intellectual structure, thematic evolution, and emerging directions of GIS-supported learning. In addition, limited attention has been devoted to examining the interconnections among spatial thinking, environmental literacy, sustainability-oriented learning, and action-oriented educational approaches within a single analytical framework. Therefore, this study extends previous reviews by combining bibliometric visualization and thematic synthesis to identify research trends, conceptual relationships, and future opportunities for GIS-based education from a broader interdisciplinary perspective.

Therefore, this study aims to conduct a bibliometric-systematic review of research related to GIS-based spatial learning, geography education, environmental literacy, and geospatial technologies. Specifically, the study seeks to: (1) map publication trends and knowledge structures within the field; (2) identify dominant themes, keyword networks, and emerging research directions through bibliometric visualization; (3) synthesize how GIS and spatial technologies contribute to spatial thinking, environmental literacy, and sustainability-oriented learning; and (4) formulate implications for future action research in science, geography, and environmental education. By integrating science mapping with thematic synthesis, this study contributes to a more comprehensive understanding of the evolving role of GIS in contemporary educational research and practice.

METHOD

Research Design

This study employed a bibliometric-systematic review approach to examine the development of research on GIS-based spatial learning, geography education, environmental literacy, and geospatial technologies. The approach combines quantitative bibliometric techniques with qualitative thematic synthesis to provide a comprehensive understanding of the intellectual structure, thematic evolution, and educational implications of the field. Bibliometric analysis was used to identify publication trends, influential authors, institutions, countries, and keyword networks, while thematic synthesis was conducted to examine the substantive contributions of the literature and identify emerging educational directions.

The integration of bibliometric analysis and systematic review enables researchers to move beyond descriptive publication statistics and develop deeper conceptual insights regarding research patterns and educational implications (Aria & Cuccurullo, 2017; Donthu et al., 2021).

Data Source and Search Strategy

The Scopus database was selected as the primary source of bibliographic data because it is widely recognized as one of the largest and most comprehensive multidisciplinary indexing databases for educational, environmental, and geospatial research. Scopus provides extensive coverage of peer-reviewed international publications and is frequently used in bibliometric studies due to its high-quality metadata and citation information (Donthu et al., 2021). The literature search was conducted in January 2026 using combinations of keywords related to Geographic Information Systems (GIS), geospatial technologies, spatial learning, environmental education, and geography education. Because the database search was performed in January 2026, publications indexed in 2026 represent a partial publication year and should therefore be interpreted with caution when compared with the complete annual records from 2020 to 2025. To ensure comprehensive coverage of studies related to GIS and geospatial education, the final search query was applied to the TITLE-ABS-KEY fields. The search strategy was formulated as follows:

TITLE-ABS-KEY (("GIS" OR "geographic information system*" OR "geospatial technolog*" OR "spatial analysis" OR "spatial mapping" OR "remote sensing") AND ("environmental education" OR "science education" OR "geography education" OR "spatial thinking" OR "spatial learning" OR "environmental literacy"))

The search was limited to publications published between 2020 and January 2026, written in English, and classified as journal articles or review articles. Subject areas were primarily restricted to Social Sciences, Environmental Science, Earth and Planetary Sciences, and Computer Science. Conference papers, editorials, notes, book chapters, and non-English publications were excluded. The search query was designed to capture studies examining the educational applications of GIS and related technologies. The database was accessed in January 2026, and the complete search strategy is presented in Appendix A to facilitate transparency and reproducibility.

Inclusion and Exclusion Criteria

To ensure the relevance and quality of the dataset, only Scopus-indexed journal articles and review articles published in English between 2020 and 2026 were included. Eligible studies focused on GIS-based learning, geography education, environmental education, spatial thinking, environmental literacy, and the application of geospatial technologies in educational contexts. Publications such as conference papers, editorials, notes, and book chapters were excluded. Studies unrelated to education, those focusing solely on technical GIS development without pedagogical implications, and research in engineering, urban planning, or environmental monitoring lacking explicit educational components were also excluded. Duplicate records identified during the screening process were removed from the final dataset.

Study Selection Process

The study selection procedure followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) framework (Page et al., 2021). The initial search identified 483 records from the Scopus database. After applying publication year, language, document type, and subject-area filters, 167 publications remained eligible for bibliometric analysis. Subsequently, titles, abstracts, and keywords were independently screened by two reviewers using predefined inclusion and exclusion criteria to assess their relevance to GIS-based learning, spatial thinking, environmental literacy, geography education, and geospatial educational applications. Studies were excluded if they were unrelated to educational applications of GIS, focused solely on technical geospatial development, or lacked explicit pedagogical relevance. Full-text assessment was then conducted to determine the eligibility of potentially relevant studies. Any disagreements between reviewers were resolved through discussion until consensus was achieved. Ultimately, 72 studies met the criteria for thematic synthesis. While all 167 publications were retained for bibliometric mapping and science mapping analyses, only the 72 most relevant studies were subjected to detailed thematic analysis. Detailed information regarding the screening process and reasons for exclusion are presented in the PRISMA 2020 flow diagram (Figure 1).

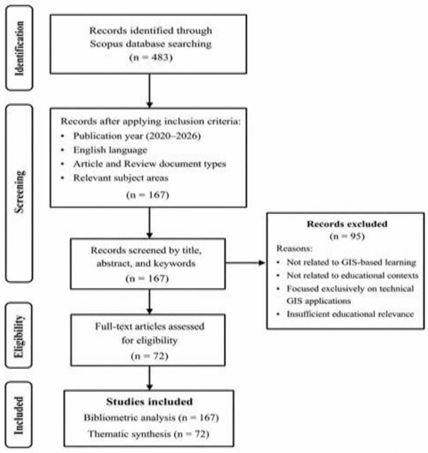

Figure 1. PRISMA 2020 flow diagram illustrating the identification, screening, eligibility assessment, and inclusion of studies used for bibliometric analysis (n = 167) and thematic synthesis (n = 72).

Bibliometric Analysis

Bibliometric analysis was performed using VOSviewer version 1.6.20 to map the intellectual structure and conceptual relationships within the selected literature (Van Eck & Waltman, 2010). The analysis focused on several bibliometric indicators, including publication trends, scientific productivity by country, institution, and author, as well as keyword co-occurrence patterns. Keyword co-occurrence analysis was conducted using author keywords as the unit of analysis to examine conceptual linkages among studies and reveal the evolution of research topics across the field. Full counting was employed as the counting method, and the association strength normalization method available in VOSviewer version 1.6.20 was used to construct the network. Prior to analysis, keyword cleaning was performed using a thesaurus file to merge synonymous terms and remove irrelevant or noise terms. For example, "GIS" and "Geographic Information Systems" were treated as equivalent concepts. A minimum occurrence threshold was applied to retain only keywords with sufficient frequency to ensure meaningful visualization. Cluster formation was generated automatically by the VOSviewer clustering algorithm based on the strength of relationships among keywords. Furthermore, science mapping techniques were employed through network, overlay, and density visualizations to identify dominant research themes, thematic clusters, and emerging directions in GIS-based spatial learning and environmental education research. The resulting visualizations provided a comprehensive overview of the knowledge structure, thematic development, and research dynamics within GIS-supported educational studies.

Thematic Synthesis

Following the bibliometric analysis, a thematic synthesis was conducted on the 72 studies included after the screening process to identify recurring educational themes, conceptual patterns, and research implications. The analysis involved iterative reading of titles, abstracts, and available full texts, followed by open coding of key educational concepts, learning approaches, and research outcomes. Similar codes were subsequently grouped into broader thematic categories. This process resulted in the identification of five dominant themes: GIS-based spatial learning, spatial thinking development, environmental literacy and sustainability education, remote sensing and geospatial environmental learning, and implications for action research. These themes provided the basis for interpreting the educational contributions and future directions of GIS-based learning research.

Reliability and Trustworthiness

To enhance the reliability of the review process, the screening and thematic classification procedures were conducted systematically using predefined criteria. Bibliometric findings were cross-validated through multiple VOSviewer visualizations, including network, overlay, and density maps. Furthermore, thematic interpretations were continuously compared with bibliometric patterns to ensure consistency between quantitative mapping and qualitative synthesis. The combination of bibliometric analysis and thematic synthesis provides methodological triangulation that strengthens the validity and credibility of the study findings (Donthu et al., 2021).

RESULT AND DISCUSSION

Dataset Characteristics and Publication Trends

As shown in Figure 2, publication output remained relatively stable between 2020 and 2023, with annual publications ranging from 16 to 20 documents. A marked increase was observed in 2024 and 2025, reaching a peak of 42 publications in 2025, indicating growing research interest in GIS-supported learning and geospatial education. The lower number of publications recorded in 2026 should be interpreted with caution because the database search was conducted in January 2026 and, therefore, the 2026 data represent only a partial publication year. Consequently, the publication count for 2026 is not directly comparable with the complete annual records from 2020 to 2025. Overall, the trend suggests increasing recognition of GIS and geospatial technologies as important tools for promoting spatial thinking, environmental literacy, and sustainability-oriented learning.

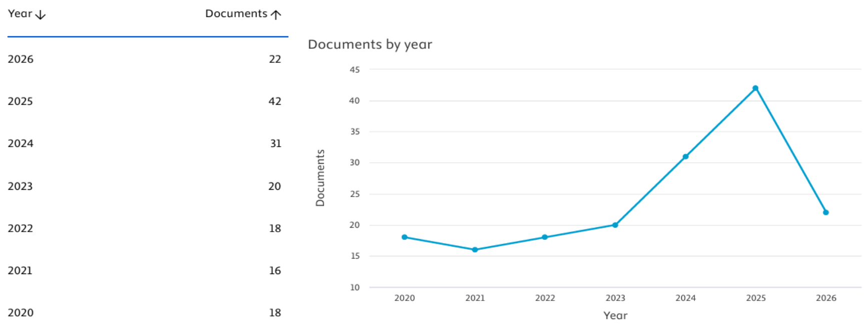

Figure 2. Annual scientific production related to GIS-based learning and geospatial education from 2020 to 2026. Data for 2026 represent a partial publication year because the database search was conducted in January 2026.

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Distribution of Research Areas

GIS-based educational research is inherently interdisciplinary, drawing upon knowledge and methodologies from education, geography, environmental science, computer science, and related fields. Examining the distribution of subject areas provides insights into the disciplinary foundations that have shaped the development of GIS-supported learning and geospatial education. Figure 3 presents the distribution of publications across subject areas based on the Scopus classification system. This analysis helps identify the dominant disciplinary perspectives contributing to the advancement of the field.

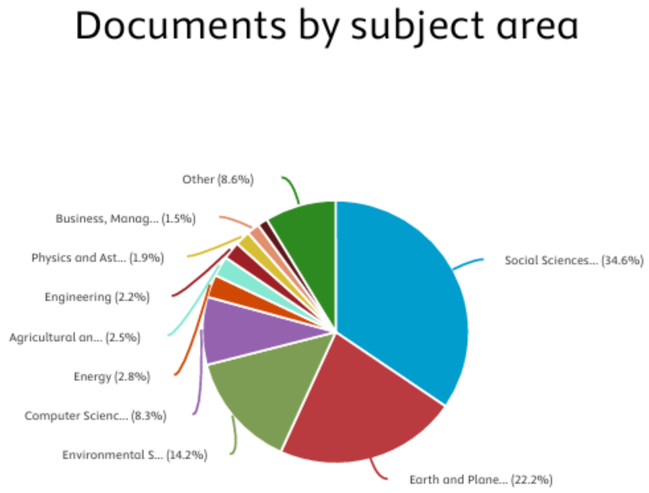

Figure 3. Distribution of publications across Scopus subject areas, illustrating the interdisciplinary nature of GIS-based educational research.

As illustrated in Figure 3, Social Sciences constituted the largest subject area, accounting for 34.6% of the total publications, followed by Earth and Planetary Sciences (22.2%) and Environmental Science (14.2%). Computer Science also contributed substantially (8.3%), highlighting the growing role of digital technologies and geospatial tools in educational contexts. Smaller contributions from Engineering, Energy, Agricultural Sciences, Physics, and Business-related fields further demonstrate the interdisciplinary nature of GIS-based educational research. Overall, the distribution suggests that GIS is increasingly positioned as both an educational and environmental learning tool, bridging pedagogical, technological, and sustainability-oriented perspectives.

Geographical Distribution of Scientific Production

The geographical distribution of publications provides valuable insights into the global development and dissemination of GIS-based educational research. Examining country-level scientific production helps identify regions that have played a significant role in advancing GIS-supported learning, spatial thinking, and environmental education. Furthermore, this analysis reveals the extent to which geospatial education has expanded across different educational and socio-economic contexts. Figure 4 presents the ten most productive countries contributing to the field during the study period.

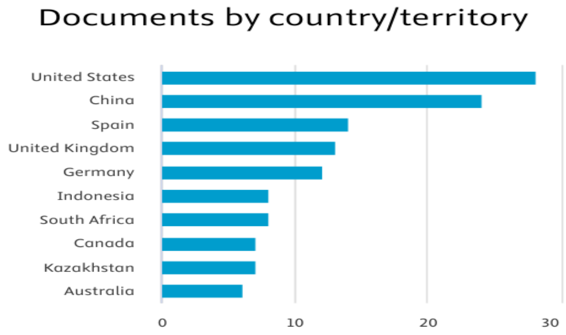

Figure 4. Top contributing countries in GIS-based educational research (2020–2026), indicating the geographical distribution of scientific production.

As shown in Figure 4, the United States emerged as the leading contributor, followed by China and Spain. Other notable contributors included the United Kingdom, Germany, Indonesia, South Africa, Kazakhstan, and Australia. The dominance of the United States and China reflects strong investments in educational technology, geospatial innovation, and research infrastructure. Meanwhile, the presence of countries from Asia, Africa, and Europe demonstrates the increasingly global nature of GIS-based educational research. This geographical diversity suggests that the integration of GIS into teaching and learning is no longer limited to developed countries but has become an important area of educational innovation across various regions of the world.

Document Characteristics

The dataset was dominated by journal articles, which accounted for 95.8% of the retrieved publications, while review articles represented only 4.2%. This distribution indicates that research on GIS-based spatial learning and environmental education remains largely driven by empirical investigations, particularly those examining classroom implementation, instructional innovation, and technology-enhanced learning practices. The relatively small proportion of review studies suggests that evidence-synthesis research in this field is still emerging, highlighting the need for more comprehensive reviews to consolidate existing knowledge and identify future research directions.

Overall, the bibliometric findings indicate that research on GIS-based education is characterized by increasing international participation, interdisciplinary expansion, and strong conceptual connections among pedagogical, cognitive, technological, and environmental dimensions. The combination of publication trends, subject-area distribution, country productivity, and science mapping analyses provides a comprehensive overview of the development and current directions of the field.

Science Mapping Analysis

Keyword Co-occurrence Network

Keyword co-occurrence analysis was conducted to explore the intellectual structure and conceptual relationships within GIS-based educational research. By examining the frequency and co-occurrence of author keywords, this analysis provides insights into the dominant research themes and the extent to which different topics are interconnected. The network visualization generated by VOSviewer reveals the major knowledge domains that have shaped the development of GIS-supported learning, spatial thinking, and environmental education.

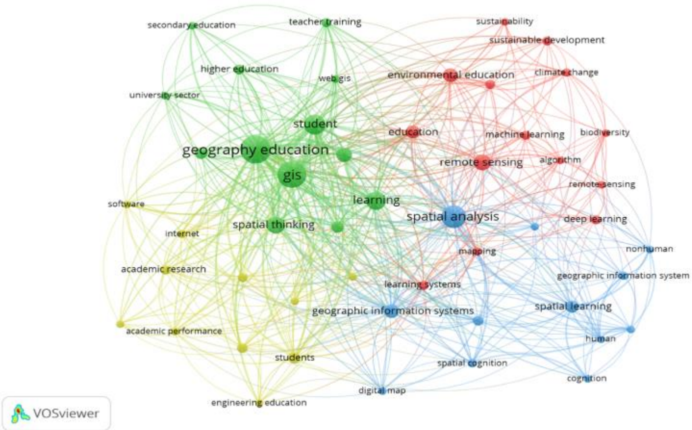

Figure 5. Network visualization of keyword co-occurrence generated using VOSviewer, illustrating conceptual relationships and thematic clusters within GIS-based educational research.

As shown in Figure 5, the keyword network consists of 50 keywords connected through 515 links, with a total link strength of 1,157, indicating a highly interconnected research landscape. The largest and most central nodes are *Geography Education*, *GIS*, *Spatial Analysis*, *Learning*, *Spatial Thinking*, and *Remote Sensing*, demonstrating their pivotal role in shaping the field. The visualization further reveals four major thematic clusters. The green cluster is centered on geography education, GIS, students, and spatial thinking, highlighting the pedagogical dimension of geospatial learning. The red cluster emphasizes environmental education, sustainability, climate change, remote sensing, and machine learning, reflecting the growing integration of geospatial technologies within environmental and sustainability studies. The blue cluster focuses on spatial analysis, spatial learning, geographic information systems, and spatial cognition, representing the cognitive and analytical foundations of GIS-based education. Meanwhile, the yellow cluster includes academic performance, academic research, engineering education, and related educational outcomes, indicating the broader educational impact of geospatial learning. Overall, the network demonstrates that GIS-based educational research is characterized by strong connections among pedagogical, cognitive, technological, and environmental domains, supporting its increasingly interdisciplinary nature.

Density Visualization

Density visualization was performed to identify the concentration and prominence of research topics within the GIS-based educational literature. Unlike network visualization, which emphasizes relationships among keywords, density mapping highlights the frequency and relative importance of topics based on their occurrence and connectivity within the dataset. Areas with warmer colors indicate higher research intensity, whereas cooler colors represent topics that have received comparatively less scholarly attention. Figure 6 presents the density visualization generated from the keyword co-occurrence analysis.

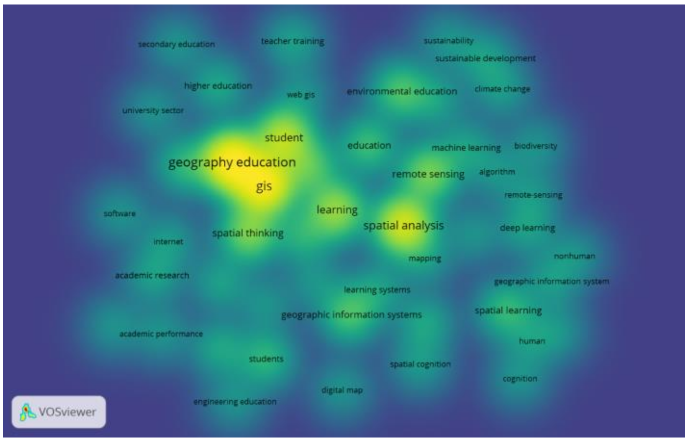

Figure 6. Density visualization of keyword occurrence generated using VOSviewer, highlighting the concentration and prominence of research topics.

As shown in Figure 6, the highest-density areas are concentrated around the keywords *Geography Education*, *GIS*, *Spatial Analysis*, *Learning*, and *Spatial Thinking*, indicating that these topics constitute the core research focus of the field. The strong concentration surrounding these keywords suggests that GIS-based educational research has primarily emphasized the development of spatial competencies, geography learning, and geospatial reasoning. In contrast, topics such as *Climate Change*, *Sustainability*, *Remote Sensing*, *Machine Learning*, *Spatial Learning*, and *Environmental Education* appear in medium-density areas, reflecting growing but comparatively less established research attention. Meanwhile, keywords related to *Academic Performance*, *Engineering Education*, *Digital Map*, and *Spatial Cognition* are located in lower-density regions, suggesting that these themes remain relatively specialized or emerging. Overall, the density map demonstrates that while geography education and spatial thinking continue to dominate the field, research is gradually expanding toward sustainability, environmental literacy, and advanced geospatial technologies, indicating increasing diversification of GIS-based educational research.

Temporal Evolution of Research Themes

Overlay visualization was conducted to examine the temporal evolution of research themes within the GIS-based educational literature. In this visualization, node colors represent the average publication year (APY) of each keyword, enabling the identification of both established and emerging research topics. Keywords with lower APY values are displayed in darker blue tones, whereas those with higher APY values appear in green and yellow tones. Figure 7 presents the temporal distribution of keywords across the study period.

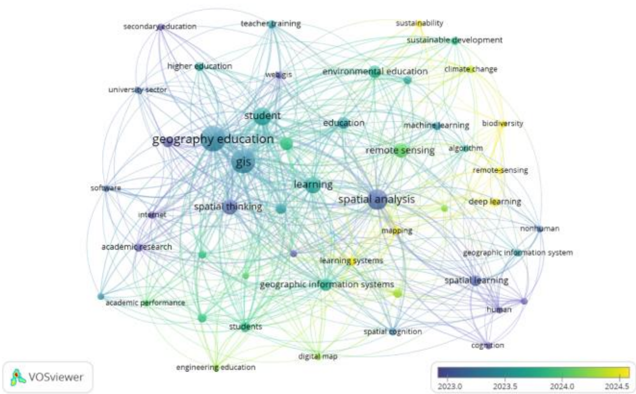

Figure 7. Overlay visualization of thematic evolution based on average publication year, showing established and emerging research themes in GIS-based educational research.

As illustrated in Figure 7, keywords such as *Geography Education*, *GIS*, *Spatial Thinking*, *Academic Research*, and *University Sector* are represented by relatively darker blue tones, indicating lower average publication years within the dataset. These themes constitute the established foundations of GIS-based educational research and have consistently shaped the field over time. In contrast, keywords including *Environmental Education*, *Remote Sensing*, *Machine Learning*, *Climate Change*, *Biodiversity*, *Sustainability*, and *Sustainable Development* appear in greener and yellowish tones, reflecting more recent average publication years and increasing scholarly attention. The prominence of these emerging themes suggests that current research is expanding beyond traditional geography instruction toward sustainability-oriented, technology-enhanced, and interdisciplinary educational applications. Overall, the overlay visualization indicates a continuing shift in research focus toward the integration of geospatial technologies, environmental literacy, and sustainable development within contemporary educational contexts.

Taken together, the network, density, and overlay visualizations provide complementary perspectives on the intellectual structure and thematic evolution of GIS-based educational research. The keyword network reveals strong conceptual linkages among geography education, spatial thinking, environmental education, and geospatial technologies, highlighting the interdisciplinary nature of the field. Density visualization indicates that geography education and spatial thinking remain the most established research domains, whereas overlay visualization demonstrates increasing scholarly attention toward sustainability, climate change, remote sensing, machine learning, and environmental literacy. According to the framework proposed by the National Research Council (2006), spatial thinking comprises three interrelated dimensions, namely concepts of space, tools of representation, and processes of spatial reasoning. These dimensions enable learners to recognize spatial relationships, interpret multiple representations, and apply analytical reasoning to geographic phenomena. GIS-based learning environments support all three dimensions by allowing students to visualize spatial patterns, manipulate geospatial information, and construct evidence-based explanations. These findings suggest that GIS-based educational research has evolved from a primary focus on geospatial technologies toward broader educational objectives emphasizing sustainability, interdisciplinary learning, and real-world problem-solving.

Thematic Synthesis of Included Studies (n = 72)

To complement the bibliometric findings, a thematic synthesis was conducted on 72 studies selected through the screening process. The analysis identified five dominant themes that collectively characterize the current landscape of GIS-based educational research.

Table 1. Distribution of studies included in thematic synthesis.

Theme	Representative Codes	Definition	Number of Studies	Percentage (%)
GIS-Based Spatial Learning	GIS learning, Web-GIS, digital mapping	Studies emphasizing GIS-supported learning environments and instructional practices	13	18.1
Spatial Thinking Development	spatial reasoning, map interpretation, spatial cognition	Studies focusing on the development of spatial thinking competencies	15	20.8
Environmental Literacy and Sustainability Education	sustainability, climate change, environmental awareness	Studies addressing environmental literacy and sustainability competencies	9	12.5
Remote Sensing and Geospatial Environmental Learning	remote sensing, UAV, environmental monitoring	Studies utilizing remote sensing and geospatial technologies for environmental learning	5	6.9

Action-Oriented and Inquiry-Based GIS Learning	inquiry learning, project-based learning, participatory mapping, authentic problem-solving	Studies emphasizing inquiry-based, project-based, and action-oriented approaches that engage learners in authentic problem-solving and active participation within GIS-supported educational contexts.	30	41.7
Total	-	-	72	100

As shown in Table 1, Action-Oriented and Inquiry-Based GIS Learning represented the largest category identified in the thematic synthesis, accounting for 41.7% of the included studies. This pattern was derived from the coding process rather than from keyword co-occurrence analysis. The high proportion of studies within this category reflects the increasing use of inquiry-based learning, project-based learning, participatory mapping, and authentic problem-solving activities in GIS-supported educational contexts. Overall, these findings suggest a gradual shift from technology-centered perspectives toward more learner-centered and action-oriented educational practices.

The synthesis further indicates that GIS-based learning contributes substantially to the development of spatial thinking, environmental literacy, and sustainability competencies. Collectively, the identified themes reveal an evolution of the field from a primary focus on geospatial technology adoption toward broader educational goals related to critical thinking, environmental awareness, and active learner engagement. Nevertheless, studies addressing environmental applications and remote sensing-based learning in school settings remain comparatively limited. These gaps highlight important opportunities for future research aimed at integrating geospatial technologies with sustainability education, environmental literacy, and community-based educational initiatives. These gaps highlight important opportunities for future research aimed at integrating geospatial technologies with coastal education, disaster literacy, sustainability learning, and community-based educational initiatives.

Across the reviewed studies, GIS-supported learning was implemented across diverse educational contexts, including primary, secondary, and higher education. Various geospatial tools, such as GIS software, Web-GIS platforms, remote sensing applications, and digital mapping technologies, were employed in conjunction with inquiry-based, project-based, and collaborative learning approaches. Methodologically, the literature comprised qualitative, quantitative, mixed-methods, and experimental designs. Despite differences in educational settings and research approaches, most studies consistently reported positive outcomes related to spatial thinking, environmental literacy, problem-solving skills, learner engagement, and sustainability-oriented competencies. These findings collectively demonstrate the broad applicability and educational value of GIS-supported learning across multiple contexts.

To enhance the transparency and auditability of the thematic synthesis, a coding framework was developed based on recurring concepts, learning approaches, and educational outcomes identified in the selected studies. Initial codes included GIS-supported learning, spatial reasoning, environmental awareness, sustainability competencies, remote sensing applications, inquiry-based learning, project-based learning, participatory mapping, and community engagement. Similar codes were subsequently grouped into broader themes according to their conceptual similarities. Each study could contribute to more than one code, but classification into the dominant theme was based on the primary educational focus of the study. Definitions of themes, representative codes, and the number of articles included in each category are presented in Table 1.

Although five dominant themes were identified, these categories should not be interpreted as mutually exclusive. Many studies addressed multiple aspects simultaneously, reflecting the interdisciplinary nature of GIS-based educational research. For example, studies focusing on GIS-supported learning frequently contributed to the development of spatial thinking, environmental literacy, and sustainability competencies. Therefore, individual studies could be associated with several codes, whereas assignment to a dominant theme was determined by the primary educational emphasis of each study. Furthermore, comparison with the overlay visualization suggests a temporal progression in which early studies predominantly emphasized GIS implementation and spatial thinking, whereas more recent research increasingly addresses environmental literacy, sustainability-oriented learning, remote sensing applications, and action-oriented learning approaches. This pattern indicates an evolving shift from technology-centered perspectives toward more integrated and learner-centered educational frameworks.

To further enhance the transparency and depth of the evidence synthesis, additional information regarding the characteristics of the reviewed studies was compiled, including authors, publication year, country, educational level, GIS tools, learning approaches, research methods, and principal findings. A summary of these characteristics is provided in Supplementary Table S1 to facilitate comparison across studies and support the interpretation of thematic patterns.

Discussion

The Evolution of GIS-Based Learning from Technology Adoption to Educational Transformation

The development of GIS-based learning reflects a broader transformation in educational technology from tool-centered adoption toward learner-centered knowledge construction. Early applications of GIS primarily emphasized technical skills and software operation, whereas recent studies position GIS as a pedagogical platform that supports inquiry, problem-solving, collaboration, and evidence-based reasoning (Bernhäuserová et al., 2022; Ortega et al., 2024). This shift aligns with constructivist learning theory, which views learning as an active process of knowledge construction through authentic experiences and contextual problem solving. Contemporary GIS-supported instruction increasingly integrates real-world spatial data, allowing students to investigate environmental and social phenomena rather than merely consume information. Consequently, GIS has evolved from a geospatial technology into a transformative educational medium that facilitates higher-order thinking and authentic learning experiences (Hürsen & Beyoğlu, 2025; Hansen, 2025).

Spatial Thinking as the Core Competency of GIS Education

Spatial thinking remains the fundamental cognitive outcome of GIS education because it enables learners to understand spatial relationships, patterns, scale, distribution, and environmental interactions. According to spatial cognition theory, geographic understanding develops when learners can visualize, interpret, and reason about spatial phenomena through multiple representations. GIS provides a unique environment for developing these competencies by transforming abstract spatial concepts into interactive and observable experiences (Pascu, 2026; Yamauchi et al., 2025). Previous studies consistently demonstrate that GIS-supported learning improves map interpretation, geospatial reasoning, and problem-solving skills, particularly when combined with inquiry-based and project-based approaches (Martínez-Hernández et al., 2024; Wijaya et al., 2026). These findings reinforce the argument that spatial thinking serves as the intellectual foundation connecting geospatial technologies with meaningful educational outcomes.

GIS, Environmental Literacy, and Education for Sustainable Development

The growing integration of GIS within environmental education reflects increasing recognition of the importance of sustainability competencies in the twenty-first century. Education for Sustainable Development (ESD) emphasizes systems thinking, environmental responsibility, and evidence-based decision-making as essential competencies for addressing complex environmental challenges (UNESCO, 2020). GIS contributes directly to these goals by enabling learners to visualize environmental change, analyze spatial patterns, and explore sustainability issues through authentic datasets. Recent studies demonstrate that GIS-supported learning enhances environmental literacy, climate-change awareness, and sustainability understanding by connecting classroom learning with real environmental problems (Kurniawan et al., 2024; Senese et al., 2026). Therefore, GIS should be viewed not merely as a digital tool but as a strategic medium for fostering sustainability-oriented learning and responsible citizenship.

Environmental literacy encompasses not only environmental knowledge but also attitudes, competencies, and responsible behaviors toward environmental issues. In parallel, UNESCO (2020) identifies key Education for Sustainable Development (ESD) competencies, including systems thinking, anticipatory competency, normative competency, strategic competency, collaboration, critical thinking, self-awareness, and integrated problem-solving. Through the analysis of authentic spatial data and environmental phenomena, GIS-supported learning provides opportunities for developing these competencies and promoting sustainability-oriented decision-making.

Action-Oriented Learning as an Emerging Direction in GIS Education

One of the prominent themes identified through the thematic synthesis is the growing adoption of action-oriented learning approaches in GIS education. This observation is based on the coding of the reviewed studies rather than on keyword co-occurrence patterns. Grounded in the principles of action research, action-oriented learning emphasizes investigation, participation, reflection, and problem-solving within authentic contexts. Grounded in the principles of action research, action-oriented learning emphasizes investigation, participation, reflection, and problem-solving within authentic contexts. Action-oriented pedagogy emphasizes learner participation, reflection, collaboration, and engagement with authentic problems to promote meaningful social and environmental action. Rather than focusing solely on knowledge acquisition, this approach encourages students to investigate issues, design solutions, implement actions, and evaluate outcomes.

These principles are closely aligned with the characteristics of GIS-supported inquiry and project-based learning, which position learners as active participants in knowledge construction and problem-solving. GIS naturally supports these processes because it enables learners to identify issues, analyze spatial evidence, propose solutions, and evaluate outcomes. Recent studies have demonstrated the effectiveness of GIS-based inquiry, phenomenon-based learning, disaster-risk education, and participatory mapping in improving student engagement and geoliteracy (Meechandee & Meekaew, 2025; Song et al., 2023). Furthermore, GIS-supported action learning aligns closely with contemporary educational priorities emphasizing learner agency, collaborative inquiry, and community engagement. This trend suggests that the future of GIS education lies not only in developing technical competence but also in empowering learners to become active problem solvers and informed decision makers.

Future Opportunities for Environmental and Sustainability Learning

Despite substantial advances in GIS-based education, several environmental and sustainability-related applications remain comparatively underrepresented within the literature. Recent developments in remote sensing, UAV technology, digital mapping, and spatial analytics offer promising opportunities for creating authentic learning experiences that connect students with real-world environmental issues. Such approaches have considerable potential to strengthen spatial thinking, environmental literacy, and sustainability competencies while promoting learner participation and community engagement. Consequently, future research should prioritize place-based, inquiry-oriented, and community-centered GIS learning models that integrate environmental monitoring, citizen science, and sustainability education. These directions may further strengthen the role of GIS as a medium for connecting geospatial technologies with meaningful environmental learning.

Integrative Conceptual Framework of GIS-Based Education

Based on the bibliometric findings and thematic synthesis, an integrative conceptual framework of GIS-based education is proposed to illustrate the relationships among geospatial technologies, GIS-supported learning, spatial thinking development, environmental literacy, sustainability-oriented learning, and action-oriented learning. As shown in Figure 8, geospatial technologies serve as enabling tools that support inquiry-based and project-based learning processes. These processes contribute to the development of spatial thinking, environmental literacy, and sustainability competencies, which ultimately foster action-oriented learning, community engagement, and responsible environmental citizenship. The framework highlights the interconnected and learner-centered nature of contemporary GIS education and provides a conceptual basis for future research and educational practice.

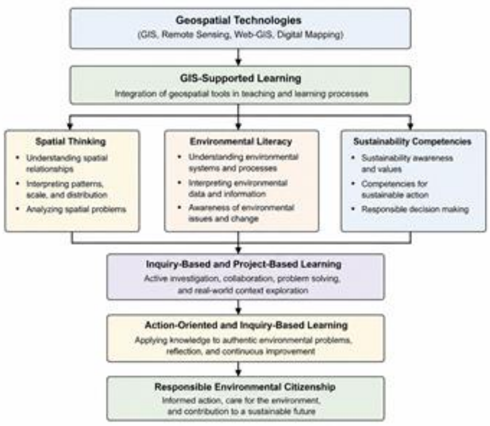

Figure 8. Integrative conceptual framework of GIS-based education derived from bibliometric analysis and thematic synthesis.

The proposed framework synthesizes the principal themes identified in this review and emphasizes the evolving role of GIS as a pedagogical medium that connects technological capabilities with cognitive, environmental, and sustainability-related learning outcomes. Rather than representing a causal model, the framework provides a conceptual representation of the major relationships emerging from the reviewed literature.

CONCLUSION

This study employed a bibliometric-systematic review approach to examine the development of research on GIS-based spatial learning, environmental education, and geospatial technologies. The findings indicate that GIS-based educational research has evolved from a technology-oriented focus toward a broader educational framework emphasizing spatial thinking, environmental literacy, sustainability competencies, and learner-centered pedagogies. The increasing integration of GIS with inquiry-based, project-based, and participatory learning demonstrates its growing role as a transformative educational tool rather than merely a geospatial technology. The review further highlights that spatial thinking serves as the central competency underpinning GIS education. Through geospatial visualization, spatial analysis, and authentic data exploration, GIS supports higher-order cognitive processes that enable learners to understand complex environmental systems and make evidence-based decisions. At the same time, the integration of GIS within environmental and sustainability education aligns closely with the objectives of Education for Sustainable Development (ESD), particularly in fostering environmental awareness, systems thinking, and responsible citizenship. A notable contribution of this study is the identification of action-oriented learning and community engagement as a prominent theme within the thematic synthesis of GIS education literature. The literature increasingly emphasizes inquiry, participation, problem-solving, and community engagement, suggesting strong alignment between GIS-supported learning and action research principles. Based on the synthesis of the reviewed studies, this article proposes an integrative conceptual framework linking geospatial technologies, spatial thinking, environmental literacy, action-oriented learning, and sustainability competencies. Despite the rapid growth of GIS-based educational research, coastal and environmental learning contexts remain relatively underrepresented. Future studies should therefore explore the integration of GIS, remote sensing, and place-based environmental learning in coastal and disaster-prone regions. Such efforts may strengthen the contribution of geospatial education to environmental sustainability, community resilience, and educational innovation.

Implications

The findings provide important implications for educators, curriculum developers, and researchers. Educational institutions should promote the integration of GIS and geospatial technologies within geography, science, and environmental education to strengthen spatial literacy and sustainability competencies. Researchers are encouraged to develop action-oriented and community-based GIS learning models that address authentic environmental challenges and support sustainable development goals.

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