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A Systematic Review of the Literature on STEM Education with GIS

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Abstract

This systematic review examined the integration of Geographic Information Systems (GIS) in STEM education. 17 peer-reviewed studies (2005–2025) were included from Scopus, ERIC, IEEE Xplore, and Google Scholar. Five research questions examined methodology, outcomes, educational levels, participants, and intervention types. Mixed methods dominated (n=7), with no strictly experimental designs identified. Integrative STEM was the most frequent outcome (n=8), and most studies reported simultaneous cognitive and affective gains. Of the 17 studies, 13 were empirical (direct educational interventions with identifiable participants) and informed the subsequent analyses. Research was concentrated at the secondary level (n=8), with students as primary participants and no in-service teachers designated as a primary group. Multidisciplinary contexts (n=10), mixed-method interventions (n=8), and extended-duration programs (n=10) defined the pedagogical profile. A number of gaps were identified including the absence of primary school research and the marked geographic concentration of American studies. Lastly, the findings highlight the need for rigorous designs, teacher-focused inquiry, and international comparative research.

Keywords

Geographic Information Systems, GIS, STEM Education, systematic review

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Introduction

The advent of cutting-edge educational strategies has shifted towards learner-centered teaching practices that draw attention not only to the comprehension and retention of the students' knowledge and skills, but to students' active engagement as well. One such area of emphasis is STEM education (Science, Technology, Engineering, and Mathematics), which has become increasingly popular as a means of providing students with the analytical and problem-solving skills required for the world's growing complexity and technological advancement (Allen & Peterman, 2019). Through tertiary settings, STEM is garnering increased attention globally in all aspects of education (Kennedy & Tunnicliffe, 2022).

Furthermore, improving academic proficiency in STEM fields has emerged as a global priority to ensure that students are properly equipped for STEM-related careers (Thibaut et al., 2018; Nugent et al., 2015), as the decision to enter STEM careers has been found to be positively impacted by high STEM participation (Franz-Odendaal et al., 2016). Students demonstrating advanced spatial reasoning defined as "the ability to generate, retain, retrieve, and transform well-structured visual images," (Lohman, 1994) are more likely to engage in higher education and pursue STEM careers (Hegarty, 2014) and succeed in them (Wai et al., 2009). Uttal and Cohen (2012) contend that a deficiency in spatial ability may be a hindrance to STEM. GIS-based training that develops spatial thinking skills should be provided to prepare adolescents for success in STEM education and careers (Lee & Bednarz, 2009).

Geographic Information Systems enable students to observe, comprehend, analyze, interpret, and visualize data in a variety of ways that highlight links, patterns, and trends through the use of maps, globes, reports, charts, and other visual aids (Kerski, 2015; Baker et al., 2015). Students in STEM fields must learn how to collect and analyze data, as well as how to formulate and respond to questions based on the information and the issue being addressed. By allowing students to visualize and interpret complex data, GIS supports them to develop evidence-based understanding of real-world issues (Kerski, 2015), enhancing the students' spatial reasoning, as a core competency across STEM fields (Jant et al., 2020).

The interdisciplinary character of this technology (Henry & Semple, 2012) further justifies its growing adoption as a pedagogical tool in STEM education (Srisawasdi, 2012). GIS provides applications that can be utilized for both gathering real data and creating technology-assisted solutions for real-world STEM-related problems (Nugent et al., 2009). According to Patterson et al. (2003), such systems may advance scientific classrooms by engaging with scientific inquiry through the integration of spatial technologies and STEM-related practices

The integration of GIS within STEM education is also supported by well-established theoretical foundations that explain why this pairing is pedagogically coherent. The first pillar relies on the spatial thinking theory, positing the ability to mentally represent, transform, and reason about spatial relations, as a general cognitive skill that is fundamental to problem-solving reasoning (National Research Council, 2006; Newcombe, 2010; Uttal & Cohen, 2012). Within this framework, GIS is considered a means of data visualization and a tool for empowering cognitive processes that externalize spatial representations and support their manipulation. Therefore, students are enabled to investigate through meaningful making, complex ideas and phenomena that may otherwise be difficult to conceptualize through conventional instructional approaches (Hegarty, 2014; Jant et al., 2020).

Spatial thinking is approached as a dynamic set of skills that is obtained through on-going cultivation and enrichment, rather than a fixed ability. Research has shown that instructional interventions using geospatial technologies can produce measurable improvements in spatial reasoning. These gains are particularly evident when the instruction is sustained over time,

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indicating that GIS as an educational tool cultivates key STEM skills (Lee & Bednarz, 2009; Wai et al., 2009).

The second theoretical pillar is the constructivist learning theory. According to this theory, the learning process is guided by real-world issues and meaningful contexts through which students actively construct knowledge (Jonassen, 1999; Vygotsky, 1978). GIS-based instruction allows students to collect, analyze, and interpret real-world geospatial data. Through inquiry and project-based learning, students can also build evidence-based arguments and address problems relevant to their own communities (Baker et al., 2015; Kerski, 2015).

A complementary theoretical foundation involves frameworks reflecting technology integration, one of which is the Technological Pedagogical Content Knowledge (TPACK) model (Mishra & Koehler, 2006). TPACK conceptualizes effective technology integration as emerging from the dynamic interaction among technological knowledge, pedagogical approaches, and subject-matter content. Based on the above, two categories emerge, learning with GIS and learning about GIS (Schulze, 2020) that gain theoretical significance. In the former approaches, GIS functions as a pedagogical tool for supporting the learning of STEM concepts and practices. In the latter, GIS itself becomes the focus of the instruction, as students develop competencies in geospatial technologies, spatial analysis, and the interpretation of spatial data.

Purpose of the Study

This study uses a systematic review to document existing research on the use of GIS in STEM education. Moreover, this study will add to the current state of knowledge in the field, and provide future researchers with an analytical framework to conduct more effective educational research around GIS in STEM education. Based on the research that has been conducted in STEM-GIS education, this study examines and answers the following research questions:

(RQ1) What are the research characteristics of studies on STEM-GIS education?

(RQ2) What outcomes have been reported in STEM-GIS education research?

(RQ3) At which educational levels is STEM-GIS empirical research conducted?

(RQ4) Who are the participants in empirical STEM-GIS education research?

(RQ5) In which disciplinary areas has STEM-GIS research been conducted, and through which types of interventions has it been implemented?

Method

The systematic review adopted the Preferred Reporting items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page et al., 2021). The methodology involved retrieving articles from specific bibliographic databases. Two researchers independently screened the titles and abstracts, then assessed the full texts of the remaining articles for eligibility, and finally extracted and analyzed the data. Disagreements at each stage were resolved through discussion until consensus was reached, taking into account both the inclusion and exclusion criteria. However, no formal inter-rater agreement statistic (e.g., Cohen's κ), was computed. This was due to the fact that the size of the retrieved articles was manageable and that the eligibility criteria were clearly defined. It is however acknowledged as a methodological limitation within this study.

It is important to clarify that the methodological classification adopted for RQ1 is conceptually distinct from the empirical/non-empirical distinction applied in RQ3–RQ5. For the purposes of the present review, a study is considered empirical only when it involves a direct educational intervention with identifiable participants, irrespective of whether its methodological approach is quantitative, qualitative, or mixed. Studies that adopt a quantitative or qualitative methodology, but rely exclusively on secondary data without a direct educational intervention are accordingly classified as non-empirical in the analyses for RQ3-RQ5.

The bibliographic databases used to retrieve articles were four, namely (1) Scopus, (2) ERIC, (3) IEEE Xplore and (4) Google Scholar. The first three databases are considered primary search systems suitable for systematic reviews, as noted by Gusenbauer and Haddaway (2020). In addition, the search for articles was extended to the Google Scholar database, mainly to search for references, check titles, and review abstracts. As suggested by Newman and Gough (2020), a systematic review in the field of education should use a variety of sources, such as the Internet (Google Scholar) and numerous bibliographic databases (Martín-Martín et al., 2021).

Google Scholar was included as a fourth search database given its superior coverage of education literature. The selection of Scopus, ERIC and IEEE Xplore as search databases is consistent with the methodology employed in recent systematic reviews in both GIS education (Havelčová et al., 2022; Konstantakatos & Galani, 2023) and STEM education research (Kefalis et al., 2025; Uludüz & Çalik, 2022; Cao et al., 2025). Database searches were conducted in January 2026. The search was limited to publications from 2005 to 2025, a period corresponding to the widespread adoption of GIS in educational contexts. Guided by the research questions, the literature search was conducted using the search strings presented in Table 1.

To ensure the relevance and quality of the retrieved literature, explicit inclusion and exclusion criteria were established prior to screening.

Articles were included if they:

(a) were published in peer-reviewed scientific journals or conference proceedings,

(b) were written in English,

(c) covered the period between 2005 and 2025,

(d) addressed the application or integration of Geographic Information Systems (GIS) in STEM education contexts,

(e) were available in open-access format at the time of retrieval, allowing full-text access for screening and data extraction.

Articles were excluded if they:

(a) examined GIS only as a technological tool without addressing educational outcomes or pedagogical dimensions,

(b) did not meet minimum quality standards for a research study, such as white papers, opinion pieces, or non-peer-reviewed technical reports.

Table 1 Search strings by database

Database	Search String	Field Tag
Scopus	("GIS" OR "Geospatial Technolog*" OR "Geographic* Information System*") AND ("STEM Education" OR "Integrated STEM")	TITLE-ABS-KEY
ERIC	("GIS" OR "Geospatial Technology" OR "Geographic Information Systems") AND ("STEM Education" OR "Integrated STEM")	All Fields
IEEE Xplore	("GIS" OR "Geospatial Technology" OR "Geographic Information Systems") AND ("STEM Education" OR "Integrated STEM")	Metadata Only
Google Scholar	("GIS" OR "Geospatial Technology" OR "Geographic Information Systems") AND ("STEM Education" OR "Integrated STEM")	Title / All Fields

The initial search resulted in a total of 134 records as shown in Figure 1. After removing the duplicates (43), 91 unique records remained. After title and abstract screening, 67 records were removed due to not addressing the application or integration of GIS in STEM contexts. Out of the 24 remaining, four were excluded because they did not meet inclusion criterion (e), as their full text was not available in open-access format and could not be retrieved. The remaining 20 articles were read in full by both researchers and verified against the literature selection criteria. However, after a full-text review, three additional records were removed due to being listed as white papers.

The final selection comprised 17 peer-reviewed studies, which were independently coded and analyzed by the two researchers using a thematic analysis approach. Data were extracted into an Excel worksheet. Extraction and analysis of the article data proceeded in two phases. In Phase 1, each of the six parts of an Excel worksheet had columns for subcategories. The first section contained the essential information, namely, country, title, year of publication, authors' details, and source. Data related to the five research questions of the current analysis were recorded in the remaining five sections. In Phase 2, thematic analysis was used to transform the qualitative data on themes once all the cells in the columns of the Excel worksheet for each article had been filled out. The thematic analysis followed the six-phase framework proposed by Braun and Clarke (2006). The five research questions provided the overarching analytical dimensions, while the specific subcategories within each dimension were allowed to emerge from the data. Both researchers independently familiarized themselves with the 17 studies, generated initial codes, and then jointly searched for, reviewed, and defined the final themes that correspond to the analytical subcategories reported in the Findings. The synthesis matrix presented in Table 2 constitutes the final output of this analytical process. Disagreements between the two researchers at any phase were resolved through iterative discussion until consensus was reached.

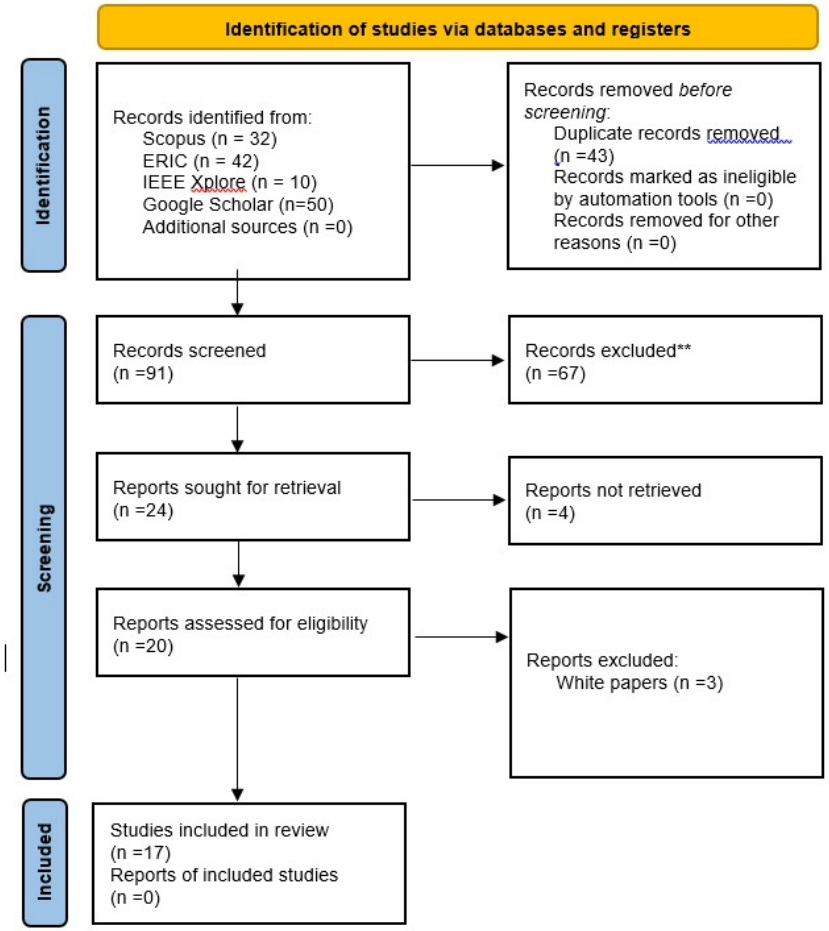


Figure 1. PRISMA flowchart for the selection process

Findings

This systematic review examined 17 peer-reviewed studies on the integration of Geographic Information Systems (GIS) in STEM education (STEM-GIS education). The findings are presented across five categories corresponding to the research questions.

In terms of country distribution, six countries were identified. Moreover, the United States accounted for the majority of publications (n=12), while the remaining five studies originated from Greece, Turkey, Taiwan, Germany, and Cyprus. Publication years ranged from 2009 to 2025. This is in line with a growing scholarly interest in GIS integration within STEM education over the past decade, with 2016 and 2019 each yielding three published studies (Figure 2).

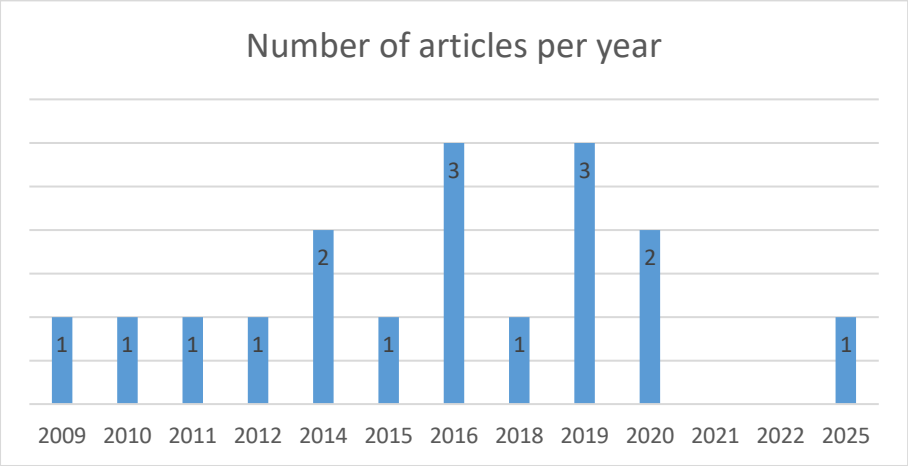


Figure 2. Distribution of articles by year

The predominance of American studies could be explained taking two factors into consideration. Firstly, due to the early and widespread adoption of GIS technologies in US educational settings, and secondly due to the prominent role of organizations such as Esri in supporting GIS-based curricula. Regarding publication type, the majority of studies appeared in peer-reviewed journals (n=11), with the remainder published in peer-reviewed conference proceedings (n=6).

Table 2 presents a synthesis matrix mapping all 17 reviewed studies onto the five analytical dimensions of this review, and serves as a navigational reference for the findings presented in the subsequent sections.

RQ1: What are the research characteristics of studies on STEM-GIS education?

To address the first research question, two subcategories were examined. The first subcategory referred to research methods. Each article was classified by the researchers into one of the five categories listed below:

Descriptive: Although these publications gave a thorough description of a program, event, or classroom environment, they lacked systematic study and measurable results.

Literature review: Based on the body of existing literature, these articles used a review of the literature as a research methodology or to make recommendations for the implementation of the program.

Mixed Methods: Each publication in this group used a research approach that combined quantitative and qualitative techniques.

Qualitative approach: To collect and present the data for this study, the authors used a methodology that was exclusively qualitative.

Quantitative approach: The authors used only a quantitative method to collect and display data.

The second subcategory referred to research design, classified as experimental, quasi-experimental, and non-experimental.

Regarding research methods, the findings of the 17 studies show that the most frequently adopted approach was mixed methods (n=7), as evidenced in the work of Jant et al. (2020), Xie and Reider (2014), Groshans et al. (2019), Borowczak and Burrows (2016), Lindner et al. (2019), Ivey et al. (2012), and Zuniga-Teran et al. (2025). The second most common approach was a quantitative approach (n=5) (Nugent et al., 2009; Nugent et al., 2010; Nazareth et al., 2019; Shiau et al., 2018; Al Mamun et al., 2015), while two studies were identified as qualitative (n=2) (Kolvoord et al., 2011; Ercan et al., 2016). The remaining three studies were classified as literature reviews (n=1) (Delparte et al., 2016) or descriptive (n=2) (Kavouras et al., 2014; Hadjimitsis et al., 2020) (Figure 3).

When investigating the quantitative studies, Al Mamun et al. (2015) appears to be a methodologically distinct case. It appears that even though the study adopts a quantitative analytical approach, drawing on secondary data (e.g., enrollment and funding statistics to assess the positioning of Geography within STEM), it does not involve a direct educational intervention or identifiable participants. Due to this, it is considered as a quantitative study but it is treated as a non-empirical in the subsequent participant, level, and intervention related analyses (RQ3-RQ5).

During the coding process, several studies were classified as mixed methods. Even though the authors did not explicitly state their methodological approach, they incorporated both quantitative and qualitative data in their design. The prevalence of mixed methods reflects the multifactorial nature of STEM-GIS interventions, which require the measurement of learning outcomes and an understanding of the qualitative dimensions of student engagement with technology.

Table 2 Synthesis matrix of the 17 reviewed studies across RQ1–RQ5

Study	Methodology (RQ1)	Design (RQ1)	Outcome (RQ2)	Level (RQ3)	Participants (RQ4)	Disciplinary area (RQ5)	Intervention type (RQ5)
Al Mamun et al., 2015	Quantitative	Non-experimental	Standards development	N/A	N/A	N/A	N/A
Borowczak & Burrows, 2016	Mixed Methods	Non-experimental	Integrative STEM	Secondary school	Secondary school students	Multidiscipline	Mixed interventions
Delparte et al., 2016	Literature review	Non-experimental	Science education	N/A	N/A	N/A	N/A
Ercan et al., 2016	Qualitative	Non-experimental	Science education	University	Pre-service teachers	Multidiscipline	Mixed interventions
Groshans et al., 2019	Mixed Methods	Quasi-experimental	Implementation	University	University students	Geography/Environment	Lecture/computer practice
Hadjimitsis et al., 2020	Descriptive	Non-experimental	Integrative STEM	N/A	N/A	N/A	N/A
Ivey et al., 2012	Mixed Methods	Quasi-experimental	Implementation	University	University students	Engineering	Lecture/computer practice
Jant et al., 2020	Mixed Methods	Quasi-experimental	Integrative STEM	Secondary school	Secondary school students	Multidiscipline	Mixed interventions
Kavouras et al., 2014	Descriptive	Non-experimental	Integrative STEM	N/A	N/A	N/A	N/A
Kolvoord et al., 2011	Qualitative	Non-experimental	Science Education	Secondary school	Secondary school students	Multidiscipline	Mixed interventions
Lindner et al., 2019	Mixed Methods	Non-experimental	Integrative STEM	Secondary school	Secondary school students	Multidiscipline	Lecture/computer practice
Nazareth et al., 2019	Quantitative	Quasi-experimental	Science education	University	University students	Geography/Environment	Lecture/computer practice
Nugent et al., 2009	Quantitative	Quasi-experimental	Integrative STEM	Secondary school	Secondary school students	Multidiscipline	Mixed interventions
Nugent et al., 2010	Quantitative	Quasi-experimental	Integrative STEM	Secondary school	Secondary school students	Multidiscipline	Mixed interventions
Shiau et al., 2018	Quantitative	Non-experimental	Implementation	University	University students	Multidiscipline	Workshops
Xie & Reider, 2014	Mixed Methods	Quasi-experimental	Integrative STEM	Secondary school	Secondary school students	Multidiscipline	Mixed interventions
Zuniga-Teran et al., 2025	Mixed Methods	Non-experimental	Implementation	Secondary school	Secondary school students	Multidiscipline	Mixed interventions

N/A = Not applicable (non-empirical study). *Al Mamun et al. (2015)* is methodologically quantitative, but classified as non-empirical, as it relies exclusively on secondary statistical data without a direct educational intervention or identifiable participants.

Regarding research design analysis, it appears that no strictly experimental study was identified within the 17 included articles. The majority used non-experimental designs (n=10), while seven studies adopted quasi-experimental designs with comparison groups and pre/post-test measurements including Nugent et al. (2009, 2010), Jant et al. (2020), and Ivey et al. (2012). This absence of experimental designs in the reviewed corpus likely reflects the practical challenges inherent to educational research, in which random assignment of participants is rarely feasible. Nonetheless, the widespread adoption of quasi-experimental designs (41.2%) signals the methodological maturity of the field.

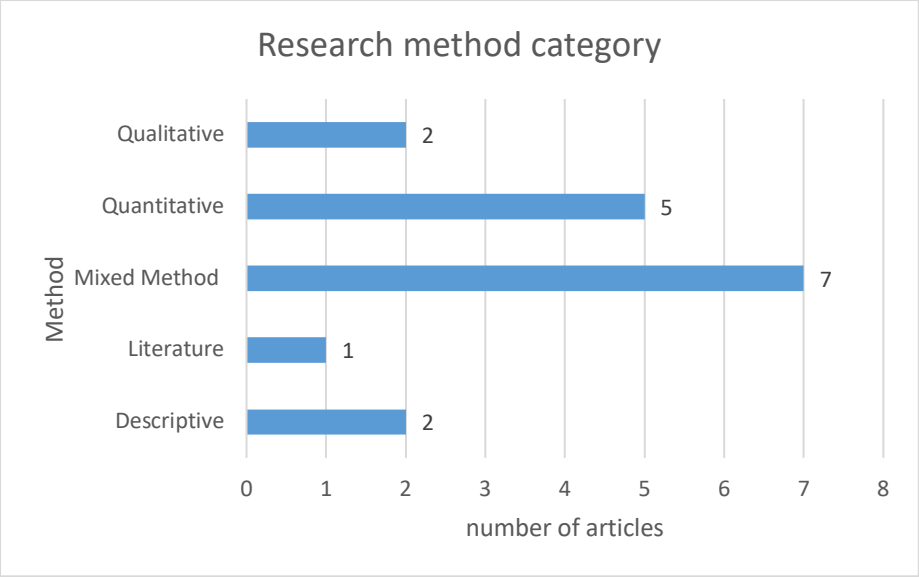


Figure 3. Distribution of articles according to research method category

As far as data collection tools are concerned, most studies incorporated more than one data collection tool, combining instruments such as questionnaires, achievement tests, surveys, and observational methods. One example is the study of Nugent et al. (2009, 2010), which included a combination of a 37-item content knowledge assessment and a 33-item attitude questionnaire based on the MSLQ. Similarly, Jant et al. (2020) combined rubric-based assessment of student geospatial reasoning within the Claim-Evidence-Reasoning framework with automated linguistic analysis of student discourse via the LIWC software. Borowczak and Burrows (2016) collected data using a 5-item pre/post achievement test alongside qualitative classroom observations, while Zuniga-Teran et al. (2025) employed a combination of Likert-scale surveys, written reflections, and direct observations. Among the quantitative tools, questionnaires and surveys were the most widely adopted, often complemented by achievement tests incorporating both pre- and post-testing phases. Qualitative data collection relied primarily on observational methods, document and text analysis, and interviews. Virtual spatial environments were also employed, as in the case of Nazareth et al. (2019), who used the Virtual Silcton platform to assess spatial navigation abilities.

RQ2: What outcomes have been reported in STEM-GIS education research?

To address the second research question, the investigation focused on the diverse results linked to the articles. The outcome of the articles was determined based on four distinct categories: 1) Standards Development, comprising the intended goal of readjusting standards to prioritize STEM, 2) Integrative STEM, regarding articles that specifically focus on outcomes involving many STEM fields, 3) Science Education, concerning articles specifically created for the purpose of education in the field of science and 4) Implementation, including articles promoting the execution of a curriculum program.

The most frequently reported outcome category was Integrative STEM (n=8), encompassing the studies of Kavouras et al. (2014), Jant et al. (2020), Nugent et al. (2009), Nugent et al. (2010), Xie and Reider (2014), Lindner et al. (2019), Hadjimitsis et al. (2020), and Borowczak and Burrows (2016). This was followed equally by Science Education (n=4), Kolvoord et al. (2011), Ercan et al. (2016), Delparte et al. (2016), and Nazareth et al. (2019) and Implementation (n=4), Shiau et al. (2018), Groshans et al. (2019), Ivey et al. (2012), and Zuniga-Teran et al. (2025). Only one study was classified under Standards Development (n=1) (Al Mamun et al., 2015), which advocated for the formal recognition of Geography as a STEM discipline to expand funding and student enrollment opportunities (Figure 4).

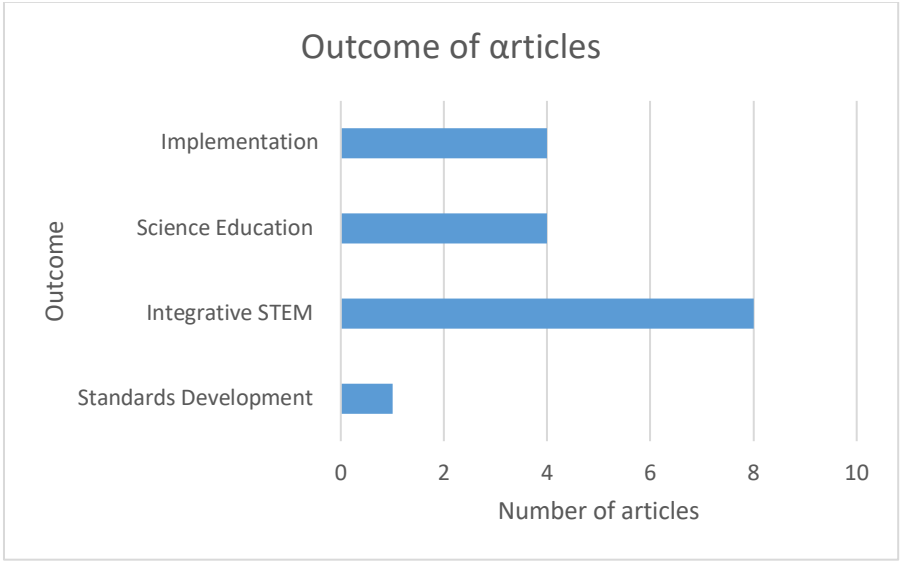


Figure 4 Distribution of outcomes categories for all studies

Within the Integrative STEM category, outcomes spanned spatial reasoning, content knowledge acquisition, attitudinal change, and STEM career orientation. Jant et al. (2020) found that students enrolled in the Geospatial Semester program demonstrated significant improvements in spatial reasoning and problem-solving. Compared to the control group, they produced more spatial language and more complete scientific arguments within the Claim-Evidence-Reasoning framework. Borowczak and Burrows (2016) documented a dramatic gain in content knowledge scores while simultaneously increasing students' confidence and perceived feasibility of a STEM career. Nugent et al. (2009, 2010) reported that their extended multi-week intervention led to significantly greater learning gains in mathematics, programming, and geospatial technology, paired with higher self-efficacy in GIS and robotics. Interestingly, the three-hour version of the same intervention was less effective for knowledge acquisition, yet produced strong positive effects on student attitudes and motivation toward science.

In the Science Education category, Nazareth et al. (2019) reported that GIS students improved significantly faster than communication students on both large-scale navigation skills and small-scale mental rotation tasks. Similarly, Ercan et al. (2016) found that a four-week GIS intervention markedly improved pre-service teachers' views on STEM integration and higher-order thinking skills, such as scientific data collection and analysis. Among the Implementation studies, Shiau et al. (2018) identified ease of use, observability, and compatibility as the most critical adoption factors for OpenStreetMap in STEM education, while Zuniga-Teran et al. (2025) documented a 12-point increase in students' sense of scientific and engineering identity following the GIS mentoring program.

Notably, the majority of studies reported outcomes spanning more than one domain, most commonly combining cognitive gains with affective or motivational outcomes. Nugent et al. (2009, 2010), Borowczak and Burrows (2016), Xie and Reider (2014), and Lindner et al. (2019) all simultaneously documented improvements in both content knowledge and attitudes toward STEM, underscoring the multidimensional impact of GIS-based instruction. When discussing mixed or non-significant findings, Ivey et al. (2012) found no significant differences in student GPA or retention rates during the first year of implementation, despite measurable gains in geospatial knowledge. On a similar note, Groshans et al. (2019) found that Esri ArcGIS StoryMaps performed equivalently to traditional instructional methods on knowledge scores, even though students consistently rated them as more engaging, user-friendly, and visually appealing. Overall, these mixed findings highlight the limits of GIS effectiveness and underscore the need for more rigorous and comparative research designs in future studies.

RQ3: At which educational levels is STEM-GIS empirical research conducted?

To address research questions three, four and five, the analysis focused on 13 empirical studies, excluding four non-empirical studies. These comprised one literature review (Delparte et al., 2016), two descriptive studies (Kavouras et al., 2014; Hadjimitsis et al., 2020), and one quantitative program-level analysis (Al Mamun et al., 2015), which examined the positioning of Geography within STEM curricular standards through secondary statistical data and did not involve a direct educational intervention or identifiable participants.

The 13 empirical studies are distributed across two educational levels, namely secondary and university level. According to the findings presented in Figure 5, the majority were conducted at the secondary school level (n=8), while the remaining five were implemented at the university (n=5). It should be noted that no study targeting primary education met the inclusion criteria of this review. This finding highlights the substantial underrepresentation of this educational stage in the indexed literature on STEM-GIS.

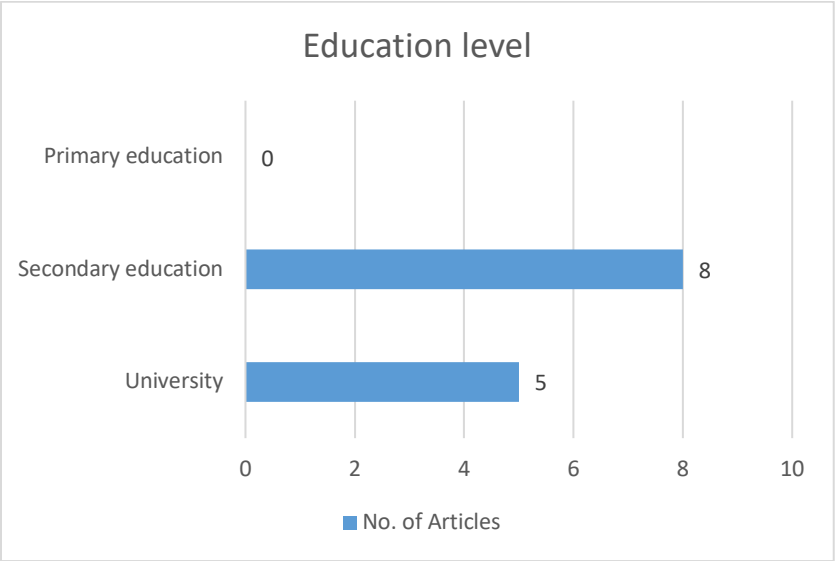


Figure 5. Distribution of levels of education in the articles.

At the secondary level, the studies covered a wide range of ages and educational contexts. For instance, Kolvoord et al. (2011) and Jant et al. (2020) focused on senior high school students participating in the Geospatial Semester program, while Nugent et al. (2009, 2010) worked with middle school students through intensive summer camps and training interventions. On the one hand, Xie and Reider (2014) analyzed data from the STEM In Action program implemented in secondary schools. On the other hand, Lindner et al. (2019), Borowczak and Burrows (2016), and Zuniga-Teran et al. (2025) applied their interventions in different geographic settings (Germany and USA). At the university level, research spans both undergraduate and graduate levels. Ercan et al. (2016) studied pre-service science teachers; Nazareth et al. (2019) included undergraduate students alongside experienced geoscientists and psychologists; Groshans et al. (2019) worked with undergraduate environmental science students and Ivey et al. (2012) with first-year civil engineering students.

Based on the studies presented above, it seems that meaningful GIS use requires a certain level of cognitive maturity and prior digital literacy. It should be highlighted that the absence of primary education studies, is particularly interesting. This is due to the fact that several easy-to-use-tools exist, such as ArcGIS StoryMaps, web-based GIS or educational mapping games, that could make geospatial technologies accessible to younger learners.

RQ4: Who are the participants in empirical STEM-GIS education research?

To address RQ4, participant groups were examined across the 13 empirical studies. Participants across the empirical corpus were predominantly students (secondary and university level), including pre-service teachers in one case (Ercan et al., 2016), with notable variation in educational level. As depicted in Figure 6, the majority of studies involved secondary school students (n=8), followed by university students (n=5). None of the retrieved studies designated primary school students or in-service teachers as a primary participant group, findings that highlight notable underrepresentations in the existing indexed literature.

Sample sizes vary substantially across studies, ranging from small qualitative samples (n=52 in Kolvoord et al., 2011) to larger quantitative samples (n=288 middle school students in Nugent et al., 2010, and n=145 undergraduate students in Shiau et al., 2018). Among secondary level studies, Jant et al. (2020) worked with 91 students enrolled in the Geospatial Semester program, Lindner et al. (2019) with 73 students in Germany and Borowczak and Burrows (2016) with 18 gifted secondary students. At university level, disciplinary diversity is notable, pre-service science teachers (Ercan et al., 2016), undergraduate environmental science students (Groshans et al., 2019, n=92), first-year civil engineering students (Ivey et al., 2012, n=51) and a mixed sample of geoscientists, psychologists, and undergraduate students (Nazareth et al., 2019).

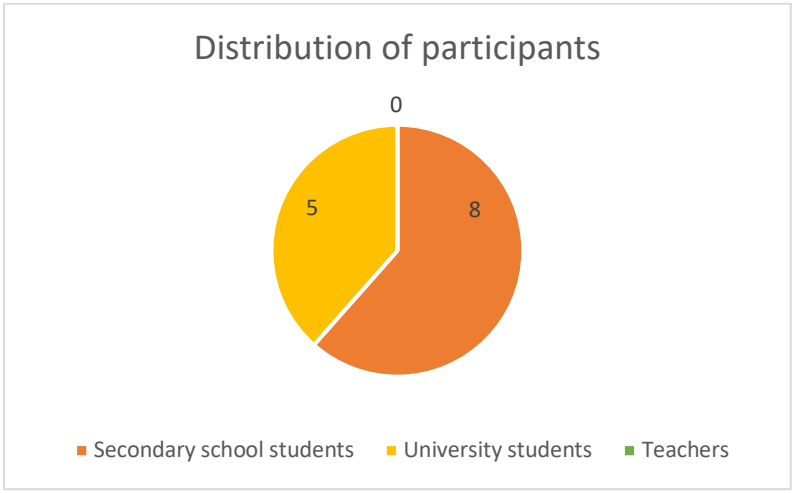


Figure 6. Distribution of participants by educational level in the empirical studies.

Of particular note is that no in-service teacher–focused empirical study was identified within the scope of this review. Although several studies report teacher involvement in supporting or facilitative roles (e.g., Nugent et al., 2009; Xie & Reider, 2014; Zuniga-Teran et al., 2025), no study designates teachers' professional development or pedagogical perceptions as its primary research focus. This gap is critical, as the sustainable integration of GIS into classroom practice depends fundamentally on teachers' competence and confidence.

RQ5: In which disciplinary areas has STEM-GIS research been conducted, and through which types of interventions has it been implemented?

Two dimensions characterize the STEM-GIS educational interventions across the 13 empirical studies: the disciplinary area in which they are situated and the type of educational intervention adopted. Analyzing these two dimensions together reveals both the thematic and pedagogical profile of the field. The thematic analysis of the discipline areas used in the teaching methods of the empirical articles was categorized into geography/environment, engineering, and multidiscipline (Figure 7) and the types of teaching interventions was categorized into lecture/computer practice, workshops and mixed interventions (Figure 8).

The most frequently identified disciplinary context was the multidisciplinary domain (n=10), encompassing studies that integrated two or more STEM disciplines within a single intervention (Kolvoord et al., 2011; Ercan et al., 2016; Jant et al., 2020; Nugent et al., 2009; Nugent et al., 2010; Shiau et al., 2018; Xie & Reider, 2014; Lindner et al., 2019; Borowczak & Burrows, 2016; Zuniga-Teran et al., 2025). The remaining studies addressed geography and the environment (n=2; Nazareth et al., 2019; Groshans et al., 2019) and engineering (n=1; Ivey et al., 2012).

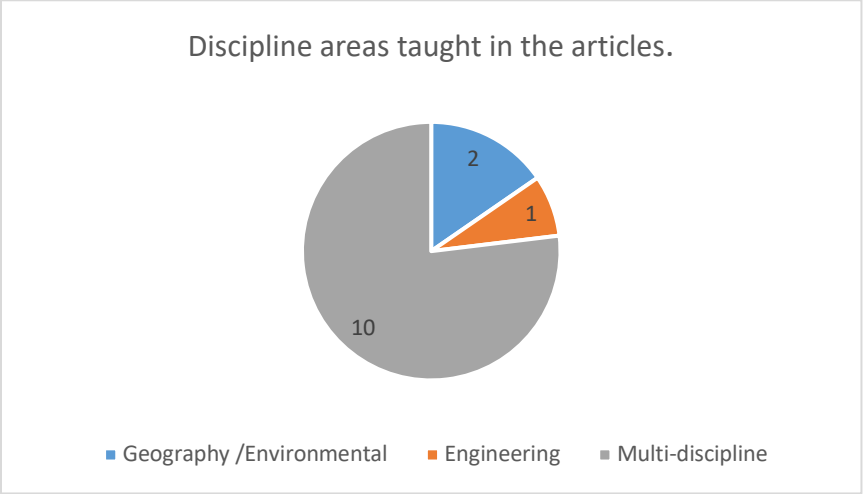


Figure 7. Distribution of discipline areas taught in the articles

Within the multidisciplinary category, the disciplinary combinations are remarkably diverse. The Geospatial Semester program (Kolvoord et al., 2011; Jant et al., 2020) introduced GIS as the intersection of geoscience, spatial thinking, and advanced coursework such as AP Physics and AP History, requiring students to apply geospatial reasoning across subject boundaries. In both their works, Nugent et al. (2009, 2010) bridged robotics, computer programming, mathematics, and GPS/GIS technologies in an intensive summer camp format. On the other hand, Lindner et al. (2019) developed a two-year "Geography-Physics" elective course incorporating remote sensing, satellite imagery, astrophysics, and augmented reality (AR).

Borowczak and Burrows (2016) combined geometry, engineering design, and socio-scientific issues (SSI) to address a real-world community problem using GPS and GIS tools. Notably, Xie and Reider (2014) represent one of the most distinctive interdisciplinary combinations integrating GIS with Information Assurance (IA) and cybersecurity within an urban outreach program. Among the geography/environment studies, Nazareth et al. (2019) investigated spatial cognition across geoscientists and undergraduate students in a university GIS course, while Groshans et al. (2019) focused on soil science and forestry education through Esri ArcGIS StoryMaps. The sole engineering study, Ivey et al. (2012), embedded GIS progressively across required Civil Engineering courses at freshman level.

In terms of intervention types it seems that mixed interventions prevailed (n=8) with the works of Kolvoord et al. (2011), Ercan et al. (2016), Jant et al. (2020), Nugent et al. (2009, 2010), Xie and Reider (2014), Borowczak and Burrows (2016), and Zuniga-Teran et al. (2025). The second category dealt with lecture combined with hands-on computer practice (n=4) as reported in the works of Nazareth et al. (2019), Lindner et al. (2019), Groshans et al. (2019), and Ivey et al. (2012). Lastly, it appears that only one study used a workshop format, namely Shiau et al. (2018), that used an OpenStreetMap (OSM) training course for undergraduate students (Figure 8).

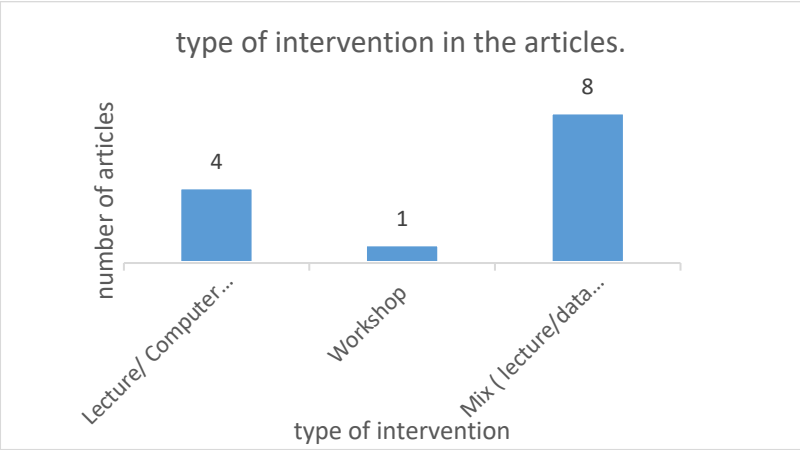


Figure 8. Distribution of type of intervention in the articles

When examining the mixed interventions, a variety of approaches is identified. For instance, the Mayor's Youth Technology Corps program (Xie & Reider, 2014) represents the most extensive intervention, combining 40-hour summer institutes, 100-hour after-school GIS and IA training courses, and 120-hour paid summer internships in real municipal departments. Taking a different approach, the Geospatial Semester (Jant et al., 2020; Kolvoord et al., 2011) offered a year-long inquiry-based course where students independently defined and solved community problems using GIS. Zuniga-Teran et al. (2025) implemented a year-long multi-generational mentoring program combining university campus visits, GIS and Survey123 training workshops, and neighborhood park mapping fieldwork, culminating in ArcGIS StoryMaps presentations at a research competition.

In their work, Ercan et al. (2016) presented a four-week Design-Based Learning intervention integrating outdoor GPS fieldwork, laboratory water analysis, and ArcGIS spatial database construction. At the other end of the scale, Borowczak and Burrows (2016) demonstrated that meaningful GIS integration can be achieved within a concentrated four-day outdoor lesson combining GPS measurement, geometric calculations, and engineering design. A pattern that emerged from the studies is that the majority of the empirical studies follows an extended-duration approach. Moreover, 10 out of the 13 empirical studies (76.9%) employed interventions spanning multiple weeks to a full academic year, underscoring the field's recognition that meaningful acquisition of geospatial skills requires sustained engagement with both the technology and its disciplinary applications.

Discussion

The findings reveal a field that is methodologically maturing yet remains conservative with respect to experimental research designs. The dominance of mixed methods (n=7) and the presence of quantitative elements in 12 of the 17 studies indicate that researchers recognize the need to capture both the cognitive and affective dimensions of STEM-GIS interventions (Schulze, 2020; Bondarenko, 2025). Concurrently, the use of specialized analytical tools like ANCOVA (Nugent et al., 2009, 2010), PLS-SEM (Shiau et al., 2018), or automated linguistic analysis via LIWC (Jant et al., 2020), suggests that the field has moved beyond the early stages of purely descriptive inquiry.

A particularly striking observation is the absence of strictly experimental designs within the reviewed corpus, alongside the prevalence of quasi-experimental (n=7) and non-experimental (n=10) designs. This pattern is not unique to STEM-GIS education. In broader educational technology reviews, Baydas et al. (2015) found a similar dominance of quasi-experimental designs, attributing it to the inherent difficulty of randomly assigning students in school settings. Jant et al. (2020) explicitly acknowledge this constraint: "students chose their electives." Nevertheless, the widespread adoption of quasi-experimental designs in educational research has been described as a credibility revolution towards a rigorous causal inquiry (Gopalan et al., 2020), revealing a compelling trajectory that the STEM-GIS field appears to be following. Future randomized controlled studies, where contextually feasible, would further consolidate the evidence base for GIS effectiveness in STEM education.

The absence of strictly experimental designs is not the only methodological concern worth discussing. Several other characteristics of the reviewed studies also affect the reliability and generalizability of the reported findings. Sample sizes vary considerably across the empirical studies. They range from fewer than 20 participants in some interventions, such as Borowczak and Burrows (2016) with n=18, to approximately 50 in others, such as Ivey et al. (2012) with n=51. Although such sample sizes are typical for educational research conducted in school settings, they constrain statistical power and limit the confidence with which conclusions can be drawn about effect sizes.

Another finding is that few studies make use of a two-group comparison design. Many rely on single-group pre- and post-test structures. A few examples are presented in the works of Borowczak and Burrows (2016) and Zuniga-Teran et al. (2025), which cannot fully rule out alternative explanations such as maturation, instrumentation, or selection effects. A major concern deals with the fact that the reported outcomes are built around author-developed instruments, without using standardized/validated scales. This limits cross-study comparability.

However, when reviewing the findings, it seems things are heading to a positive direction. Even though the evidence base for STEM-GIS instruction remains relatively limited in terms of how confident we can be that the results are reliable and can be generalized to other contexts. Future research should prioritize larger samples, stronger comparison-group designs, and the use of validated measurement instruments to strengthen the evidentiary basis of the field.

One of the most revealing findings of this review is the dominance of Integrative STEM (n=8) and Science Education (n=4). This distribution clearly indicates that GIS is treated by the research community as a pedagogical tool for delivering other STEM subject content, rather than as an object of educational research in its own right. This observation aligns with Kerski's (2015) conceptualization of GIS as a tool that serves student learning through geospatial data visualization and analysis for STEM problem-solving, as well as with Schulze's (2020) theoretical distinction between "learning with GIS" and "learning about GIS" with the overwhelming majority of the literature falling into the former category.

This instrumental orientation is consistent with the theoretical framing established in the introduction, where GIS was presented as an interdisciplinary tool for data collection, spatial analysis, and visualization (Kerski, 2015; Henry & Semple, 2012; Patterson et al., 2003). It also corroborates Jant et al.'s (2020) finding that GIS primarily supports the development of spatial thinking as a core STEM-relevant competency. While this instrumental use of GIS highlights its considerable pedagogical versatility, it simultaneously raises a critical question. If no study systematically examines the pedagogical practices and curricula for developing geoinformatic competencies, it remains unclear how learners can acquire the technical and conceptual skills required to use the tool effectively. This constitutes a discrete and under-addressed research gap warranting systematic attention in future studies.

Another pattern that emerged from the analysis deals with the fact that the majority of studies documented multidimensional results spanning both cognitive and affective domains simultaneously.This finding reinforces the role of GIS as a holistic pedagogical tool rather than a purely instructional one. For instance, works such as Nugent et al. (2009, 2010), Borowczak and Burrows (2016), Xie and Reider (2014), and Lindner et al. (2019) concurrently documented gains in content knowledge alongside improvements in students' attitudes, motivation, and STEM career orientation. All the above highlight that GIS-based instruction operates on multiple learning dimensions at once.

This dual-impact pattern is consistent with broader trends in the Integrated STEM literature regarding the multidimensional outcomes of authentic, technology-enhanced learning experiences (Thibaut et al., 2018). Of equal importance are the mixed findings on the works of Ivey et al. (2012) and Groshans et al. (2019). Moreover, Ivey et al. (2012) reported no significant effects on GPA or retention rates despite measurable geospatial knowledge gains. On the other hand, Groshans et al. (2019) found that Esri ArcGIS StoryMaps matched PowerPoint on knowledge scores, yet received consistently higher student ratings for engagement and usability. These findings are methodologically significant as they delineate the boundaries of GIS effectiveness and highlight that attitudinal and motivational gains do not always translate directly into measurable academic performance outcomes, underscoring the need for more nuanced and longitudinal research designs in future STEM-GIS studies.

One of the most prominent gaps that was highlighted by this review deals with absence of GIS-STEM based interventions in primary education. It appears that this finding is not new, as the National Research Council (NRC,2006) reported in 2006, that GIS use in the early grades lags far behind higher levels, and that meaningful exposure is typically delayed until adolescence. It should be emphasized that two decades later, this review confirms that gap that seems to remain unaddressed. The problem is not that GIS is too difficult for young children, but that software developers and researchers have not yet designed tools and studies that meet their learning needs.

This research gap is significant for two reasons. First, spatial skills are strongly linked to STEM success (Wai et al., 2009; Uttal & Cohen, 2012; Hegarty, 2014), and their development should begin in early childhood. Second, modern GIS platforms such as ArcGIS Online, ArcGIS StoryMaps, and web-based mapping applications have substantially reduced the technical barriers to entry. Geospatial technologies are increasingly accessible to younger learners, as evidenced by initiatives such as Esri's ConnectED program. Despite these developments, the STEM-GIS research community has yet to generate systematic empirical evidence on GIS use with primary-school-age populations. Addressing this gap is an urgent priority for future research, as spatial thinking skills are best developed from the earliest stages of students' education.

Closely linked to the previous gap is the absence of in-service teachers as a primary participant group across the 13 empirical studies. Several studies report teacher involvement in supportive or facilitative roles as classroom implementers (e.g., Nugent et al., 2009; Xie & Reider, 2014; Zuniga-Teran et al., 2025). However, no study designates teachers' professional development, instructional beliefs, or pedagogical practices as its primary research focus. The only study that

partially approaches this domain is Ercan et al. (2016), which engaged pre-service teachers but focused on shifts in Nature of Science conceptions rather than on GIS instructional competence. This gap is particularly important, as successful and lasting GIS integration in schools depends on teachers being well-prepared, confident, and adequately supported.

Three interrelated findings characterize the pedagogical profile of STEM-GIS research. Most studies were situated in multidisciplinary contexts (n=10), used mixed interventions combining instruction, computer practice, fieldwork, and project work (n=8), and employed extended-duration programs spanning multiple weeks to a full academic year (n=10). These findings suggest that GIS is most effectively taught through long-term, interdisciplinary, and multi-method approaches. This aligns with Thibaut et al. (2018), who identified disciplinary connections, learner-centered approaches, and extended time as key features of effective integrated STEM teaching.

The above-mentioned is further supported by the interdisciplinary nature of GIS itself (Henry & Semple, 2012; Patterson et al., 2003). Several studies illustrate this clearly. The Geospatial Semester program (Kolvoord et al., 2011; Jant et al., 2020) lasted a full academic year and centered on inquiry-based learning with real-world geospatial projects. Nugent et al. (2009, 2010) designed intensive multi-week summer camps combining robotics, GPS/GIS, and collaborative problem-solving. Lindner et al. (2019) integrated geography, mathematics, and economics within a sustained two-year course. The message for practice is clear. Effective GIS integration in STEM education cannot be achieved through short or single-subject lessons. It requires time, interdisciplinary design, and varied teaching methods. These are important considerations for educators involved in the integration of geospatial technologies in schools.

As reported in the Findings section, 12 of the 17 studies originate from the United States. The remaining five studies come from Greece, Turkey, Taiwan, Germany, and Cyprus (one each). This dominance is not surprising. GIS was adopted early and widely in American schools, supported by organizations such as Esri, which provides free software to K-12 institutions. GIS competencies are also formally embedded in the National Geography Standards and the Next Generation Science Standards (Henry & Semple, 2012; Baker et al., 2015). American research has undoubtedly contributed greatly to the field. However, this geographic concentration raises concerns about generalizability. Educational systems differ considerably across countries in terms of governance, funding, curriculum, and technological infrastructure. Findings from the U.S. context may not transfer directly to other settings.

Limitations

A number of limitations has been presented throughout this review. The first one deals with the number of databases that were used for the systematic review, namely Scopus, ERIC, IEEE Xplore, and Google Scholar, between 2005 and 2025. It should be noted that some empirical studies outside these databases search criteria as well as inclusion and exclusion criteria may not be included. Secondly, the final corpus of the studies is relatively small (n=17). This could limit statistical comparison or meta-analysis synthesis. Thirdly, no formal inter-rater agreement coefficient was computed during the screening process. Although the consensus-based approach adopted is appropriate for the size and clarity of the present corpus, the use of a quantified agreement metric, such as Cohen's κ, would have further strengthened the methodological transparency of the review. Lastly, this review focused on peer-reviewed open access publications. It did not include grey literature (e.g., technical reports, doctoral dissertations) nor subscription based journal. It should be noted that the above restrictions (while adopted for practical and reproducibility reasons) introduced relevant risk of publication bias. Studies reporting positive or statistically significant effects of GIS-based instruction are generally more likely to be published in open-access venues, whereas null or negative findings may be disproportionately located in subscription-based outlets or grey literature that fell outside the scope of this review. This bias may therefore have led to a partial overestimation of the consistency and magnitude of the positive outcomes reported here. The content-related validity of this review is consequently limited to the extent of the open-access, peer-reviewed literature retrieved and analyzed.

Conclusions

The purpose of this systematic review was to investigate the current landscape on the use of GIS in STEM education. The review highlights several important observations. One example has to do with methodological progress, while on the other hand, several structural gaps have been identified. It seems that the majority of studies adopt a mixed method approach without following a strictly experimental design. Most studies investigated outcomes related to Integrative STEM and Science Education, with simultaneous gains in both knowledge and attitudes. An interesting finding that this study highlighted deals with the sample and education level. Apparently, the majority of research was conducted at secondary or university level. Neither primary school students nor in-service teachers were designated as a primary research group in any of the included studies. The pedagogical profile is consistent, with effective GIS instruction tending to be multidisciplinary, extended in duration, and methodologically varied.

From a theoretical standpoint, this review makes four contributions to the literature. First, it confirms and extends Baker et al.'s (2015) and Schulze's (2020) distinction between 'learning with GIS' and 'learning about GIS' at a broader scale. Second, a consistent dual-impact pattern was identified across GIS-based interventions, with simultaneous improvements in both cognitive and affective domains. Third, the review updates the research agenda proposed by Baker et al. (2015) for geospatial technologies, documenting specific methodological and population-related gaps that had not previously been systematically mapped. Fourth, the geographic concentration of the literature poses as a structural concern. As mentioned above, 12 of the 17 studies originated from the United States, which limits generalizability of the findings.

All the above have important implications for educators and policymakers as well. It appears that GIS works best when being part of a sustained and interdisciplinary approach, rather than an isolated course. Also, it appears that there is a serious underrepresentation of in-service teachers when investigating STEM-GIS literature. The lack of primary school STEM-GIS based studies highlights the need to investigate further. Lastly, for policymakers, the dominance of

American studies underscores the importance of funding international research and supporting open-source platforms such as QGIS and OpenStreetMap in resource-limited settings.

Five directions for future research emerge from this review. First, primary school GIS research is the most pressing priority, as younger learners have been entirely overlooked despite the growing accessibility of geospatial tools. Second, where feasible, future studies should employ randomized controlled trials to strengthen causal claims about GIS effectiveness in STEM learning. Third, international comparative studies are equally important, examining how different cultural, institutional, and infrastructural contexts shape GIS adoption. Fourth, future studies should also directly target the "learning about GIS" gap, examining how geoinformatic competencies are actually developed rather than assumed. Finally, longitudinal designs are needed to track whether gains in knowledge, spatial thinking, and attitudes endure well beyond the immediate post-intervention period.

In conclusion, this review documented the educational value of GIS in STEM education and at the same time highlighted critical structural gaps. GIS-based instruction in STEM education consistently yields positive results across knowledge, spatial thinking, and student motivation. The field is moving forward, yet structural blind spots remain, as primary education, teacher-centered research, experimental rigor, international diversity, and geoinformatic competence development are all underserved. In a world where geospatial information increasingly shapes science, technology, and civic life, these gaps are not merely academic concerns. Based on all the above, the development of spatial and geospatial literacy in early stages of student's education should not just be a research priority, but an educational necessity.

Disclosure Statement

The authors did not report any potential conflict of interest.

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