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EDITED BY

Catalina Huilcapí-Collantes,
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REVIEWED BY

Aan Hendrayana,
Sultan Ageng Tirtayasa University,
Indonesia

María Luisa De Lázaro Torres,
National University of Distance
Education (UNED), Spain

*CORRESPONDENCE

Nurbol Ussenov

✉ n.ussenov@abaiuniver.kz

Yerlan Issakov

✉ erlan.issakov@gmail.com

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A systematic review of the effectiveness of teaching geoecological issues to geography students using digital technologies

Ainur Murzinova¹, Sagyngali Kalkashev², Damezhan Sadykova¹,
Nurbol Ussenov^{3*}, Assan Zheldibayev⁴, Aidana Ospanbayeva¹,
Yerdaulet Tulegenov¹, Saken Irkitbaev³ and Yerlan Issakov^{3*}

¹Department of Geography, Institute of Natural Sciences, Kazakh National Women's Teacher Training University, Almaty, Kazakhstan, ²Department of Geography, Faculty of Natural Sciences and Informatization, Arkalyk Pedagogical University Named After Ybrai Altynsarin, Arkalyk, Kazakhstan, ³Department of Geography and Ecology, Faculty of Natural Sciences and Geography, Abai Kazakh National Pedagogical University, Almaty, Kazakhstan, ⁴Department of Tourism and Service, Faculty of Economics and Business, Almaty Technological University, Almaty, Kazakhstan

The introduction of innovative pedagogical approaches to teaching geoenvironmental issues is considered one of the key directions of contemporary educational practice. Although digital technologies and active learning strategies are widely used, their effectiveness in the context of teaching geography students has not been systematically studied. This systematic review was conducted in accordance with the PRISMA 2020 guidelines: 64 relevant articles were selected, and from these, the most fully documented studies were taken for in-depth analysis. The novelty of the study lies in its comprehensive consideration of pedagogical approaches to digital technologies in geoenvironmental education, linking them to the requirements for the training of geography students. The results show that geospatial tools and immersive technologies are widely used, but that the outcomes are often limited to short-term affective indicators, indicates a lack of rigorous designs that isolate the technology's independent contribution, and that teacher preparation and institutional support remain a persistent barrier. The study proposes a conceptual model that integrates digital technologies, experiential learning, and interdisciplinary integration, and includes concrete recommendations for teachers and policymakers.

KEYWORDS

digital technologies, geoecological education, geography teacher training, international experience, systematic literature review

1 Introduction

The intensification of global geoenvironmental threats such as climate change, biodiversity loss and land degradation has increased the strategic importance of geographical education. However, in many national education systems, geography curricula leave geoenvironmental content at a descriptive level and do not sufficiently link it with modern digital tools, which limits learners' ability to analyse real-world environmental problems (Urbańska et al., 2022).

Over the last decade, there has been a shift in geography education from traditional lectures towards models based on student engagement. Geospatial analysis tools are a key manifestation of this: While ArcGIS-based mapping improved the geographical content comprehension of underperforming students (Bikar et al., 2022), Google Earth-based imagery significantly enhanced spatial thinking (Hadi et al., 2021). However, the risk of using GIS in isolation from geographical concepts is also noted (Labianca, 2021).

Alongside geospatial tools, immersive virtual and augmented reality technologies hold a special place in visualising geoenvironmental phenomena. The multinational Erasmus + project implements geohistory teaching through 360-degree virtual field trips (Vandelli et al., 2024), a collaborative immersive environment visualises abstract climate concepts at a higher level than traditional teaching (Střechová et al., 2025), while an AR application in a museum setting achieves high satisfaction in developing climate change literacy (Kondyli et al., 2024).

These technological approaches are based on constructivist learning theory, which posits that learners actively construct knowledge through experience. The project-based STEAM approach in Indonesia, in exploring the topic of global warming, develops ecological thinking adapted to the local context (Syamsudin et al., 2025), while a geoscience education programme in rural Colombia achieved significant success in mastering hydrological content by drawing on constructivist paradigms (Delgado-Guerrero et al., 2025).

However, the integration of digital technologies into geoenvironmental education is not without significant challenges. Despite the availability of equipment, teachers often revert to traditional strategies (Shakhislam et al., 2025), while the introduction of GIS is hampered by teachers' technical concerns and the 'digital divide' (Li et al., 2022). This issue is further compounded in resource-limited settings: A study in rural, electricity-free schools in South Africa identifies institutional barriers, such as inadequate teacher training. For this reason, it is important to specifically consider the review of research in this context: they reflect the issue of unequal access to digital technology, provide some of the few empirical evidences in developing regions, and highlight the underrepresentation of Africa and Central Asia in international research. This systematic review was conducted based on works published in peer-reviewed bibliographic databases, in accordance with the PRISMA guidelines.

This review differs from prior syntheses in the field in three respects. First, unlike broader reviews of digital tools in environmental education that only incidentally include geography students (e.g., Husamah et al., 2025), it is disciplinarily specific to geography training. Second, unlike GIS-focused reviews that stop short of quantitative or cross-study synthesis because of the scarcity of comparable outcome data (e.g., Bondarenko, 2025), it explicitly synthesises findings across immersive, geospatial, and gamified technologies rather than treating them separately. Third, it evaluates studies not only on which technologies were used but on the rigour of the evidence behind their claimed effectiveness, a dimension left largely unexamined in reviews that focus on the technological variable alone (e.g., Mašterová, 2023).

RQ1: Which pedagogical approaches are effective in teaching geoenvironmental issues, and what is the quality of the evidence supporting them?

Current literature indicates a trend in the teaching of geoenvironmental content from traditional formats towards models based on active participation. Immersive technologies and geospatial tools are considered promising avenues, although most of the reviewed studies lack a control group and are based solely on self-reporting, while rigorous designs that isolate the technology's independent pedagogical contribution are rare. Therefore, a systematic analysis of the effectiveness of pedagogical approaches and the quality of their evidence is a pressing research priority.

RQ2: To what extent does international experience align with the competency requirements for geography students, and how can it be adapted?

Although geography graduates are expected to solve complex ecological problems, the geo-ecological content of curricula often remains within a narrow, subject-technical framework (Guo and Meadows, 2020). This gap is also evident in the case of argumentation competence: although educators theoretically support its importance, it is not taught explicitly in the classroom (Wolff-Seidel and Budke, 2022). Several avenues for adaptation are proposed in the literature: the integration of GIS and digital modelling, as well as the design of participatory curricula (Ricoy and Sánchez-Martínez, 2022). This issue is a complex task that requires a review at both institutional and methodological levels.

RQ3: What are the main gaps in geoenvironmental education research, and what are the priority areas for curriculum renewal?

The literature under review identifies an imbalance in the geographical distribution of studies: the majority are concentrated in developed or middle-income regions, while resource-limited settings are underrepresented. The mismatch between academic programmes and the specific requirements for the practical application of digital technology has also been documented in several contexts. Furthermore, the predominance of short-term outcome indicators highlights the need for assessing long-term impact. Among the directions for renewal, the implementation of available web-based models, the combination of fieldwork with active learning, as well as the integration of geoenvironmental science with GIS and social dimensions are frequently mentioned.

2 Materials and methods

The integration of digital technologies into teaching geoenvironmental issues to geography students is still considered a methodologically underdeveloped, independent research area. For example Husamah et al. (2025), although it broadly covers digital tools in environmental education, only one of the 21 studies reviewed specifically target geography students, which indicates that the disciplinary distinctiveness of environmental education and geoenvironmental teaching should not be conflated Bondarenko (2025), in a more extensive review of GIS integration covering 257 articles, also notes that not a single study was found suitable for a quantitative synthesis, indicating that the field is still in its early empirical stages. Similarly Mašterová (2023), analysing 36 studies on geospatial technologies, finds that much of the literature focuses on the technological variable, neglecting to independently measure the quality of research-based pedagogy. These gaps-an insufficient

disciplinary rigour, a lack of quantitative synthesis, and a conflation of technological accessibility with pedagogical effectiveness—served as the explicit rationale for developing the protocol for this review.

This work conducted a systematic literature review based on the PRISMA 2020 guidelines (Page et al., 2021). This approach was chosen to ensure methodological transparency and to maintain the rigor typical of high-ranking scientific publications. The complete structure of the article selection process is shown in Figure 1. The search was conducted using international bibliographic databases that comprehensively cover peer-reviewed literature in education, earth sciences, and environmental sciences; the subject area was limited to the social sciences, earth sciences, and environmental sciences. The review included articles published in internationally peer-reviewed scientific journals; the scope of the analysis covers the period 2020–2025, providing a comprehensive representation of the most recent developments and trends in the field.

Two independent scientific databases—Scopus and Web of Science—were used to search the literature. An identical thematic query was applied to both databases: terms related to environmental education (“geoecology”, “geoecological”,

“ecology”, “environmental education”), terms related to earth sciences (“geography”, “geoscience”, “earth science”, “natural science”), and terms related to digital technologies (“digital”, “technology”, “ICT”, “e-learning”) were combined using the logical AND operator, while synonyms within each block were joined using the OR operator.

2.1 Search in the scopus database

TITLE-ABS-KEY [(“geoecology” OR “geoecological” OR “ecology” OR “environmental education”) AND (“geography” OR “geoscience” OR “earth science” OR “natural science”) AND (“digital” OR “technology” OR “ICT” OR “e-learning”)] AND PUBYEAR > 2019 AND PUBYEAR < 2026 AND (LIMIT-TO (DOCTYPE, “ar”)) AND (LIMIT-TO (OA, “all”)). The search was conducted in four stages: the initial, unrestricted search identified 1,277 records; limiting the publication year to 2020–2025 reduced this to 548 records; restricting the document type to articles only yielded 275 articles; and retaining only open-access publications produced a final total of 151 articles.

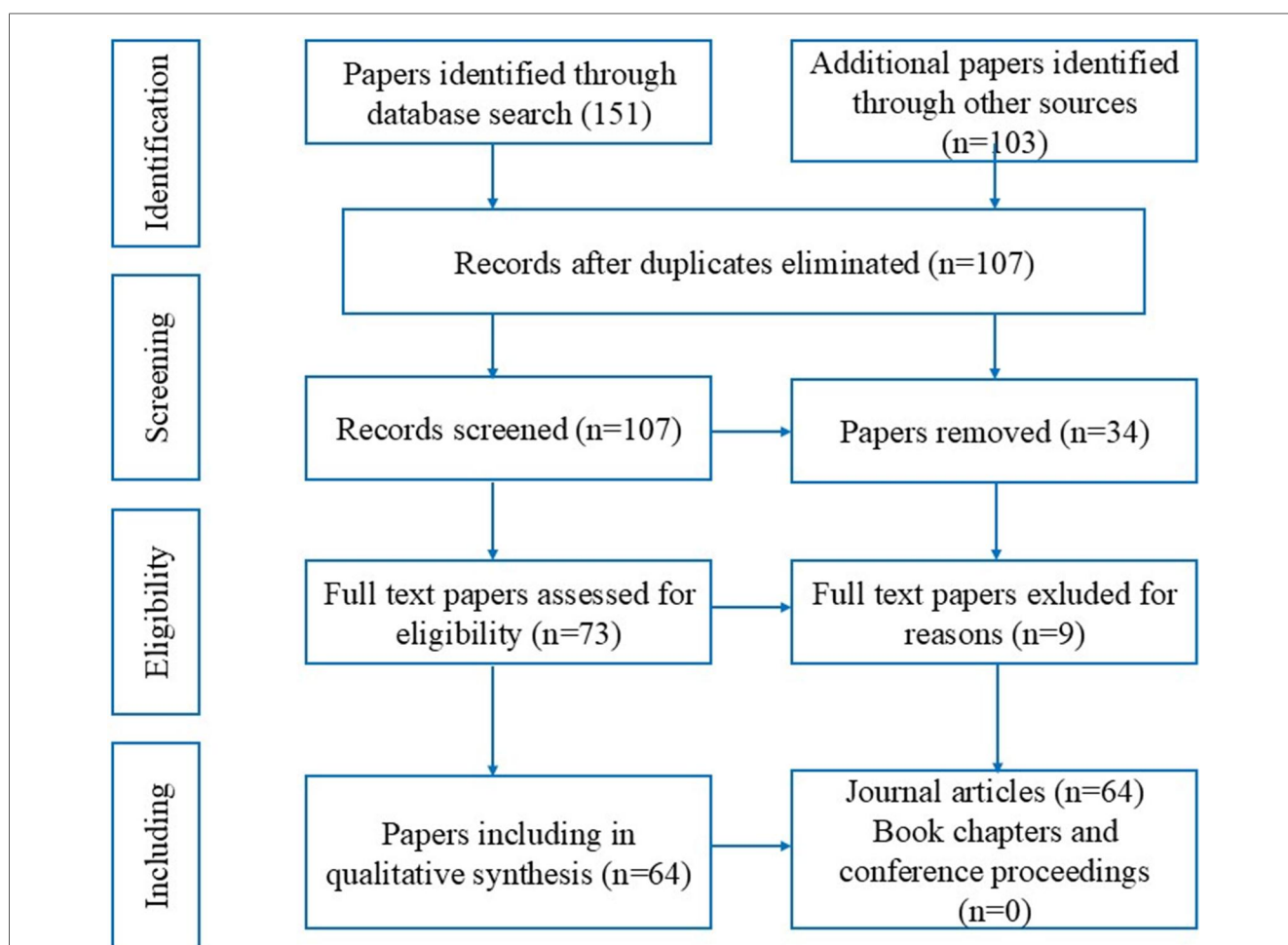


FIGURE 1

A PRISMA 2020 flow diagram illustrating the systematic article selection process, from the identification of the initial 254 records (151 databases+103 supplementary sources) to the final inclusion of 64 studies.

2.2 Search in the web of science database

The query was constructed using the TS = (Topic Search) operator:

TS = [(“geoecology” OR “geoecological” OR “ecology” OR “environmental education”) AND (“geography” OR “geoscience” OR “earth science” OR “natural science”) AND (“digital” OR “technology” OR “ICT” OR “e-learning”)].

The year (2020–2025), document type (Article), and Open Access parameters were subsequently applied using the filter panel on the left after the initial query results were generated. The search identified approximately 950 records; restricting by year range left approximately 410 records; limiting to articles only yielded approximately 205 articles; and retaining only open-access publications resulted in a final total of 103 articles.

The articles retrieved from both databases (151 from Scopus and 103 from Web of Science, totalling 254 records) were then merged, and duplicate records were removed, leaving 107 unique records. These were further screened following the PRISMA methodology: 34 records were excluded at the screening stage, leaving 73 full-text papers assessed for eligibility; 9 of these were subsequently excluded for specific reasons, resulting in a final set of 64 papers included in the qualitative synthesis, all of which were journal articles (Figure 1).

During the screening phase, the titles and abstracts of all 107 records were independently assessed by two researchers in parallel, without prior agreement, to minimize selection bias. In cases of disagreement between the researchers, a third member of the research team acted as arbiter; all discrepancies were resolved through structured discussion until full consensus was reached. The Cohen’s kappa coefficient was used to formally assess the level of agreement between the reviewers, and according to the Landis and Koch (1977) interpretation scale, a substantial agreement threshold ($\kappa \geq 0.61$) was set as the criterion for proceeding without further calibration of the screening protocol. Studies were deemed eligible if they: (1) involved geography students, the training of geography teachers, or geography curricula; (2) report the use of digital technology specifically aimed at teaching, modelling, or researching a geoenvironmental issue; (3) provide empirical or qualitative evidence regarding learning outcomes or perceived effectiveness of the teaching; (4) is published as a peer-reviewed journal article in English. Of the 34 records excluded at the title/abstract screening stage, 16 lacked a specific geoenvironmental content focus, 12 lacked a pedagogical intervention or a learner sample, and 6 were not peer-reviewed. Of the 9 records excluded at the full-text stage, a study (Chen et al., 2025) that strictly performed GIS-based landform analysis but did not include an educational objective and learning outcome measurement was assessed at the full-text stage and ultimately excluded, together with 5 further studies excluded for the same reason and 3 for lacking a clearly defined learner sample. All 64 included studies met these criteria and formed the empirical basis for the subsequent synthesis.

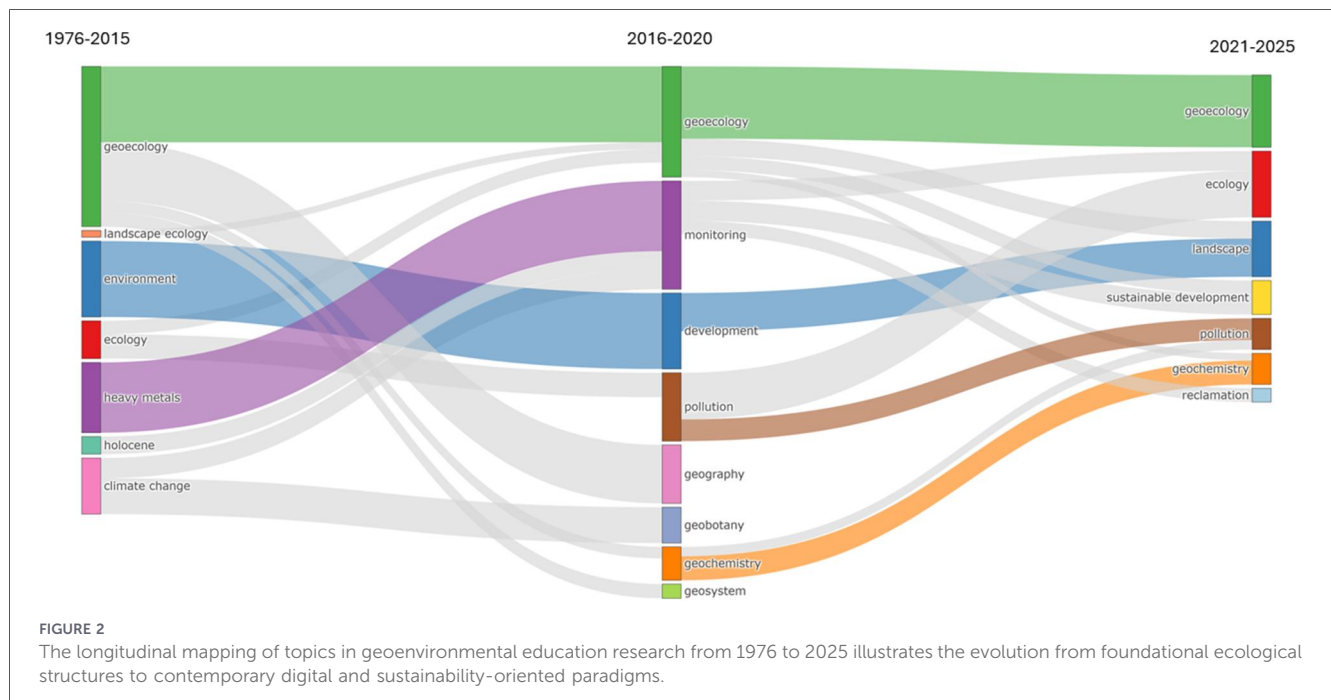
A standardised, *de novo* data extraction form was developed to systematically structure and conduct a comparative analysis of the evidence from the selected 64 studies. This form was pilot tested on a small sample of five randomly selected studies to assess its validity and inter-rater agreement before its main application. Each study was coded by two independent researchers across

seven analytical dimensions: (1) the type of technology used (e.g., GIS/WebGIS, virtual reality, augmented reality, mobile and digital game-based platforms); (2) pedagogical rationale (e.g., inquiry-based learning, TPACK, project-based learning); (3) learner level (primary, secondary, higher education); (4) research methodology (e.g., quasi-experiment, case study, mixed methods); (5) learning outcomes (e.g., content mastery, spatial thinking, engagement and motivation); (6) the geoenvironmental issue or thematic content addressed (e.g., land-use change, pollution, hydrological processes, sustainable development); (7) infrastructural and ethical issues (e.g., access to technology, teacher training). This multidimensional coding system provided a robust analytical foundation for the systematic categorisation of research findings and for conducting an in-depth, evidence-based thematic synthesis.

No standardised critical-appraisal instrument (e.g., JBI, CASP, MMAT, or ROBIS) was applied to formally score the risk of bias or methodological quality of individual studies. Instead, the fourth coding dimension (research methodology) captured, for every included study, whether a control or comparison group, a pre-/post-test design, or a validated measurement instrument was used, and these descriptors were then used qualitatively, throughout the Discussion and Conclusion, to flag where reported effects rest on descriptive, self-reported, or uncontrolled evidence. We recognise that this qualitative approach is less standardised than a formal appraisal tool, and we treat the resulting methodological heterogeneity of the corpus explicitly as a limitation of this review (Section 5.6) rather than leaving it implicit.

A diachronic thematic analysis was conducted, dividing the period into three phases to situate the analysed pedagogical practices within the broader intellectual trajectory of geoenvironmental education research: 1976–2015, 2016–2020 and 2021–2025. For this analysis, the dataset was drawn from a separate, broader bibliographic corpus spanning the full 1976–2025 publication period; further detail on this corpus is provided below. Research topics were identified based on author keywords and indexed terms, which were subsequently normalised and merged into conceptual clusters. The temporal evolution of these clusters was visualised using a Sankey-type topic map (Figure 2), constructed from bibliographic data retrieved from the Scopus database and processed using the bibliometrix package in the R/RStudio environment (biblioshiny interface). This approach allowed for the tracking of the emergence, continuity, and transformation of dominant research topics across the three defined periods.

In Figure 2, the gradual transformation of research topics across the three periods is clearly evident. Throughout 1976–2025, ‘geoecology’ remains the single largest and most persistent thematic band, indicating strong conceptual continuity across the discipline. In the earliest phase (1976–2015), the vocabulary is dominated by classical, descriptive terms—landscape ecology, environment, ecology, heavy metals, Holocene, and climate change. Between 2016 and 2020, this descriptive vocabulary is progressively absorbed into more applied and process-oriented themes, including monitoring, development, pollution, geography, geobotany, geochemistry, and geosystem, indicating a shift from purely descriptive geoecology towards management- and impact-oriented research. In 2021–2025, the topic structure consolidates further around geoecology, ecology, landscape, sustainable development, pollution, geochemistry, and reclamation, with sustainable development and reclamation emerging as new, previously absent



keywords—this demonstrates the field’s growing orientation towards applied environmental management and remediation. This diachronic perspective is analytically important, as it allows for the simultaneous identification of structural continuity and conceptual change within the discipline, laying an evidence-based foundation for geography teachers to develop future geo-ecological curricula.

The set of methodological procedures described above—a structural search strategy based on bibliographic databases, a phased screening process in line with the PRISMA 2020 standard, substantial agreement between reviewers ($\kappa \geq 0.61$), a seven-dimensional coding system, and a diachronic thematic analysis covering the period 1976–2025—ensured the formation of a final systematic-review corpus of 64 studies through an open, iterative and quality-controlled process. It should be emphasised that the diachronic thematic analysis (Figure 2) draws on a separate, broader bibliographic corpus of 1,277 records covering the period 1976–2025, corresponding to the initial, unrestricted stage of the Scopus search reported above, before the 2020–2025 publication-year, document-type, and open-access filters were applied to arrive at the systematic-review corpus; this longitudinal corpus was used exclusively for bibliometric and historical contextualisation and did not affect the eligibility criteria or the composition of the 64 included studies. This methodological foundation provides the necessary reliability and analytical depth for the comparative and pedagogical analysis presented in the following sections.

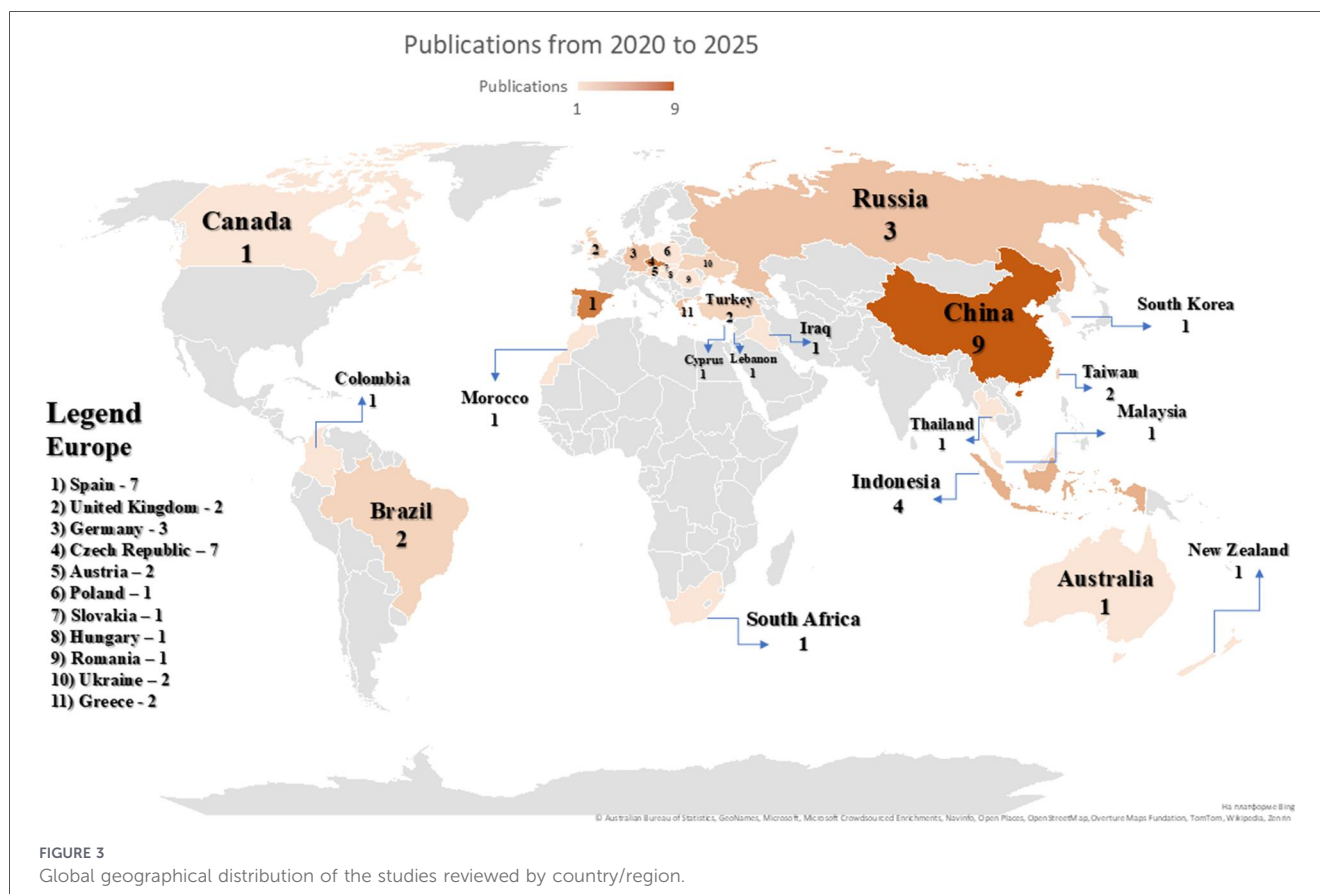
3 Results

3.1 Geographical and chronological distribution of the studies

The complete corpus of the systematic review comprises 64 studies and includes authors from twenty-nine countries,

demonstrating the global scope and geographical diversity of this research area. The corpus’s geographical distribution is broad but uneven; it encompasses Southeast and East Asia, Europe, North and South America, and Africa. Indonesia is the single country that has contributed the most studies four studies were conducted here covering topics such as global warming, disaster prevention, marine ecosystem literacy, and the interpretation of geomorphosites (Hadi et al., 2021; Istiana et al., 2021). China and Spain each contribute two studies: multimedia and drone/VR-based learning, respectively (Guo and Meadows, 2020; Lu et al., 2023), as well as the development of mobile GIS competence and CT gamification among future teachers (Sebastián-López and de Miguel González, 2020). Taiwan is also represented by two studies: one for teaching plant ecology through augmented reality, and the other for a museum-based palaeoecological game (Lo et al., 2021; Lu et al., 2025). The remaining countries are represented by a single study each: Germany (Jekel Könnel et al., 2025), Hong Kong SAR (Jong, 2020), Brazil (dos Santos et al., 2025), Russia (Shefer et al., 2021), Ukraine (Barna et al., 2020), Canada (leBrasseur, 2023) and Morocco (Rachad and Oughdir, 2023). One study reports a truly multinational design involving six European countries and a sample of Polish pupils, while another study documents a cross-border curriculum coordination initiative between Poland and the Czech Republic. A number of studies did not specify the data collection country sufficiently to allow for geographical classification (Sedlák et al., 2022; Shen et al., 2022). The overall distribution is shown in Figure 3.

This distribution is statistically significant. The contribution of Southeast Asia, particularly Indonesia, is attributable to the region’s geoenvironmental hazards—volcanic activity, flooding, coastal erosion and biodiversity loss—may be linked to the region’s constant and intense exposure to geoenvironmental hazards, which in turn generates a sustained curricular and policy demand for applied, technology-supported environmental



education (Masruroh et al., 2024). In contrast, the European contribution is not concentrated, but rather thematically dispersed: citizen science-based water quality monitoring in Germany, mobile-GIS teacher training and gamified energy education in Spain, as well as an initiative to coordinate a European Union-funded cross-border study programme between Poland and the Czech Republic (Štěpánek et al., 2024)—this fragmentation reflects the diversity of national curricula and funding mechanisms in the European higher education space, but does not represent a unified regional research programme. Relatively small but geographically dispersed contributions from Brazil, Russia, Ukraine, Colombia, Canada and Morocco demonstrate that digital geoenvironmental pedagogy is not limited to a few technologically advanced systems, being independently tested in diverse institutional and socio-economic contexts, often in response to local ecological or infrastructural constraints.

3.2 Methodological characteristics of the study

The 64 studies are scattered across 43 different outlets, but the field is far from evenly distributed (Table 1). Sustainability alone accounts for nearly one in six papers (15.6%), an outlet whose broad, interdisciplinary scope makes it a natural home for research bridging environmental education and digital pedagogy. Education Sciences follows at a distance (6.3%), while Cultural geographies and the ISPRS International Journal of Geo-

Information each contribute three studies (4.7%), reflecting the field's dual roots in educational research and geospatial science.

Beyond this handful of recurring venues, the picture fragments quickly: 34 of the 43 journals contribute just a single paper each. This long tail suggests the topic has yet to settle into a small set of dedicated journals, and is instead being picked up piecemeal across education, geography, environmental science, and technology outlets alike—a sign of a genuinely interdisciplinary, but still consolidating, research field.

3.3 Thematic directions: fields of application in geo-ecological and digital teaching

A thematic analysis of a corpus of 64 studies identifies five distinct, yet partially overlapping, directions for the application of digital technologies in geo-ecological education.

The first strand concerns GIS and spatial analysis tools used for geoenvironmental modelling and the development of spatial thinking. This includes mapping the distribution of forests, vegetation and wildlife among underperforming secondary school pupils using ArcGIS (Bikar et al., 2022), and dynamic Google Earth-based imagery used for spatial thinking tasks on disaster prevention among geography education students, as well as a suite of WebGIS and GPS-based field applications-ArcGIS Collector-used to assess the geospatial competence of future teachers according to the European DigComp 2.1 framework, Iberpix and StoryMaps (Sebastián-López and de Miguel

TABLE 1 Distribution papers by publishers.

№	Publisher	Number of studies	Percentage
1	Sustainability	10	15.62%
2	Education Sciences	4	6.25%
3	Cultural geographies	3	4.69%
4	ISPRS International Journal of Geo-Information	3	4.69%
5	Discover Education	2	3.12%
6	E3S Web of Conferences	2	3.12%
7	International Journal of Emerging Technologies in Learning	2	3.12%
8	International Research in Geographical and Environmental Education	2	3.12%
9	International journal of environmental research and public health	2	3.12%
10	Algorithms	1	1.56%
11	Applied Sciences	1	1.56%
12	Australian Journal of Environmental Education	1	1.56%
13	Chemistry-Didactics-Ecology-Metrology	1	1.56%
14	Cypriot Journal of Educational Sciences	1	1.56%
15	Educat, Revista Electrónica de Tecnología Educativa	1	1.56%
16	Ekológia (Bratislava)	1	1.56%
17	Electronics	1	1.56%
18	Engineering Proceedings	1	1.56%
19	European Journal of Geography	1	1.56%
20	European Journal of Investigation in Health, Psychology and Education	1	1.56%
21	Frontiers in education	1	1.56%
22	Geography	1	1.56%
23	Geoscience	1	1.56%
24	Geosciences	1	1.56%
25	Heritage	1	1.56%
26	IOP Conference Series: Earth and Environmental Science	1	1.56%
27	In Journal of Physics: Conference Series	1	1.56%
28	International Journal of Environmental Impacts	1	1.56%
29	International Journal of Geoinformatics	1	1.56%
30	International Journal of Interactive Mobile Technologies	1	1.56%
31	Janus	1	1.56%
32	Journal of Adventure Education and Outdoor Learning	1	1.56%
33	Journal of Curriculum Studies Research	1	1.56%
34	Journal of Education and e-Learning Research	1	1.56%
35	Journal of Environmental & Earth Sciences	1	1.56%
36	Plos One	1	1.56%
37	Postmodern Openings	1	1.56%
38	Progress in Geography	1	1.56%
39	Review of International Geographical Education Online	1	1.56%
40	Sustainable Engineering and Innovation	1	1.56%
41	Sustainable Futures	1	1.56%
42	TEM Journal	1	1.56%
43	Tikrit Journal for Agricultural Sciences	1	1.56%
Total		64	100

González 2020) are included. A related, but more cautious, finding comes from a Q-method study among Chinese pre-service teachers: regardless of module completion, a persistent ambivalence towards GIS was identified across all identified perspective groups, indicating concerns about technical complexity and a lack of institutional support (Guo and Meadows, 2020). In summary, these studies consistently show that when GIS and remote sensing tools are integrated into structural curricula, they reliably enhance spatial-analytical and disaster-related thinking, furthermore, technical accessibility and teacher confidence remain unresolved prerequisites for their effective adoption in the classroom.

The second direction includes virtual and augmented reality applications, as well as the modelling of environmental degradation and geoenvironmental phenomena. A combined approach using 360-degree immersive video and electroencephalographic measurements demonstrated that the positive emotional state induced by VR enhances intrinsic motivation and flow experience when engaging with natural disaster and environmental protection content (Shen et al., 2022), while a collaborative immersive virtual environment was found to support significant learning outcomes in hypsographic and contour relief thinking, regardless of the task structure, whether individual or collaborative (Sedlák et al., 2022). A virtual site visit, substituting for actual fieldwork in a landscape ecology restoration course, partially successfully replicated the initial, experience-based stages of Kolb's experiential learning model, although it could not fully substitute for physical attendance at the site (leBrasseur, 2023). Institution-wide, integrated drone and VR instruction across several disciplines, including the geography and ecology cohorts at, generated positive reception regarding student engagement and understanding, tempered by infrastructural limitations reported by instructors (Lu et al., 2023), while a virtual tour of a geomorphosite on a volcanic slope, based on UAV and 360-degree panoramas, achieved strong user ratings as an alternative tool for visiting hazardous terrain (Masrurroh et al., 2024). A campus augmented reality application also showed that younger primary school pupils found AR-based plant ecology content more useful and easier to comprehend than adults, confirming the Technology Acceptance Model in this context (Lo et al., 2021). Although immersive technologies have been shown to be particularly effective in generating motivational and affective engagement with geo-ecological content in this domain, evidence directly linking this engagement to sustained learning gains remains limited.

The third strand includes mobile and web-based platforms that support students' fieldwork, as well as open-source or citizen science-based geodata. A GPS-based, context-aware mobile application, structured through an embedded research-cycle framework, compared with traditional paper-based fieldwork, attention during wetland ecosystem education, yielded significantly stronger results in terms of reliability and satisfaction (Jong, 2020), while the portable photometer-based citizen science app achieved statistically significant gains in water quality knowledge, however, there was no corresponding change in key ecological values (Jekel Könnel et al., 2025). A four-phase geoscience education programme in a rural area of Colombia, a digitally administered assessment platform, was largely analogue, combined with place-based field strategies,

delivered significant gains in understanding of tectonic, hydrological, and disaster-related content (Delgado-Guerrero et al., 2025). A proposed, yet-to-be-tested smartphone app for coastal marine ecosystem literacy provides a needs-based justification for implementing mobile learning in under-resourced educational settings (Istiana et al., 2021), a finding confirmed by a large-scale evaluative audit of commercially available ecology apps—which found that technical quality and interactivity, rather than download popularity, are true predictors of pedagogical value (dos Santos et al., 2025). Summarising these studies, mobile and citizen science-based platforms are particularly well-suited to extending authentic field geo-ecological learning in situations where real fieldwork is logistically constrained, and that popularity metrics are an unreliable guide to the actual quality of teaching.

The fourth strand includes collaborative digital tools, gamification and multimedia platforms for developing environmental competence and professional skills. An integrated suite of applications comprising an interactive whiteboard, a mind-mapping programme, an infographic tool and a cloud-based document-sharing service was used among Ukrainian ecology students to model real-world environmental impact assessment workflows (Barna et al., 2020), and the CT-gamification of renewable energy content among primary school pupils produced a significant increase in achievement, satisfaction and motivation, irrespective of academic performance, indicating a dissociation between affective and cognitive outcomes (Bilbao-Aiastui and Miranda-Urquijo, 2022). A computer game on palaeoecology, especially in terms of design dimensions related to creativity, achieved high satisfaction among museum visitors without directly measured learning achievements (Lu et al., 2025). STEAM-integrated, design-based pedagogy on the theme of global warming, combined with project-based learning and randomised digital tools, achieved significant gains in environmental awareness in both rural and urban school settings (Syamsudin et al., 2025), while a relatively unspecified suite of desktop and mobile applications introduced within a proprietary motivational framework resulted in a characteristic, but causally unexplained, increase in professional interest among students of a Russian technical university (Shefer et al., 2021). Overall, this line of research indicates that collaborative and gamified digital tools reliably enhance motivation, satisfaction, and professional engagement with geoenvironmental content, however, it is difficult to disentangle their independent contribution to a broader pedagogical model or their translation into measurable learning gains.

The fifth strand addresses the digital competence frameworks at the curriculum level and inter-institutional or needs-based diagnostics. A quantitative difficulty index, applied to a sample of Polish pupils from six European countries, identified the pedosphere as the least attractive and the least mastered within the geo-ecological domain. this gap was attributed primarily to the reported lack of specially developed digital didactic materials, rather than to a deficiency in teachers' self-assessed ICT competence (Urbańska et al., 2022). A comparative e-learning study among Moroccan baccalaureate graduates identified a content-dependent asymmetry: digital learning was significantly preferred over traditional teaching in declarative, knowledge-transmission-oriented modules, but offered no advantage in

modules requiring applied or practical engagement (Rachad and Oughdir, 2023). At the institutional level, a four-year, EU-funded cross-border initiative between Polish and Czech universities, using PC-based atmospheric emission dispersion modelling templates incorporated into the framework of a bilingual internship, achieved statistically equivalent soft and hard skill outcomes across two national cohorts (Štěpánek et al., 2024), and the DigComp 2.1 competency framework assessment exercise discussed in the first strand also serves as a diagnostic tool at the curriculum level, indicates that awareness of the Sustainable Development Goals is more easily achieved through mobile fieldwork than technical geospatial competence. In summary, this strand demonstrates that diagnosing the curriculum and exploring the competency framework plays a complementary role to intervention-oriented research, identifying precisely which geo-ecological domain and competency dimension most urgently requires targeted digital investment.

3.4 Main thematic clusters according to the co-occurrence analysis

In order to support the qualitative thematic synthesis outlined above, a keyword co-occurrence analysis was additionally performed across the wider review corpus, based on data retrieved from the Web of Science database and processed using the bibliometrix package in the R/RStudio environment. As illustrated in Figure 4, the generated network reveals a conceptual landscape organized into four discrete clusters, each distinguished by a unique colour coding.

The largest and most central cluster, shown in red, is anchored by the “geoecology” node, occupying the highest-density position in the network. It includes landscape, pollution, human impact, environmental management, geodynamics, Holocene, geomorphology, biodiversity, plant community, and permafrost, extending to broader earth-science descriptors such as soil and

heavy metals, country-level descriptors such as China, Germany, and the Russian Federation, and thematic descriptors such as sustainable development, mountain regions, and anthropogenic impact. The prominence of this cluster indicates that the geoenvironmental literature underlying this review remains largely grounded in descriptive, regionally based earth science research, with “geoecology” serving as the field’s main organising concept.

The second, blue cluster, on the right-hand side of the network, groups ecology, remote sensing, GIS, landscape ecology, land use, geology, landforms, ecological monitoring, environmental protection, erosion, climate change, physical geography, and, notably, education. The thick link connecting “geoecology” to this cluster—particularly to “ecology,” “remote sensing,” and “education”—forms the network’s main conceptual bridge, empirically confirming this review’s central premise: that geoenvironmental knowledge, geospatial technologies, and formal education function not as separate fields but as closely interlinked domains.

The third, purple cluster, at the bottom of the network, brings together ecosystems, halophytes, hydrogeology, groundwater, and the regional descriptor New Zealand—reflecting specialised literature on aquatic-wetland and saline environments and their hydrogeological processes, positioned outside the discipline’s conceptual core as region-specific case studies. The fourth, smaller green cluster, at the network’s edge, links mapping, Eurasia, and Central Europe, marking a minor sub-theme around regional cartographic and geospatial characterisation.

Beyond these four clusters, the keyword “change” holds a structurally central position, bridging ecological, curricular, and methodological dimensions alike. Overall, the co-occurrence network confirms the thematic synthesis proposed in Section 3.3: geoecology forms the field’s conceptual core, GIS and remote sensing constitute its technological bridge, and education is the applied domain where both converge. This structure offers a coherent, empirically grounded basis for the synthesis presented in the Discussion section.

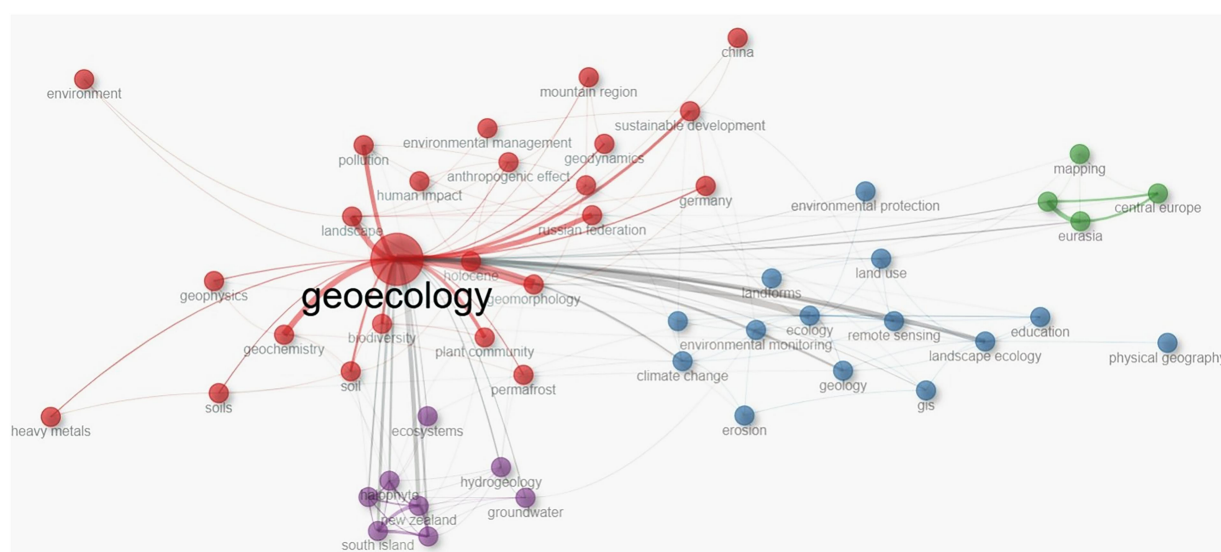


FIGURE 4

Co-occurrence network of keywords showing the conceptual structure of the literature reviewed on geoenvironmental and digital technology in the field of geography education (Bibliometrix).

4 Discussion

The results of this systematic review indicate that contemporary geoeological education in international higher and secondary education systems is, on the one hand, expanding, and on the other, characterised by persistent structural contradictions. The reviewed literature demonstrates that no single and universal pedagogical paradigm has emerged for teaching geoenvironmental issues. On the contrary, the field is characterised by persistent structural contradictions, from immersive virtual technologies to geospatial analysis tools (Sulzer and Gspurning, 2025) and gamified or mainstream digital products; their combination, whilst not fully systematised, often proves effective. Overall, the studies reviewed indicate that the effectiveness of geo-environmental education is not limited to the delivery of technical content—it requires a consciously designed pedagogical rationale that equally encompasses the cognitive, affective, and practical aspects of learning. This discussion is aimed at answering three research questions: what pedagogical approaches to teaching geo-environmental issues through digital technologies are effective, and what is the quality of the evidence that supports them (RQ1); to what extent international experience corresponds to the specific needs of training geography students and teachers, and what structural-methodological adaptation is required (RQ2); what geographical, institutional, and technological gaps in the field define the priority directions for curriculum renewal (RQ3). The following discussion systematically addresses these three questions, summarising the main thematic patterns and analysing the current theoretical and methodological contradictions in the field.

4.1 Pedagogical approaches and the quality of evidence for their effectiveness (RQ1)

Regarding the first research question (RQ1), the most common model in the reviewed literature is—that immersive and gamified digital tools are frequently reported to increase the motivation and engagement of students and learners, but these gains are rarely confirmed with rigorously controlled measurement tools, and, as the cases below show, most are affective or self-reported rather than objectively assessed learning outcomes. The GeoVT project, funded under the Erasmus+ programme, delivers geomorphology and geoheritage education through 360-degree virtual field trips among partner institutions in five countries, and approximately 90% of respondents found the material understandable and engaging, but this result was derived from a descriptive satisfaction survey rather than a controlled pre/post-test design (Vandelli et al., 2024). A similar pattern is replicated in Biomes, a collaborative immersive virtual environment for classifying climatic belts: although participants scored significantly higher in terms of sense of presence and the visualisation of abstract climatic concepts compared to traditional instruction, the study is based on perceived experience rather than objectively measured learning achievements, and the age-related affective response (younger pupils being much more engaged than adults) suggests that immersive tools do not have a uniform effect (Střechová et al., 2025). The augmented reality application for

museums, ARTutor, presents a similar profile: 86% of pupils who engaged with content about extinct species reported an increase in their knowledge and 95% reported liking the app, but these are self-reported affective and recall measures, and the absence of a control group precludes the study from causally demonstrating any additional benefit of the AR intervention over traditional museum pedagogy (Kondyli et al., 2024).

The analysis of GIS-based tools reveals a completely different, yet no less significant, contradiction: the pedagogical value of geospatial technologies does not lie in the technical complexity of the software, but in the extent to which it is embedded in a participatory, real-life case study architecture Labianca (2021). In a socio-economically vulnerable inland area of Southern Italy (Monti Dauni) shows that when using QGIS to study sustainable development, students progressed visually from map-based description to interpretive and critically-applied engagement, but the author warns that GIS is an 'isolated tool' from geographical concepts as a 'separate tool' may lead to a narrow, reductive understanding. This caveat resonates directly with a rigorous, STEM-oriented research project that integrated ArcGIS, MapInfo, GNSS, and Landsat technologies to study erosion of the Precarpathian river channel in Ukraine: Although this work provides a promising model for developing students' skills in working with real scientific data, it completely avoids formal assessment of learning outcomes, meaning its pedagogical claims remain hypothetical rather than proven (Yushchenko et al., 2022). The field module at Graz University, a postgraduate-level course with over 20 years of experience in Slovakia's High Tatras, also confirms this approach: although the integration of raw data from dGPS, unmanned aerial vehicle photogrammetry, and terrestrial laser scanning with auxiliary geodata is claimed to foster students' professional-level flexibility, these assertions are also based on illustrative case studies, without a control group or a standardised measure of outcome. In contrast, a study analysing teacher acceptance of paper-based GIS (PBGIS) in South Africa found no pupil-level data, relying instead on descriptive case studies citing inadequate teacher training and identifying structural barriers such as time scarcity in the curriculum and linguistic complexity—indicating that it is not the digital technology itself, but the institutional preconditions for its implementation that are crucial (Mkhize, 2023).

Another significant example that challenges the assumption of the primacy of immersive technologies is that inexpensive and accessible digital tools, when integrated into a structured research chain, can produce results that are as, or even more, illustrative than comparatively complex virtual systems. In a ten-stage didactic sequence for Brazil's six biomes, students, using only general productivity tools such as smartphones, PowerPoint, and Canva, were reported to have successfully mastered a topic that is systematically underrepresented in the national examination programme, however, the assessment is based on the teacher-researcher's field diary and descriptive tasks, and not on a psychometrically validated instrument (Boer et al., 2024). Tablet-based gamified recycling games in three primary schools in north-west Spain also yielded similar results: although a significant change in pupils' ecological habits and a 'very good' score of 91.57% in digital literacy were achieved, the lack of post-intervention measurement makes it difficult to determine the separate contribution of gamification from the broader pedagogical intervention (Ricoy and Sánchez-Martínez,

2022). An annual environmental education programme on the geocultural heritage of the sea cliffs of the Pelion coast, Greece, also shows a similarly limited level of evidence for value-based outcomes: although a qualitative thematic analysis identified that five students had successfully acquired geological, aesthetic, and sustainability values, a deeper acquisition of cultural values was partially unsuccessful, which the authors attribute to insufficiently immersive pedagogical approaches (Georgousis et al., 2021). A similar dissociation is also observed in a study of German prospective teachers' competence in digital geomedial literacy: students' self-assessment of their competence is considerably higher than that of their lecturers, indicating that everyday digital literacy does not automatically translate into the disciplinary, evidence-based thinking required for geoenvironmental argumentation.

A review that analyses the theoretical foundations of these contradictions at a more fundamental level unpacks the PRISMA-based framework of 'geographical thinking': Synthesising fifty records, the authors identify conceptual, procedural, and synthesising approaches and point to a lack of empirical evidence confirming that digital tools genuinely foster 'geographic thinking' in classroom practice. This diagnosis has direct methodological relevance for this review: assessing the effectiveness of digital technologies in teaching geoenvironmental issues must first determine which dimension of geographic thinking (conceptual, procedural, or relational) must be precisely determined, and the absence of such precision renders conclusions about comparative effectiveness unclear (AlGerafi et al., 2023).

Taken together, these cases converge on one point and diverge on another. They converge in showing that affective and motivational gains—engagement, presence, self-reported enjoyment—are reported almost universally, regardless of technology type, learner level, or geographical setting; on this point the literature agrees. They diverge sharply, however, on what that engagement translates into: in GIS-based work the divide is whether the tool is embedded in a real research chain (Labianca, 2021; Yushchenko et al., 2022) or used in technical isolation (Mkhize, 2023), while in immersive and gamified work the divide is between studies that stop at satisfaction metrics (Kondyli et al., 2024; Vandelli et al., 2024) and the minority that attempt any form of controlled or repeated measurement (Ricoy and Sánchez-Martínez, 2022). This suggests the field is not short of technologies that engage students, but short of a shared standard for what counts as evidence that engagement has become learning—a gap the methodological transparency called for in Section 2 is intended to make explicit rather than resolve.

4.2 Alignment between international practice and the needs of geography students: structural and methodological adaptation (RQ2)

The key finding, identified in response to the second research question (RQ2), is a persistent structural gap between international digital education practices and the preparation, confidence, and institutional positioning of the teachers who implement them in the actual classroom. This issue is particularly evident in Slovak primary schools: despite the

availability of interactive whiteboard equipment, teachers often revert to traditional, memorisation-based teaching strategies and rarely design project-based or nature-based tasks, indicating that technological accessibility alone is insufficient. It also indicates that investment is needed in teacher digital competence and curriculum reform (Brečka et al., 2022). A similar gap is also confirmed in a case study on ArcGIS Online-based disaster prevention education in Chinese secondary schools: the authors openly acknowledge that the introduction of GIS is often disrupted by the 'digital divide' between well-equipped and under-equipped schools, due to the geographical teachers' technical concerns (Li et al., 2022). A study on argumentation competence in German higher education further clarifies this gap: although 86% of lecturers theoretically fully support the curricular relevance of geomedial-based argumentation, in actual teaching this competence is often not taught explicitly but is merely assumed, only in isolated cases are targeted argumentation modules introduced. In the South African context, this gap is most acutely apparent: research into teacher uptake identifies inadequate teacher preparation, the ambiguity of required resources, time constraints in the curriculum and language complexity for learners of a second language as the main barriers—indicating that the issue is not a lack of technology, but a lack of the socio-infrastructure prerequisites for its implementation.

The difficulty in adapting geo-environmental content for geography students stems primarily from the nature of the subject itself and the students' prior knowledge and academic backgrounds. It is worth noting that if GIS is used in isolation from the foundational concepts of the discipline of geography, it can lead to a simplified, reductive understanding rather than a focus on complexity. This assertion resonates directly with the structural gap in argumentation competence identified by Wolff-Seidel and Budke (2022): students' everyday digital freedom does not automatically translate into the evidence-based, critically-sourced thinking required for geoenvironmental argumentation. This pattern extends to value-based outcomes, which are likewise distinct from cognitive outcomes and require specific immersive pedagogical approaches to develop. A synthesis of these three studies leads to an important methodological conclusion: evaluating the effectiveness of digital technologies in geoenvironmental education first requires a clear identification of which specific construct—technical skill, argumentation competence, value orientation, or geographical thinking—is being targeted (Mendoza et al., 2025), as success in one construct does not automatically transfer to another.

4.3 Geographical, institutional and technological gaps and curriculum renewal priorities (RQ3)

In response to the third research question (RQ3), the geographical distribution of the literature reviewed reveals a structural asymmetry, which we consider in this review as an important empirical finding and a methodological limitation. Well-funded, multinational consortia (e.g., the Erasmus + GeoVT project, implemented in partnership with five European countries) or large German universities when using

available infrastructure, resource-limited settings—powerless rural schools in South Africa, topics systematically underrepresented in Brazil's national programme (Guimarães, 2018), or the Russian hydrometeorological programme, whose funding was cut due to the pandemic (Abramov et al., 2021)—require entirely different solutions. As in Section 4.2, this asymmetry is institutional rather than purely technological in nature; here it manifests specifically as unequal funding and infrastructure across regions and countries.

Based on this review, several priority directions for updating the geoenvironmental curriculum are identified. The first is the use of inexpensive, widely accessible digital tools (such as general productivity software and tablet applications) as a substitute for, or in addition to, expensive immersive systems integrating them into a structured research chain, which can ensure meaningful engagement even in resource-limited settings (Georgousis et al., 2021). The second is to integrate GIS and geospatial tools not as an isolated technical exercise, but into real, participatory research projects, linking the pedagogical value of the technology to its context of use rather than its technical complexity. Thirdly, to consider teachers' professional development as a priority alongside, and even before, the provision of technological equipment, as the availability of equipment does not automatically lead to pedagogical change. Fourthly, and consistent with the construct-specific evaluation principle discussed in Section 4.2, digital tools should be introduced alongside deliberate instruction in the higher-order structures they are meant to support (argumentation competence, value orientation, geographical thinking), since these structures are not automatically formed by mere familiarity with the technology. The fifth is to pay attention to the more-than-human and ethical dimensions of digital-environmental pedagogy: While field video and mapping applications can extend learning for families and

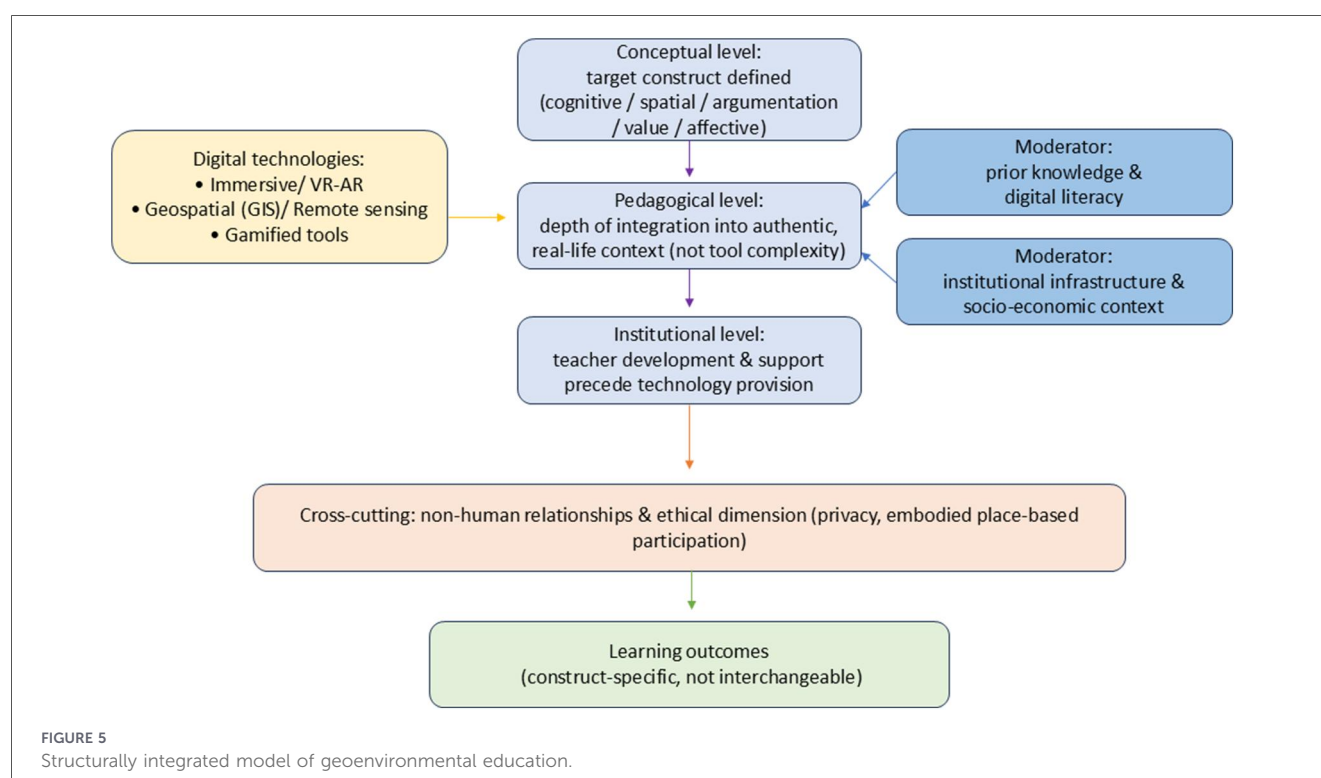
communities, experienced educators themselves highlight the need for some secluded, child-initiated spaces as 'non-digital space' due to the risk of invasion of privacy, reminding us that digitalisation is not a universal good (Jukes and Lynch, 2024; Lynch and Thomas, 2024).

Furthermore, a number of borderline works identified during this review but not included in the direct evidence synthesis—an autoethnographic account of the experience of digitally sensing microbial ecology (Bradshaw, 2024), a study on designing an app for snake conflict management (Kirkham, 2024), and the editorial introduction to the special issue from which these two works are drawn (Davies et al., 2024)—do not serve as direct evidence, as there are no students, teaching objectives, or assessment of learning outcomes. However, their inclusion demonstrates the stringency of this review's inclusion criteria and indicates the broader methodological pool from which digital-ecological sensing technologies could be adapted for a geoenvironmental curriculum in the future.

4.4 Synthesis: towards a structurally integrated model

An analysis that integrates the literature reviewed and the contradictions discussed above allows for the formulation of the key structural principles of an integrated model for geoenvironmental education for geography students.

Firstly, as established in Section 4.2, effectiveness must be assessed against a clearly defined target construct—cognitive knowledge, spatial thinking, argumentation competence, value orientation, or affective engagement—since success on one construct does not automatically transfer to another (Radianti et al., 2020).



Secondly, and consistent with the GIS-embedding priority discussed in Section 4.3, pedagogical value derives not from technical complexity but from the depth of integration into an authentic, real-life context; both high-tech immersive systems and simple productivity tools can yield meaningful results when applied on this basis.

Thirdly, as noted in Section 4.3, teacher professional development and institutional support are prerequisites that precede the technology itself, since equipment alone, without appropriate training, does not guarantee pedagogical change (Ghazali et al., 2024).

Fourthly, methodological rigour-control group, pre/post-measurement, and validated tools-is systematically lacking in the

reviewed literature; many studies rely on descriptive case designs, which makes it difficult to isolate the specific causal effect of the technology from the broader pedagogical intervention.

Fifth, digital-ecological pedagogy must consider non-human relationships and ethical issues (privacy violations, data use) must be considered, as digitalisation does not always expand learning; at times, it can disrupt embodied, place-based participation.

Based on these five structural principles, a model for a modular and vertically integrated curriculum can be constructed. Such a model is oriented towards specific regional needs, spatial and conceptual foundations, field-based and

TABLE 2 Correlation between study characteristics and the structurally integrated model (Figure 5), for the studies discussed in Section 4.

Study	Technology	Pedagogical approach/context	Reported learning outcome & evidentiary rigour	Institutional/contextual note	Model dimension illustrated (Figure 5)
Vandelli et al., 2024	360° VR field trips (GeoVT/Erasmus+)	Immersive experiential learning	Affective: ~90% found material engaging/understandable; descriptive survey, no pre/post-test	Multinational consortium, 5 EU countries	Technology input → Pedagogical level; well-resourced institutional level
Střechová et al., 2025	Collaborative immersive VR (Biomes)	Constructivist visualisation	Affective/perceived: higher presence & concept scores vs. traditional teaching; no objective measure	Single-institution pilot	Pedagogical level; construct not isolated (Conceptual level gap)
Kondyli et al., 2024	AR app (ARTutor)	Museum-based informal learning	Self-report: 86% knowledge increase, 95% liked app; no control group	Museum setting	Illustrates affective–cognitive gap (Conceptual level)
Labianca, 2021	QGIS	Participatory, real-life case study	Qualitative: progression from descriptive to critical engagement	Socio-economically vulnerable region, Southern Italy	Pedagogical level—technology embedded in authentic context
Yushchenko et al., 2022	ArcGIS, MapInfo, GNSS, Landsat	STEM research project	No formal learning-outcome assessment	University level, Ukraine	Fourth principle: methodological-rigour gap
Graz University field module	dGPS, UAV photogrammetry, terrestrial laser scanning	Postgraduate field course	Illustrative case studies; no control group	20+ years institutional experience, Slovakia	Institutional level—sustained programme, but no outcome data
Mkhize, 2023	Paper-based GIS (PBGIS)	Teacher-acceptance study	No pupil-level data	Under-resourced rural schools, South Africa	Institutional level—teacher training, time, language barriers
Boer et al., 2024	Smartphones, PowerPoint, Canva	Ten-stage didactic sequence	Descriptive: field diary and classroom tasks, not psychometrically validated	Brazil, low-cost setting	Pedagogical level—low-tech tool, high contextual integration
Ricoy and Sánchez-Martínez, 2022	Tablet-based gamified games	Gamification	Ecological-habit change; 91.57% digital-literacy score; no follow-up measurement	Primary schools, north-west Spain	Fourth principle—no post-intervention follow-up
Georgousis et al., 2021	Field-based heritage programme	Annual environmental-education programme	Qualitative: partial acquisition of values	Pelion coast, Greece	Fifth principle—value-based outcomes need targeted design
Wolff-Seidel and Budke, 2022	Digital geomeia	Argumentation-competence study	Self-assessed competence exceeds lecturer assessment	German higher education	Conceptual level—construct mismatch
Brečka et al., 2022	Interactive whiteboards	Available but underused equipment	Teachers revert to traditional strategies	Slovak primary schools	Institutional level—equipment ≠ pedagogical change

digital learning approaches, as well as ethical and value-based components. The proposed framework recognises two additional variables that regulate the relationship between learning outcomes and pedagogical intervention: the first is students' prior knowledge and digital literacy, which serves as a key data point determining the effectiveness of active learning strategies; the second is the institutional infrastructure, curriculum flexibility, and variations in the educational context, including socio-economic factors, which determine the conditions for the effective implementation of pedagogical innovations. [Figure 5](#) represents these relationships visually.

As shown in [Figure 5](#), the model is organised as a vertical chain of three levels, linked by the arrows running from top to bottom. At the top, the conceptual level requires that the target construct (cognitive knowledge, spatial thinking, argumentation competence, value orientation, or affective engagement) be defined before effectiveness is assessed, since, as shown throughout [Section 4](#), success on one construct does not automatically transfer to another. This feeds into the pedagogical level, where the decisive factor is not the technical sophistication of the tool but the depth of its integration into an authentic, real-life context; the model deliberately places this level, rather than the technology itself, at the centre of the chain. The institutional level, at the base of the vertical chain, represents the precondition established throughout [Sections 4.2](#) and [5.3](#): teacher professional development and sustained institutional support must precede, or at minimum accompany, the provision of equipment, since access to technology alone does not produce pedagogical change.

On the left, the digital technologies box, grouping immersive/VR-AR tools, geospatial (GIS) tools/Remote sensing, and gamified tools, feeds directly into the pedagogical level rather than into the model as a whole. This visually reinforces the finding that these three technology families are functionally interchangeable inputs: what determines their pedagogical value is the level they are integrated into, not which of the three is chosen. On the right, the two moderator boxes, learners' prior knowledge and digital literacy, and institutional infrastructure together with socio-economic context, are shown feeding into the pedagogical level as well. This reflects their role, identified in [Section 5.2](#), as variables that condition how effectively any given technology-pedagogy combination can be implemented in a specific setting, rather than as direct drivers of learning outcomes.

Beneath the three-level chain, the cross-cutting band (non-human relationships and ethical dimension) spans the full width of the model to indicate that privacy and embodied, place-based participation are not a fourth, separate level but a constraint that applies across all three. This reflects the fifth structural principle discussed in [Section 4.4](#), that digitalisation does not always expand learning and can, at times, disrupt it. The model terminates in a single outcome box, learning outcomes, labelled as construct-specific and not interchangeable. This closing element visually reiterates the model's central claim, namely that a positive result recorded for one construct (for example, motivation) cannot be read as evidence of effectiveness for another (for example, cognitive mastery) unless that construct was itself the one being measured.

[Table 2](#) summarises this correlation for a representative subset of the studies discussed above, showing, for each study, the

technology and pedagogical approach used, the reported learning outcome and its evidentiary rigour, relevant institutional or contextual factors, and which specific dimension of the structurally integrated model ([Figure 5](#)) the study illustrates.

5 Conclusion

5.1 Summary of the research findings

This systematic review describes the pedagogical landscape of teaching geoenvironmental issues to geography students through digital technologies, based on an international corpus of 64 studies, of which studies with more comprehensive methodological and thematic descriptions were included for in-depth synthesis. The analysis centres on three technology clusters—immersive virtual environments, geospatial analysis tools, and gamified digital products—and on two cross-cutting dimensions: the epistemological transition from theory to applied practice, and the cognitive understanding of geoenvironmental systems. This, in turn, indicates a structurally persistent and significant gap between the pedagogical approaches that govern their integration into higher and secondary education programmes.

This picture is consistent across both technology types discussed in [Sections 4.1](#) and [4.2](#): motivational and engagement gains are common, but rigorously assessed learning outcomes are not, and effective teaching therefore depends less on the tool itself than on the continuous integration of its theoretical, cognitive and practical components.

5.2 Geographical-institutional asymmetry and resource inequality

One of the main conclusions of this systematic review is that the pedagogical effectiveness of digital technologies in geoenvironmental education cannot be considered in isolation from resource inequalities at national and institutional levels. This issue is regarded not as an additional factor but as a fundamental systemic condition that determines the quality of learning outcomes. The main empirical evidence for this conclusion is apparent in the contrast between well-funded, multinational consortia and resource-constrained settings: the Erasmus+ GeoVT project, implemented in partnership with five European countries, when using a full institutional infrastructure, South Africa's under-provisioned rural schools in terms of electricity and computers, and the Russian hydrometeorological programme, whose funding was cut due to the pandemic, require entirely different solutions ([Dantas da Silva Júnior et al., 2021](#)). Although the full review corpus includes authors from twenty-nine countries, the majority of studies included in the in-depth synthesis are concentrated in a limited number of medium-income Asian and European countries (Indonesia, China, Spain, Taiwan), while regions such as Africa and Central Asia are represented only by isolated studies. Such geographical asymmetry means that the findings cannot be directly transferred to resource-constrained settings.

5.3 The human factor: the priority of pedagogical support and defining a clear structure

A comprehensive analysis of the literature under review highlights an important principle: mastering digital tools or simply having access to quality data is not sufficient to develop geospatial competence on its own. The decisive factor is teacher preparation and the prior definition of the specific construct to be assessed. A review analysing the structure of ‘geographical thinking’ indicates a systematic lack of empirical evidence confirming that digital technologies genuinely foster this structure in classroom practice, which precludes any conclusion about its effectiveness (Bendl et al., 2025). More broadly, evaluating effectiveness first requires determining which specific construct is being targeted—e.g., cognitive knowledge, spatial thinking, argumentation competence, or value orientation—since success on one dimension does not automatically transfer to another. This conclusion is confirmed by findings from primary schools in Slovakia (Brečka et al., 2022), secondary schools in China, and rural schools in South Africa, which consistently show a lack of teacher preparation and institutional support: the availability of equipment, without appropriate professional training, does not lead to pedagogical change. Furthermore, value-based and evidence-competence-based outcomes are distinct from cognitive outcomes and require specific, targeted pedagogical design for their development.

5.4 Practical implications

The findings translate into concrete implications for three audiences. For curriculum developers, the priority is to embed GIS and immersive tools within existing subject content—participatory case studies, local geoenvironmental problems—rather than teaching them as stand-alone technical modules, and to build in explicit assessment of higher-order constructs (argumentation, spatial or geographical thinking) rather than relying on satisfaction surveys alone. Curricula that pair a tool with an explicit target construct—for example, a GIS unit assessed for argumentation about local land-use trade-offs rather than for software proficiency alone—are more likely to generate evidence of learning than technology-led redesigns that introduce a tool first and decide what it should teach afterwards. For teacher educators, the review points to professional development that precedes or accompanies equipment provision, with training that addresses not just tool operation but how to design controlled, outcome-based classroom evaluation; where budgets are limited, this training is arguably the higher-leverage investment, since several of the studies reviewed in Section 4.2 show well-equipped classrooms reverting to traditional methods in the absence of adequate teacher preparation. For policymakers, the geographical asymmetry documented in Section 5.2 suggests that funding low-cost, widely accessible tools (smartphones, generic productivity software) in under-resourced settings may do more for equitable access than investment in high-end immersive systems alone, and that monitoring frameworks should require disaggregated reporting of affective vs. cognitive learning

outcomes. Taken together, these three sets of implications reflect the same underlying principle as the model set out in Section 4.4: sustained impact depends less on which technology is adopted than on how deliberately its pedagogical, institutional, and evaluative components are designed around it.

5.5 Future research directions

This review identifies several priority directions for future research. Firstly, the majority of the studies reviewed measure only short-term affective or motivational gains, and there are virtually no longitudinal studies monitoring the long-term retention of knowledge and skills or their specific outcomes in professional practice; such studies could provide an evidence base for the sustained impact of digital interventions. Secondly, there is a lack of rigorously controlled, quasi-experimental designs that can disentangle the specific causal contribution of digital technology from a broader pedagogical model: a number of studies combine digital tools with project-based learning or STEAM approaches, which makes it difficult to determine the technology’s independent contribution. Thirdly, there is a need to develop specifically validated tools to measure understudied constructs such as argumentation competence, value orientation, and non-human relationships, as current literature often relies on general satisfaction or motivation scales (Jukes and Lynch, 2024). Fourth, the evidence base needs to be extended to resource-limited and under-represented areas: Based on isolated examples such as Mkhize (2023) and Boer et al. (2024), research should be conducted to examine the extent to which findings from well-resourced settings are transferable to education systems in developing countries.

5.6 Limitations of the study

There are several limitations that should be considered when interpreting the results of this systematic review. Firstly, the search strategy was limited to specific bibliographic sources, language (in English) and a preference for open access, which may have resulted in the omission of relevant studies published in regional journals, conference proceedings, or in languages other than English. In particular, studies on geoenvironmental digital education from underrepresented regions such as Central Asia, Sub-Saharan Africa, and South Asia, may be disproportionately underrepresented in the corpus due to this limitation. Secondly, the number of studies included in the in-depth methodological and thematic synthesis constitutes a relatively limited group within the full corpus of 64 studies. This is not indicative of a lack of research activity in the field, but rather of the specificity of the inclusion criteria; whilst this focused scope has enabled a thorough, evidence-based synthesis, it limits the generalisability of the findings. Thirdly, the methodological heterogeneity of the included studies—ranging from quasi-experimental designs to case studies, Q-methodology, and conceptual reviews—complicates the synthesis. Although the predominance of case and descriptive studies reinforces the applied orientation of the field, it limits the possibility of comparing or synthesising the findings.

Relatedly, because no standardised critical-appraisal tool (e.g., JBI, CASP, MMAT, ROBIS) was applied, study quality was tracked only through the descriptive methodological indicators noted in Section 2, and this less formal approach should be taken into account when weighing the strength of the conclusions drawn. Fourthly, the majority of the studies reviewed assess immediate gains in spatial thinking, conceptual understanding, or motivation, rather than long-term competency development or post-graduation professional outcomes; the lack of longitudinal evidence requires caution in drawing conclusions about the sustained impact of specific pedagogical interventions. Fifth, although the full review corpus included authors from twenty-nine countries, the geographical concentration of the studies included in the in-depth synthesis was concentrated in certain high-income regions. Therefore, the conclusions drawn should not be directly applied to resource-limited or developing education systems without contextual adaptation.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

AM: Writing – review & editing, Formal analysis, Methodology, Writing – original draft. SK: Formal analysis, Writing – original draft, Methodology, Writing – review & editing. DS: Formal analysis, Writing – review & editing, Investigation. NU: Writing – original draft, Methodology, Conceptualization, Formal analysis, Writing – review & editing. AZ: Writing – original draft, Formal analysis. AO: Writing – original draft, Formal analysis. YT: Writing – original draft, Writing – review & editing. SI: Writing – review & editing.

References

- Abramov, V. M., Tatarnikova, T. M., Sikarev, I. A., Shilin, M. B., and Chusov, A. N. (2021). Educational digital tools for university level under climate change and COVID-19. *J. Phys.: Conf. Ser.* 2001, 012037. doi: 10.1088/1742-6596/2001/1/012037
- AlGerafi, M. A., Zhou, Y., Oubibi, M., and Wijaya, T. T. (2023). Unlocking the potential: a comprehensive evaluation of augmented reality and virtual reality in education. *Electronics (Basel)* 12, 3953. doi: 10.3390/electronics12183953
- Barna, I., Hrytsak, L., and Henseruk, H. (2020). “The use of information and communication technologies in training ecology students,” in *E3S Web of Conferences, the International Conference on Sustainable Futures: Environmental, Technological, Social and Economic* (EDP Sciences), 166, 10027–10027. doi: 10.1051/e3sconf/202016610027
- Bendl, T., Krajňáková, L., Marada, M., and Řezníčková, D. (2025). Geographical thinking in geography education: a systematic review. *Int. Res. Geogr. Environ. Educ.* 34, 326–352. doi: 10.1080/10382046.2024.2354097
- Bikar, S. S., Rathakrishnan, B., Rabe, Z., Mahat, H., Sharif, S., and Talin, R. (2022). The impact of geography information system integrated teaching on underachieving students' intrinsic motivation. *Int. Res. Geogr. Environ. Educ.* 31, 304–319. doi: 10.1080/10382046.2021.2001983
- Bilbao-Aiastui, E., and Miranda-Urquijo, I. (2022). Development of natural science through the gamification and ICT in primary education. *Educat. Revista Electrónica de Tecnología Educativa* 81, 72–87. doi: 10.21556/edutec.2022.81.2577
- Boer, N., Scheid, N. M. J., and Schneider, C. R. (2024). Brazilian biomes and environmental education: potentials for the scientific and ecological formation of high school students. *Janus* 15, 6–23. doi: 10.26619/1647-7251.DT0224.1
- Bondarenko, O. V. (2025). Teaching geography with GIS: a systematic review, 2010–2024. *Sci. Educ. Q.* 2, 24–40. doi: 10.55056/seq.903
- Bradshaw, A. (2024). Digital encounters with microbial ecologies in a polluted urban river. *Cult. Geogr.* 31, 519–527. doi: 10.1177/14744740231215508
- Brečka, P., Valentová, M., and Tureková, I. (2022). Digital technologies in environmental education. *TEM J.* 11, 726–730. doi: 10.18421/TEM112-28
- Chen, Y., Chen, Y., Hu, X., and Feng, J. (2025). Characterizing pattern of topography and geomorphology in the Hengduan mountains, southwest China. *J. Environ. Earth Sci.* 7, 414–422. doi: 10.30564/jees.v7i1.7300
- Dantas da Silva Júnior, J. R., Pedruzzi, R., De Souza, F. M., Ferraz, P. S., Silva, D. G., Vieira, C. S., et al. (2021). Feasibility analysis on the construction of a web solution for hydrometeorological forecasting considering water body management and indicators for the SARS-COV-2 pandemic. *AI Perspect.* 3, 4. doi: 10.1186/s42467-021-00011-0
- Davies, O. H., Turnbull, J., and Searle, A. (2024). Digital ecologies in practice. *Cult. Geogr.* 31, 509–517. doi: 10.1177/14744740241269172
- Delgado-Guerrero, Y. M., López-Ramírez, P. A., Viviescas-Beltrán, L. S., and Ríos-Reyes, C. A. (2025). Geoeeducation for sustainable rural development: enhancing

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- environmental literacy through geoscience learning in Guaca, Santander (Colombia). *Sustain. Fut.* 10, 101520. doi: 10.1016/j.sfr.2025.101520
- Dos Santos, L. L., França, M. L. C., Da Costa, D. G., and Demetrio, G. R. (2025). Exploring the potential of smartphone applications as educational tools in the ecology teaching-learning process. *Discov. Educ.* 4, 193. doi: 10.1007/s44217-025-00615-2
- Georgousis, E., Savelidi, M., Savelides, S., Holokolos, M. V., and Drinia, H. (2021). Teaching geoheritage values: implementation and thematic analysis evaluation of a synchronous online educational approach. *Heritage* 4, 3523–3542. doi: 10.3390/heritage4040195
- Ghazali, M., Makrakakis, V., Kostoulas-Makrakakis, N., Yakob, N., Rashid, R. A. A., Othman, W., et al. (2024). Predicting teacher's information and communication technology-enabled education for sustainability self-efficacy. *Sustainability* 16, 5323. doi: 10.3390/su16135323
- Guimarães, I. V. (2018). Ensinar e aprender geografia na base nacional comum curricular (BNCC). *Ensino em Re-vista*, 25, 1036–1055. doi: 10.14393/ER-v25n3e2018-11
- Guo, F., Meadows, M. E., Duan, Y., and Gao, C. (2020). Geography pre-service Teachers' perspectives on multimedia technology and environmental education. *Sustainability* 12, 6903. doi: 10.3390/su12176903
- Hadi, B. S., Mukminan Muhsinatun Siasah, M., and Sariyono, K. E. (2021). "The effect of google earth-assisted remote sensing learning on Students' spatial thinking ability in solving disaster mitigation problems," in *IOP Conference Series: Earth and Environmental Science* (IOP Publishing), 012013.
- Husamah, H., Rahardjanto, A., Permana, T. I., and Shukri, A. A. M. (2025). Integration of digital technologies in environmental education: a systematic review of trends, impacts, and future directions. *Jurnal Varidika* 37, 30–47. doi: 10.23917/varidika.v37i1.9908
- Istiana, R., Rahmayanti, H., and Sumargo, B. (2021). Marine environmental education learning system recommendation model based on student needs analysis in Indonesian coastal areas. *Cypriot J. Educ. Sci.* 16, 2236–2247. doi: 10.18844/cjes.v16i5.6305
- Jong, M. S. Y. (2020). Promoting elementary pupils' learning motivation in environmental education with mobile inquiry-oriented ambience-aware fieldwork. *Int. J. Environ. Res. Public Health* 17, 2504. doi: 10.3390/ijerph17072504
- Jukes, S., and Lynch, J. (2024). Digital technology and environmental pedagogies in tertiary outdoor education: linking digital spaces to more-than-human places. *J. Advent. Educ. Outd. Learn.* 24, 108–122. doi: 10.1080/14729679.2023.2230502
- Kirkham, G. (2024). Snakes and smartphones: exploring transdisciplinary design collaborations for the governance of snakebite. *Cult. Geogr.* 31, 591–596. doi: 10.1177/14744740231203715
- Kondyli, C., Psychogiou, M., and Drinia, H. (2024). The museums of geology and paleontology as geoeeducational learning environments for raising climate change awareness. *Sustainability* 16, 4481. doi: 10.3390/su16114481
- Könnel, E. J., Geuer, L., Schlindwein, A., Perret, S., and Ulber, R. (2025). The effects of an outdoor learning program, 'GewässerCampus', in the context of environmental education. *Educ. Sci.* 15, 550. doi: 10.3390/educsci15050550
- Labianca, M. (2021). Can GIS foster conscious and critical learning in geography? An application from students to a real case included in the national strategy for inner areas: Monti Dauni, Apulia (Italy). *Sustainability* 13 (16), 9246. doi: 10.3390/su13169246
- Landis, J. R., and Koch, G. G. (1977). The measurement of observer agreement for categorical data. *Biometrics* 33, 159–174. doi: 10.2307/2529310
- Lebrasseur, R. (2023). Virtual site visits: student perception and preferences towards technology enabled experiential learning. *Int. J. Emerg. Technol. Learn.* 18, 115–140. doi: 10.3991/ijet.v18i02.32013
- Li, J., Xia, H., Qin, Y., Fu, P., Guo, X., Li, R., et al. (2022). Web GIS for sustainable education: towards natural disaster education for high school students. *Sustainability* 14, 2694. doi: 10.3390/su14052694
- Lo, J. H., Lai, Y. F., and Hsu, T. L. (2021). The study of AR-based learning for natural science inquiry activities in Taiwan's elementary school from the perspective of sustainable development. *Sustainability* 13, 6283. doi: 10.3390/su13116283
- Lu, J., Dawod, A. Y., and Ying, F. (2023). From traditional to digital: the impact of drones and virtual reality technologies on educational models in the post-epidemic era. *Sustain. Eng. Innov.* 5, 261–280. doi: 10.37868/sei.v5i2.id233
- Lu, T. C., Chen, Y. C., and Chang, C. H. (2025). Serious game design integrating design-play-experience framework: digital interactive experience exploring ecology of palaeoloxodon. *Eng. Proc.* 98, 21. doi: 10.3390/engproc2025098021
- Lynch, J., and Thomas, H. (2024). Digital technology in outdoor and environmental education: affects, assemblages and curriculum-making. *Aust. J. Environ. Educ.* 40, 288–304. doi: 10.1017/ae.2024.32
- Masruroh, H., Sahrina, A., Al Khalidy, D., and Trihatmoko, E. (2024). Generating Mobile virtual tour using UAV and 360 degree panorama for geography-environmental learning in higher education. *Int. J. Interact. Mob. Technol.* 18, 118–133. doi: 10.3991/ijim.v18i02.45961
- Mašterová, V. (2023). Learning and teaching through inquiry with geospatial technologies: a systematic review. *Eur. J. Geogr.* 14, 42–54. doi: 10.48088/ejg.v.mas.14.3.042.054
- Mendoza, K. R., Glaser, N., Krüger, J. M., Yang, M., and Moeller, K. (2025). A systematic literature review on the impact of XR on pro-environmental knowledge, attitudes, and behaviors. *J. Environ. Educ.* 56, 85–125. doi: 10.1080/00958964.2025.2471299
- Mkhize, T. F. (2023). Teachers' perceptions of paper-based GIS implementation in the rural learning ecology. *J. Curric. Stud. Res.* 5, 118–135. doi: 10.46303/jcsr.2023.20
- Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., et al. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *Br. Med. J.* 372, n71. doi: 10.1136/bmj.n71
- Rachad, S., and Oughdir, L. (2023). Exploring the benefits of e-learning for life and earth sciences education in Moroccan high schools. *J. Educ. e-Learn. Res.* 10, 474–480. doi: 10.20448/jeelr.v10i3.4887
- Radianti, J., Majchrzak, T. A., Fromm, J., and Wohlgenannt, I. (2020). A systematic review of immersive virtual reality applications for higher education: design elements, lessons learned, and research agenda. *Comput. Educ.* 147, 103778. doi: 10.1016/j.compedu.2019.103778
- Ricoy, M. C., and Sánchez-Martínez, C. (2022). Raising ecological awareness and digital literacy in primary school children through gamification. *Int. J. Environ. Res. Public Health* 19, 1149. doi: 10.3390/ijerph19031149
- Sebastián-López, M., and De Miguel González, R. (2020). Mobile learning for sustainable development and environmental teacher education. *Sustainability* 12, 9757. doi: 10.3390/su12229757
- Sedlák, M., Šašinka, Č., Stachoň, Z., Chmelík, J., and Doležal, M. (2022). Collaborative and individual learning of geography in immersive virtual reality: an effectiveness study. *PLoS One* 17, e0276267. doi: 10.1371/journal.pone.0276267
- Shakhislam, L., Yerlan, I., Duman, A., Ussenov, N., Zhu, K., and Dávid, L. D. (2025). Opportunities and challenges of using geospatial technologies in teaching school geography in Kazakhstan. *Int. Res. Geogr. Environ. Educ.* 34, 428–446. doi: 10.1080/10382046.2024.2380173
- Shefer, O., Kraineva, S., and Lebedeva, T. (2021). "New educational technologies in the educational and professional motivation of undergraduate students in the field of ecology," in *In E3S Web of Conferences* (EDP Sciences), 258 10004. doi: 10.1051/e3sconf/202125810004
- Shen, Y., Wang, Z., Li, M., Yuan, J., and Gu, Y. (2022). An empirical study of geography learning on students' emotions and motivation in immersive virtual reality. *Front. Educ.* 7, 831619. doi: 10.3389/feduc.2022.831619
- Štěchová, M., Černý, M., Šašinka, Č., Stachoň, Z., Šašinková, A., Holubec, F., et al. (2025). Collaborative immersive virtual environments in geography education on climate zones: a UX case study. *ISPRS. Int. J. GeoInf.* 14, 455. doi: 10.3390/ijgi14120455
- Sulzer, W., and Gspurning, J. (2025). Fieldwork and geodata acquisition—experiences with students in the high tatra. *Ekológia (Bratislava)* 44, 52–59. doi: 10.2478/eko-2025-0007
- Syamsudin, F. I., Saputro, S., Sarwanto Karyanto, P., and Kamari, A. (2025). Enhancing students' environmental awareness in rural and urban schools through problem and design process based learning model with steam. *Discov. Educ.* 4, 555. doi: 10.1007/s44217-025-01006-3
- Štěpánek, V., Hyšplerová, L., Kříž, J., Studnička, F., Wacławek, M., and Lyčka, A. (2024). Convergence of environmental education in technical natural sciences with cross-border CZ-PL practice. *Chemistry-Didactics-Ecology-Metrology* 29, 53–63. doi: 10.2478/cdem-2024-0004
- Urbańska, M., Charzyński, P., Gadsby, H., Novák, T. J., Şahin, S., and Yilmaz, M. D. (2022). Environmental threats and geographical education: students' sustainability awareness-evaluation. *Educ. Sci.* 12, 1. doi: 10.3390/educsci12010001
- Vandelli, V., Migoñ, P., Palmgren, Y., Spyrou, E., Saitis, G., Andrikopoulou, M. E., et al. (2024). Towards enhanced understanding and experience of landforms, geohazards, and geoheritage through virtual reality technologies in education: lessons from the GeoVT project. *Geosciences (Basel)* 14, 127. doi: 10.3390/geosciences14050127
- Wolff-Seidel, S., and Budke, A. (2022). Self-assessment of students of geography education and primary social and science teaching towards the use of digital (geo-) media for written and oral argumentation. *Eur. J. Invest. Health Psychol. Educ.* 12, 516–533. doi: 10.3390/ejihpe12060038
- Yushchenko, Y., Pasichnyk, M., Darchuk, K., Kostashchuk, I., and Zakrevskiy, O. (2022). Contemporary geoinformation technologies in postmodern education of geographers, hydrometeorologists, land surveyors. *Postmod. Open.* 13, 409–429. doi: 10.18662/po/13.2/462