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Developing interdisciplinary and meta-subject competencies in school geography: a systematic review of digital and mobile learning approaches

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The integration of digital and mobile learning approaches into school geography has become an important direction of pedagogical innovation in recent years, however, how these approaches systematically develop interdisciplinary and meta-subject competencies remains insufficiently theorized and empirically developed. Although individual studies have demonstrated the pedagogical potential of geospatial technologies, mobile augmented reality, immersive virtual environments, and artificial intelligence-based platforms, no previous review has conducted a comprehensive, systematic analysis of this body of evidence, linking it to the cross-curricular and meta-subject competency frameworks that are central to the reform agenda for national and international curricula. The proposed study fills this gap through a systematic review conducted according to PRISMA 2020 requirements: Ninety-one peer-reviewed studies published between 2020 and 2025 were included, selected from the Scopus database, and the level of agreement among the experts was confirmed with a $\kappa = 0.79$. The results of the analysis showed that GIS-based research, mobile augmented reality, and AI-supported learning tools make a measurable contribution to competencies such as spatial thinking, metacognitive regulation, systemic reasoning, and critical argumentation. These competencies are central both in international geography curricula and in post-Soviet interdisciplinary concepts. However, a persistent “policy–competency gap” was identified: curricular ambitions for high-level interdisciplinary teaching are often undermined by structural constraints, an insufficient pedagogical scaffolding, and the lack of validated assessment tools. Theoretical frameworks for digital competence development, such as Falloon's Teacher Digital Competency model and Chiu and colleagues' needs-supporting institutional model, are not sufficiently applied in the context of geography. Based on this synthesis, a conceptual

model is proposed that systematizes the conditions for the targeted integration of digital and mobile learning approaches in school geography with the aim of developing interdisciplinary and transdisciplinary competencies, along with priority directions for future empirical research and curriculum design.

KEYWORDS

digital and mobile learning, interdisciplinary and meta-subject competencies, PRISMA, school geography, systematic review

1 Introduction

The ability to think beyond disciplinary boundaries has become one of the defining imperatives of 21st-century education. Global challenges such as climate change, sustainable management of natural resources, and rapid technological transformation are beyond the explanatory capabilities of any single academic discipline, the development of interdisciplinary and meta-subject competencies has been formally recognized as a strategic priority within national and supranational curricula (Anderson-Levitt and Gardinier, 2021; Drake and Reid, 2020). Geography is uniquely positioned to fulfill this mandate, due to its distinctive epistemological place at the intersection of the natural sciences, social sciences, and humanities. Its potential to integrate spatial reasoning, systems thinking, and civic literacy leads Meadows (2020) to define it as one of the leading disciplines in sustainability education, with its potential as a tool for developing transferable competencies increasingly prominent on national and international reform agendas. In the terminology of Russian-language and post-Soviet pedagogical theory—a tradition particularly relevant for the contexts of Kazakhstan and Central Asia—these abilities are operationalized and described through the concept of meta-subject competencies, i.e., as cognitive, communicative, and regulatory skills that are developed beyond the confines of individual subjects and are applied across the entire curriculum (Yesnazar et al., 2025). At the global level, this intersection of disciplinary ambition and transferable learning outcomes has placed geography at the center of debates about how schools can effectively prepare students for the complex epistemic and civic demands of contemporary society.

Over the last two decades, pedagogical philosophy in geography education has undergone a significant shift, moving away from teacher-centered, transmissive models based on the didactic delivery of factual knowledge about physical and social landscapes to approaches that engage learners with authentic geographic data, real-life issues and collaborative knowledge-building processes—a shift toward active, inquiry-based, and project-based approaches. This change is not merely a matter of choosing a teaching style; it is about cultivating the competencies most valued in the 21st century—critical thinking, creativity, communication, and collaborative problem-solving skills, the abilities framed within the widely recognized 4Cs (Ye and Xu, 2023)—a recognition that these competencies are developed more effectively through active, context-based engagement rather than passive reception. Within this pedagogical transformation, digital and mobile learning (DML) technologies have become increasingly important. Falloon (2020)

describes this trend through the Teacher Digital Competency (TDC) framework, which holds that digital integration in education is not limited to the use of technical tools but rather requires a multifaceted competence encompassing critical thinking, digital citizenship, ethical responsibility, and interdisciplinary synthesis. Drake and Reid (2020) show that integrated curricula-spanning interdisciplinarity to transdisciplinarity—naturally support the development of transferable competencies when organized around real-world problems and supported by purposefully designed digital tools, which enable the learning environment itself to be reconfigured, enhancing spatial, analytical, and collaborative modes of action within the traditional classroom. From this perspective, the implications for geography education are significant: digital and mobile technologies do not simply supplement traditional teaching but restructure the learning environment itself, enabling modes of engagement previously inaccessible within the traditional classroom.

Despite the growing volume of empirical and theoretical research in this area, the field remains significantly fragmented along disciplinary traditions, methodological paradigms, and linguistic scientific communities. To date, no single systematic review has been conducted that comprehensively synthesizes the intersection of digital and mobile pedagogies with the development of interdisciplinary and transdisciplinary competencies in the context of school geography at a global level. Research on digital tools in geography education appears in geographically and institutionally scattered publications: International Research in Geographical and Environmental Education, which specializes in geography, from journals such as *Journal of Geography* to interdisciplinary Scopus Q1 publications like *Computers & Education* and *Educational Technology Research and Development*. However, these works have not been systematically compared and analyzed as a unified body of evidence. Furthermore, research on Russian-language and post-Soviet meta-subject competencies, which are of great theoretical significance in the educational contexts of Kazakhstan and Central Asia, have been systematically underrepresented in English-language reviews (Yesnazar et al., 2025). The absence of such systematization has led to conflicting conclusions within the field, a weak methodological comparability, and the persistent gap between the normative ambitions of curricula and their empirical implementation; This gap has been documented in various national contexts by Virranmäki et al. (2021), Golightly and Sprenger (2024), and Solem (2023). The present systematic review aims to address this gap by mapping empirical and theoretical work in the international literature, evaluate, and synthesize empirical and

theoretical works in the international literature to establish a conceptual foundation that will guide future research and evidence-based curriculum practice.

It is essential to situate this claim in relation to the closest existing reviews rather than asserting it in isolation. Table 1 (below) positions the present review against systematic and bibliometric reviews already identified within our own corpus. Reviews with an explicit geography focus remain technology-specific—Schmidt and Stumpe (2025) synthesize mobile augmented reality alone, and Czimre et al. (2024) synthesize virtual reality alone—rather than spanning the full spectrum of digital and mobile learning approaches. Conversely, reviews that address transversal or meta-subject competencies at a broader scale, such as Deroncele-Acosta et al. (2025) on generative artificial intelligence and García-Álvarez et al. (2022) on employability competencies, are not discipline-specific to geography and do not engage with the post-Soviet meta-subject tradition. Hallinger and Nguyen (2020) and Horn et al. (2022) offer bibliometric or systematic mappings of sustainability-oriented education more broadly, again without a geography-specific or competency-integration focus. None of these prior reviews jointly addresses (a) the full range of digital and mobile

learning approaches, (b) interdisciplinary and meta-subject competency development, and (c) school geography as the disciplinary context—the specific intersection targeted by the present review.

During the review phase (2020–2025) the technological transformation in geography education was characterized by the rapid proliferation and diversification of digital and mobile tools that simultaneously possess discipline-specific geospatial functionality and offer pedagogical interdisciplinary possibilities. Geographic Information Systems (GIS)—in its various forms such as ArcGIS Online, ESRI StoryMaps, Google Earth, and participatory GIS platforms—has established itself in the current literature as the most consistently represented technological cluster. Kolvoord and Peterson (2024), drawing on neuroimaging data, showed that long-term engagement with GIS-based inquiry in a school setting not only improves spatial thinking but also measurably strengthens neural activation patterns associated with higher-order abstract reasoning; this result goes far beyond the boundaries of the geography subject. Mobile augmented reality (AR) represents the next facet of this transformation: synthesizing eighteen empirical studies, Schmidt and Stumpe (2025) highlighted the ability of mobile augmented reality (AR) to visualize otherwise invisible or inaccessible geographic phenomena—such as atmospheric pollution gradients, landform formation, and ecosystems—through three-dimensional visualization, which in turn directly develops the spatial meta-competencies envisioned by current geography curricula. Immersive technologies—virtual reality (VR) and collaborative immersive virtual environments (CIVEs)—add another layer of pedagogical possibilities. Czimre et al., (2024), based on a systematic review of forty-seven VR studies, confirmed that immersive environments consistently enhance spatial understanding, collaborative problem-solving, and learner motivation in the context of geography, while Střechová et al. (2025) demonstrated through qualitative data that CIVEs contribute to developing spatial thinking, emotional engagement, and practical cognition among middle school students. In the final phase, AI-enhanced tools have also entered the geography education space: Deroncele-Acosta et al., (2025) identified fifteen transversal competencies developed through working with generative AI tools—including AI literacy, critical thinking, and autonomous learning skills—while Donmez Bayrakci (2025) presented one of the first quasi-experimental studies to directly examine the impact of AI integration at the school level on geographic competencies. Overall, these technological changes—GIS, mobile applications, and AI/AR tools—are described not merely as mechanisms for delivering geographic content, but as catalysts that enhance interdisciplinary connections and deepen spatial, analytical, and metacognitive thinking.

However, it is increasingly evident in the scientific literature that the potential of digital and mobile learning in geography education is constrained by a number of persistent cognitive, institutional, and epistemological barriers. Bagoly-Simó (2023) expresses a fundamental concern that if the content rigidity of physical geography is overshadowed by an competence-based discourse and a value-driven sustainable development agenda, the epistemic foundation for geographically deep transdisciplinary thinking could weaken. This assertion is

TABLE 1 Positioning of the present review relative to the closest prior reviews identified in the corpus.

Review	Scope	Competency framework	Gap relative to present review
Schmidt and Stumpe (2025)	Mobile augmented reality in geography education	Not explicit; spatial competencies implied	Single technology (AR) only
Czimre et al. (2024)	Virtual reality in geography education (47 studies)	Spatial understanding, collaborative problem-solving	Single technology (VR) only
Deroncele-Acosta et al. (2025)	Generative AI and transversal competencies, higher education	Transversal competencies (broad, non-discipline-specific)	Not geography-specific; higher education, not school level
García-Álvarez et al. (2022)	Employability, employer perspective, higher education	Transversal competencies for employability	Not geography-specific; no digital-learning focus
Hallinger and Nguyen (2020)	Bibliometric mapping of sustainability education	Not competency-specific	Bibliometric only, no thematic synthesis
Present review	Full range of digital and mobile learning approaches (GIS, AR, VR, AI, games)	Interdisciplinary/meta-subject competencies, integrating post-Soviet and international frameworks	School geography, global scope

supported to some extent by Virranmäki et al. (2021): Although 39 percent of the objectives in Finland's national geography curriculum are formally classified as higher-order thinking skills, in traditional teaching, students have not been able to systematically achieve evaluative and creative competencies, and metacognitive knowledge was not reflected in either the curricular documents or the actual learning outcomes. This gap between curricular ambitions and the actual classroom experience—a phenomenon in this review termed the “policy–competency gap”—has been documented in various national contexts. For example, Golightly and Sprenger (2024), in a large-scale study of 130 geography teachers in South Africa, showed that structural factors such as class size, exam pressure, and language barriers limit pedagogical innovations, regardless of teachers' professional preparation. Solem (2023), through an analysis of national NAEP data, confirmed that unequal access to technology-based geographic learning opportunities significantly hinders the development of competencies in underserved student groups. In the field of digital game-based learning, Baßeng and Budke (2025) showed that commercial mobile games yield metacognitive results only when combined with structured discussion and collaborative reflection, meaning the game itself does not automatically produce a pedagogical impact. Using a structural equation model involving 370 middle school teachers, Chiu et al. (2024) showed that access to digital AI platforms, and the resulting personal-ethical and professional digital competencies, are fully mediated by the school's motivational culture and the satisfaction of teachers' basic psychological needs. This set of findings indicates that access to technology and curricular ambitions are necessary, but not sufficient, conditions for developing genuine interdisciplinary and transdisciplinary competencies; the decisive factor remains the school's institutional and motivational ecosystem.

To ensure maximum methodological transparency and international reproducibility, this study was conducted in strict accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines (Page et al., 2021). The PRISMA system is the internationally recognized gold standard for reporting systematic reviews and requires detailed documentation, as well as a clear description of the decision-making criteria at each stage of the process: identifying sources, screening, eligibility assessment, and final data extraction. The search was conducted in one peer-reviewed academic database: Scopus. The final corpus consisted of ninety-one studies published between 2020 and 2025, selected based on predefined inclusion and exclusion criteria; these criteria were operationalized before the search process began. The level of agreement among experts during the full-text validity assessment phase was measured using Cohen's kappa coefficient ($\kappa = 0.79$), indicating substantial agreement (Landis and Koch, 1977). The thematic synthesis was conducted using the three-stage procedure adapted from Thomas and Harden (2008), and all coding was carried out in the NVivo qualitative analysis software. A bibliometric analysis conducted using VOSviewer identified eight thematic clusters based on approximately 130 nodes, while a Sankey diagram revealed the diachronic evolution of thematic descriptors within the broader disciplinary literature across three cohorts (1973–2015; 2016–2020; 2021–2026).

Within this research-methodological context, the proposed systematic review is based on three interrelated research questions; each of which is aimed at analyzing an independent aspect of the relationship between digital and mobile learning approaches in school geography and the development of interdisciplinary and transdisciplinary competencies:

RQ1: What digital and mobile learning models exist in school geography that have been empirically proven effective in developing students' interdisciplinary and meta-subject competencies, and what are the key pedagogical and contextual conditions that determine their effectiveness?

RQ2: To what extent do the digital and mobile learning approaches described in the international scientific literature align with the interdisciplinary and meta-subject competency requirements defined in current national and international geography curricula, and what are the key pedagogical and contextual conditions that determine their effectiveness in this context? What forms of the “policy–competency gap” can be identified?

RQ3: What significant knowledge gaps, significant knowledge gaps, insufficiently researched competency areas, and strategic imperatives for curriculum renewal are identified, and what directions are most relevant for future research and evidence-based curriculum design?

By answering these research questions through a systematic review of the international scientific literature conducted in accordance with strict methodological requirements and with maximum transparency, the present work aims to achieve two main results: first, to systematize the existing body of knowledge based on a structured synthesis; secondly, to establish a conceptual framework that can serve as a guide for designing future scientific research programs and for developing evidence-based geography curricula at the school level.

2 Materials and methods

Developing interdisciplinary and meta-subject competencies in school geography is one of the most methodologically complex challenges facing contemporary educational research. Since geography holds a unique epistemological position that links the natural sciences, social sciences, and humanities, its curricular potential for fostering interdisciplinary thinking, systemic thinking, and civic literacy from the perspective of national and international educational reforms, which are increasingly taking a prominent place on the agenda (Hammond et al., 2025; Meadows, 2020). In this context, meta-subject competencies—which are formed beyond the boundaries of individual subjects—are increasingly becoming a central objective of competency-based education models in various national education systems (Anderson-Levitt and Gardinier, 2021; Hammond et al., 2025). Meta-subject competencies—interpreted as transferable cognitive, communicative, and regulatory skills that are formed beyond the boundaries of individual subjects—represent a key theoretical construct underpinning this review (Drake and Reid, 2020). Furthermore, the widespread adoption of digital and mobile learning technologies offers new

opportunities to develop such competencies in geography lessons, allowing learners to work with geospatial data, model real-world environments, and participate in collaborative knowledge-building processes that are inherently interdisciplinary (Gubevu and Mncube, 2024; Jekel et al., 2025; Schmidt and Stumpe, 2025).

Internationally, meta-subject competencies overlap closely with several widely used constructs: transversal competencies (the term favored in EU and OECD policy discourse), transferable skills (common in employability research), cross-curricular competencies (used in curriculum-integration literature), and the 21st-century skills/4Cs framework (Ye and Xu, 2023). What distinguishes the meta-subject construct, rooted in Russian-language activity theory, is its emphasis on the cognitive transfer mechanism between school subjects within a single curriculum, whereas the other frameworks more often foreground generic, cross-context outcomes such as employability or civic participation. We use “meta-subject competencies” throughout as the umbrella term for this review, given its centrality to the Kazakhstan and Central Asian curricular context, while treating it as conceptually continuous with these international constructs.

Despite the volume of relevant scholarly work, the field remains fragmented along disciplinary orientations, methodological traditions, and language communities. No review has previously been conducted that systematically integrates the global evidence base at the intersection of digital pedagogy and the development of interdisciplinary competencies in school geography. This study addresses this gap by systematically mapping, appraising, and synthesizing empirical and theoretical work from the international literature, resulting in a conceptual framework that can guide both future research and evidence-based curriculum practice. The complexity of this work is related to the need to integrate literature from the fields of geography education, digital pedagogy, competency-based curriculum theory, and educational psychology-requiring a methodological approach that demands transparency and reproducibility.

To ensure methodological transparency and international reproducibility, this systematic literature review was conducted in full accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines (Page et al., 2021). The PRISMA framework is the internationally recognized gold standard for reporting systematic reviews and requires transparent reporting of decision-making criteria at each stage of the review process-identification, screening, eligibility assessment, and inclusion-as well as the transparent reporting of decision-making criteria at each stage. The PRISMA 2020 flow diagram (Figure 1) provides a visual representation of the study selection process and is presented in full in this section to facilitate auditing and reproducibility. Adherence to the PRISMA protocol was chosen as a concrete stance on epistemological values such as transparency, rigor, and methodological reflexivity-not merely as a tool for meeting formal requirements, but as an embodiment of the standards of high-quality systematic reviews in social sciences and educational research.

A multi-level, iterative search strategy was used to identify the broadest possible range of relevant publications while maintaining thematic focus in line with the review’s objectives. The primary

search was conducted in one peer-reviewed academic database: Scopus. Search strategies were constructed using Boolean operators and field-specific controlled terminology, combining the following three conceptual clusters: (1) geography education or geographical education or school geography; (2) interdisciplinary competencies or meta-subject competencies or transversal skills or cross-curricular learning; and (3) digital learning or mobile learning or geospatial technologies or ICT in education or technology-enhanced learning. These clusters were combined using AND operators across the title, abstract, and keywords fields. The search was conducted exclusively in English.

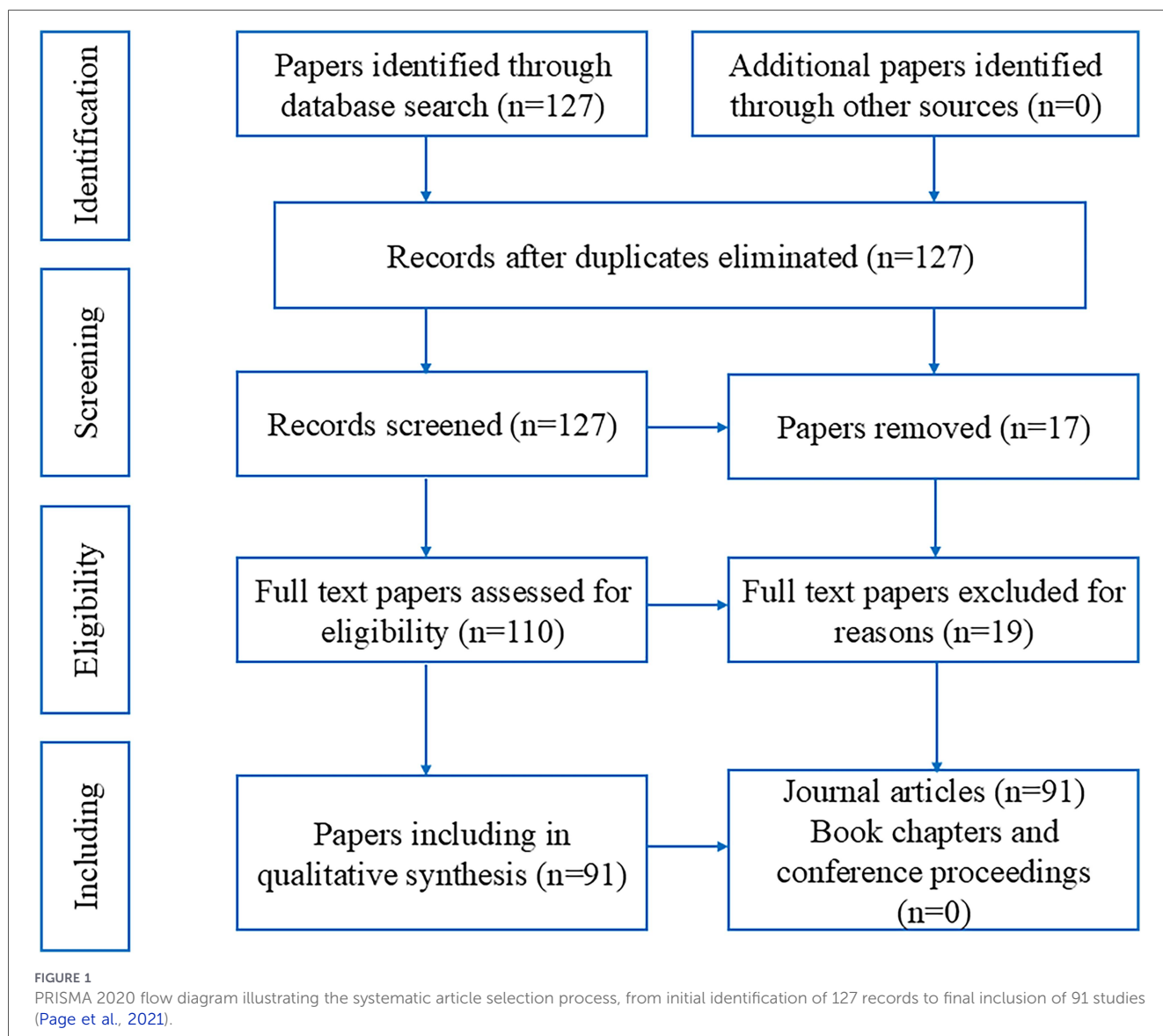
In Scopus, the primary database search was executed using the following Boolean query across the TITLE-ABS-KEY fields: (“interdisciplinary” OR “meta-subject” OR “cross-curricular” OR “transversal” OR “21st century skill*”) AND (“geography” OR “geography education” OR “geography teaching” OR “geography learning” OR “geographic* education”) AND (“digital” OR “mobile learning” OR “ICT” OR “e-learning” OR “GIS” OR “technology” OR “blended learning” OR “online learning”).

The initial unrestricted Scopus search yielded $n = 842$ records. To ensure temporal relevance and alignment with contemporary developments in digital pedagogy and competency-based education, the search was subsequently limited to publications from 2020 to 2025, reducing the corpus to $n = 420$ records. In order to maintain methodological consistency and ensure peer-reviewed scholarly quality, the results were further filtered to include only journal articles (DOCTYPE: “ar”), yielding $n = 215$ records. A final filter was applied to restrict results to open-access publications, resulting in a corpus of $n = 127$ records available for the screening stage. No additional records were identified through supplementary sources ($n = 0$).

No supplementary search methods (e.g., citation snowballing or manual reference screening) were applied; the review corpus was derived exclusively from the Scopus database search described above. The complete study selection process is illustrated in the PRISMA 2020 flow diagram (Figure 1).

The selection and exclusion criteria were developed *a priori* before the search process began, in order to minimize confirmation bias and ensure consistency of eligibility decisions. Studies were included in the review if they met all of the following inclusion criteria: (1) publication in a peer-reviewed journal, an edited academic collection, or an equivalent scholarly publication; (2) availability in English or Russian; (3) coverage of the period 2020–2025, with exceptions made for methodologically foundational works whose theoretical contributions remain relevant (e.g., Drake and Reid, 2020; Falloon, 2020); (4) direct or substantive alignment with at least one of the main focus areas of the review-digital or mobile learning technologies, the development of interdisciplinary or meta-subject competencies, and geography education or similar disciplinary contexts; and (5) presentation of original empirical data, a validated theoretical or conceptual foundation, use of a systematic or narrative review methodology, or analysis of the curriculum conducted on a rigorous methodological basis.

The exclusion criteria were operationalized as follows: studies were excluded if they (1) focused solely on discipline-specific competencies and lacked a transferable or interdisciplinary dimension; (2) were not peer-reviewed or lacked methodological



transparency; (3) considered digital technologies only at an infrastructural or policy level without linking them to the development of pedagogical outcomes and competencies; (4) were a duplication of previously identified records; or (5) the full text was not accessible through institutional repositories or open-access platforms. Conference abstracts, opinion editorials, and non-scholarly practice reports were excluded if they did not present a substantive empirical or theoretical contribution.

The inclusion and exclusion criteria above, and the research questions in Section 1, are formalized here using the PICOS framework (Table 2) to make the review's eligibility structure explicit and reproducible. A Comparator is reported only where the primary studies themselves specify one: the quantitative and quasi-experimental studies in the corpus typically compare DML-mediated instruction against traditional, non-DML-mediated instruction, whereas the qualitative, conceptual, and curriculum-analysis studies—which form a substantial part of the corpus—report no explicit comparator, consistent with their descriptive or theory-building aims.

After removing 0 duplicate entries from the initial 127 records, all records proceeded to the title and abstract screening stage. The screening was conducted independently by two trained researchers, each applying the pre-determined inclusion and exclusion criteria independently of the other's assessment. Such a two-stage independent screening protocol is widely recognized as a necessary condition for preventing selection bias in systematic review methodology (Egger et al., 2022). During the title and abstract screening stage, 17 records were excluded due to obvious inconsistencies with the inclusion criteria, resulting in $n = 110$ studies proceeding to the full-text assessment stage.

The level of agreement among the reviewers during the full-text eligibility assessment stage was evaluated using Cohen's kappa (κ) coefficient, which statistically measures inter-rater agreement beyond that expected by chance. The resulting κ value was 0.79, indicating substantial agreement (Landis and Koch, 1977), thereby confirming the reliability of the assessment process. In cases of disagreement—which occurred for 19 studies—a decision was made through structured discussion between the

TABLE 2 PICOS framework for the review's eligibility criteria.

Element	Definition applied in this review
Population	School-age learners (primary through upper-secondary) and their geography teachers, in national and international school curricular contexts.
Intervention	Digital and mobile learning (DML) technologies and approaches: GIS, mobile augmented reality, virtual/collaborative immersive virtual environments, AI-based tools, digital games, and blended-learning architectures.
Comparator	Traditional, non-DML-mediated instruction, where reported by the primary study; not applicable to the qualitative, conceptual, and curriculum-analysis studies in the corpus, which report no explicit comparator.
Outcome	Interdisciplinary and meta-subject competencies-spatial thinking, systemic reasoning, metacognitive regulation, critical argumentation, and civic competence-and the pedagogical and contextual conditions that determine their development.
Study design	Quantitative (quasi-experimental, cross-sectional, SEM/CFA/HLM), qualitative (case study, IPA, ethnographic), mixed-methods, systematic/narrative reviews, and theoretical/conceptual papers.

two main reviewers, and where consensus could not be reached, a third independent expert was involved as an arbitrator. At the full-text stage, 19 articles were excluded for the following reasons: insufficient empirical justification ($n=5$), the research topic not aligning with the main focus of the review ($n=6$), full text unavailable ($n=3$), and other methodological grounds ($n=5$). As shown in Figure 1, the final corpus included in the qualitative synthesis consisted of $n=91$ studies.

Data extraction was conducted using a *de novo* data collection form developed specifically for this review, which was pilot-tested on a random sample of ten included studies and iteratively refined before full-scale application. The choice of a *de novo* approach over a pre-existing standardized tool was justified by the need for an adequately tailored analytical model at the intersection of digital learning, geography education, and the development of interdisciplinary competencies. For each included study, the data extraction form captured the following fields: author(s) and year of publication; country and institutional context; study design and methodology; level of education and sample characteristics; digital or technological tools studied; types of competencies addressed; main findings and theoretical contributions; and methodological limitations reported by the authors.

The thematic synthesis was conducted by adapting the three-stage procedure proposed by Thomas and Harden (2008): (1) line-by-line coding of the results of each study; (2) forming descriptive themes by grouping codes with similar conceptual content; and (3) generating analytical themes based on interpretation across different domains, resulting in the conceptual framework presented in the results section. The data were structured into five coding domains of analysis: (1) teaching methods and pedagogical approaches; (2) types of competencies considered; (3) level of education and institutional context; (4) digital and

mobile technologies used; and (5) theoretical and conceptual foundations applied. All coding was conducted in NVivo qualitative analysis software, which allowed for systematic re-examination of coded segments and the creation of cross-tabulated thematic matrices.

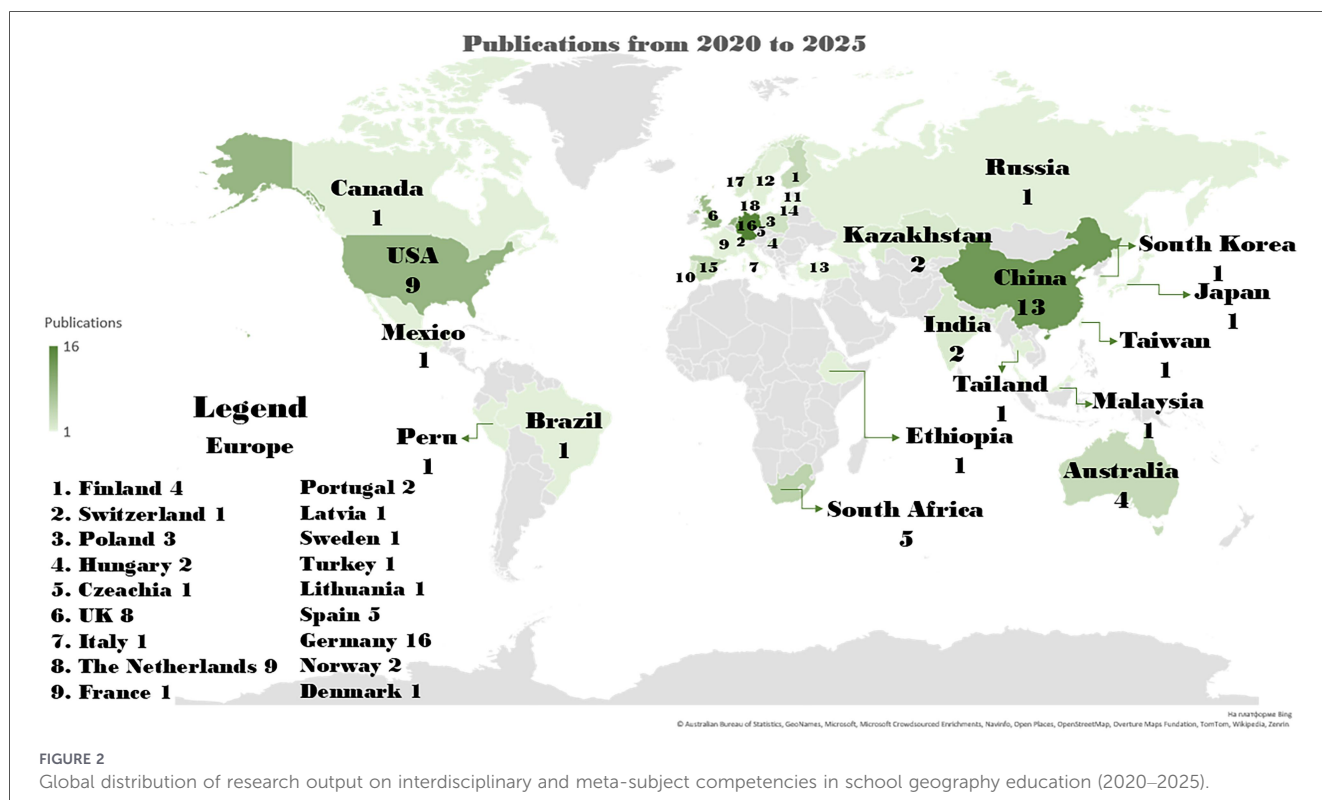
3 Results

3.1 Descriptive statistics and bibliometric review

The systematic search and selection process identified 91 studies published between 2020 and 2025 that met the full selection criteria. Overall, these studies constitute a rapidly growing and thematically diverse body of literature focused on developing interdisciplinary and transdisciplinary competencies in, school geography, and related educational fields. The temporal distribution of the included publications shows a clear increase in the number of scholarly publications starting from 2023, with the majority of research concentrated in the 2023–2025 period. This trend aligns with the growing global interest in competency-based education reforms, This is partly driven by the post-pandemic rebuilding of education systems, the widespread adoption of digital pedagogies, and the emergence of generative artificial intelligence, which is having a transformative impact on educational practice.

Geographically, this body of research shows a clear concentration in Europe and East Asia, with Germany standing out as the leading contributor with 16 studies (Figure 2).

Based at institutions such as the University of Cologne and the KN–Journal of Cartography and Geographic Information, as well as the European Journal of Investigation in Health, German-language geography education research, as featured in journals such as the KN–Journal of Cartography and Geographic Information and the European Journal of Investigation in Health, Psychology and Education, has made a particularly significant contribution to the empirical literature on digital geomedium, argumentation competence, and game-based learning (Baßeng and Budke, 2025; Gebele et al., 2022; Morawski and Budke, 2025; Steingröbl and Budke, 2024; Vasiljuk and Budke, 2021; Wolff-Seidel and Budke, 2022). China follows with 13 publications, reflecting the rapid development of research on STEM-integrated and technology-enhanced education in China's higher education and school systems (Rehman et al., 2025; Ye and Xu, 2023; Zhu et al., 2023). The United States contributed 9 studies, with a particular focus on large-scale quantitative analysis of geographic achievement and the integration of geospatial technologies (Kolvoord and Peterson, 2024; Mitchell, 2023; Solem, 2023; Solem and Vaughan, 2023). Additional contributions were identified from the Netherlands ($n=9$), South Africa ($n=5$), Finland ($n=4$), the United Kingdom ($n=8$), Kazakhstan ($n=2$), Spain ($n=5$), Australia ($n=4$), as well as a number of other countries in Asia, Africa, and Latin America, indicating the truly global, but unevenly distributed, nature of the research field (Figure 3). The relatively low representation of post-Soviet and Central Asian scholarly works in international databases-despite the theoretical importance of the concept of meta-subject competency in



Russian-language pedagogy-represents a significant gap that requires dedicated research in the future (Yesnazar et al., 2025).

The included studies were published in a wide range of journals covering geography education, general education, sustainable development, and interdisciplinary STEM research. Geography-focused publications-International Research in Geographical and Environmental Education, Journal of Geography, Journal of Geography in Higher Education, and ISPRS International Journal of Geo-Information-accounted for approximately 29% of the total studies, while the remainder were in interdisciplinary journals indexed in the Scopus Q1 (e.g., Computers & Education, Educational Technology Research and Development, Sustainability, Frontiers in Education) belonged to interdisciplinary journals included in the Scopus Q1 index. This distribution indicates that the phenomenon under study is inherently interdisciplinary and that the epistemological boundaries between broader fields such as geography education and learning science, indicates the gradual erosion of epistemological boundaries between broader fields such as digital pedagogy and competency research.

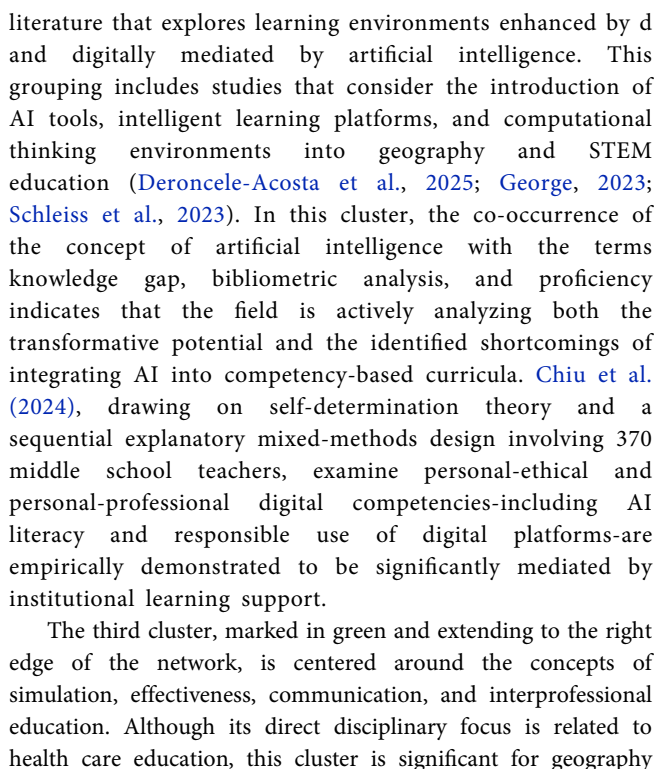
3.2 Keyword co-occurrence and topic cluster analysis

The bibliometric analysis of keyword co-occurrence patterns, conducted using VOSviewer and visualized in Figure 3, reveals a dense and highly interconnected semantic network organized into eight distinct thematic clusters. The size of each node

represents the term's frequency level, while the thickness of the lines connecting them indicates the strength of the co-occurrence relationships among the terms in the 91 research areas. The overall topological structure of the network-a large cluster of high-frequency nodes in the center, surrounded by peripheral, specialized groups-indicates that the literature is unified by a single conceptual core, and also indicates the presence of a content-based differentiation among the internal domains.

The dominant cluster, marked in red, is characterized by the terms framework, curriculum, integration, knowledge, and content, all of which appear with high frequency in the corpus. This cluster encompasses the main pedagogical and curricular dimension of the literature: It brings together research focused on how interdisciplinary and transdisciplinary competencies are conceptualized, structured, and embedded in educational systems. Among the theoretically significant contributions to this cluster is the Teacher Digital Competency (TDC) framework proposed by Falloon (2020), which is considered a multidimensional basis for integrating digital tools across disciplinary boundaries, as well as Drake and Reid (2020) considered the integrated curriculum within a continuum from multidisciplinary to transdisciplinarity. Laasch et al. (2023) further developed this cluster, constructing a 3 × 2 matrix of responsible governance competencies that operationalizes the knowledge, behavioral, and personal dimensions of interdisciplinary teaching.

The second major cluster, highlighted in yellow and centered around the concepts of artificial intelligence, decision-making, and technology, represents the emerging



The fourth cluster, labeled in blue and positioned in the upper right of the network, combines the terms “systematic review,” “Scopus,” “PRISMA,” and “Preferred Reporting Items.” This cluster illustrates the methodological infrastructure of the literature-especially the prevalence of PRISMA-based systematic reviews among the included studies-and is an important bibliometric indicator representing the field’s stance on evidence synthesis and methodological transparency. This cluster includes studies such as Schmidt and Stumpe (2025), Yemini et al. (2025), Rehman et al. (2025), and Deroncele-Acosta et al. (2025), all of which use systematic review methodology to synthesize evidence related to the implementation of digital tools and the development of competencies.

Additional peripheral clusters include terms related to sustainability and climate change (planetary health, sustainability, wellbeing, and teacher), indicating a body of research that considers geography education within the framework of Education for Sustainable Development (ESD). Meadows (2020), Bagoly-Simó (2023), Skarstein and Wolff (2020), as well as Mitchell (2023) contribute to this cluster, analyzes how geospatial technologies—including GIS, remote sensing, digital cartography, and interactive simulations—serve as a cognitive support for developing systems thinking and multi-level reasoning in the context of sustainable development issues. Another cluster, based on the terms educator, learner, capacity, and educational program, indicates a growing body of literature focused on teacher professional development as a prerequisite for the effective integration of digital and interdisciplinary approaches to geography education (Cheuk and Lam, 2025; Golightly and Sprenger, 2024; Rehman et al., 2025; Smit et al., 2024).

Overall, the VOSviewer network indicates that the literature on interdisciplinary and transdisciplinary competencies in geography education is not fragmented but rather structurally integrated, with a common conceptual core—curriculum integration, structures of knowledge, digital technology-centered artificial intelligence pedagogy, immersive simulation, sustainable development education, and teacher training, characterized by its content specialization in these areas. The co-occurrence of the concept of curriculum with artificial intelligence, the concept of simulation with communication, and the concept of framework with systematic review indicates that researchers are increasingly using multi-tool and multi-paradigm approaches in the design, implementation, and assessment of competency-based geography education (Figure 3).

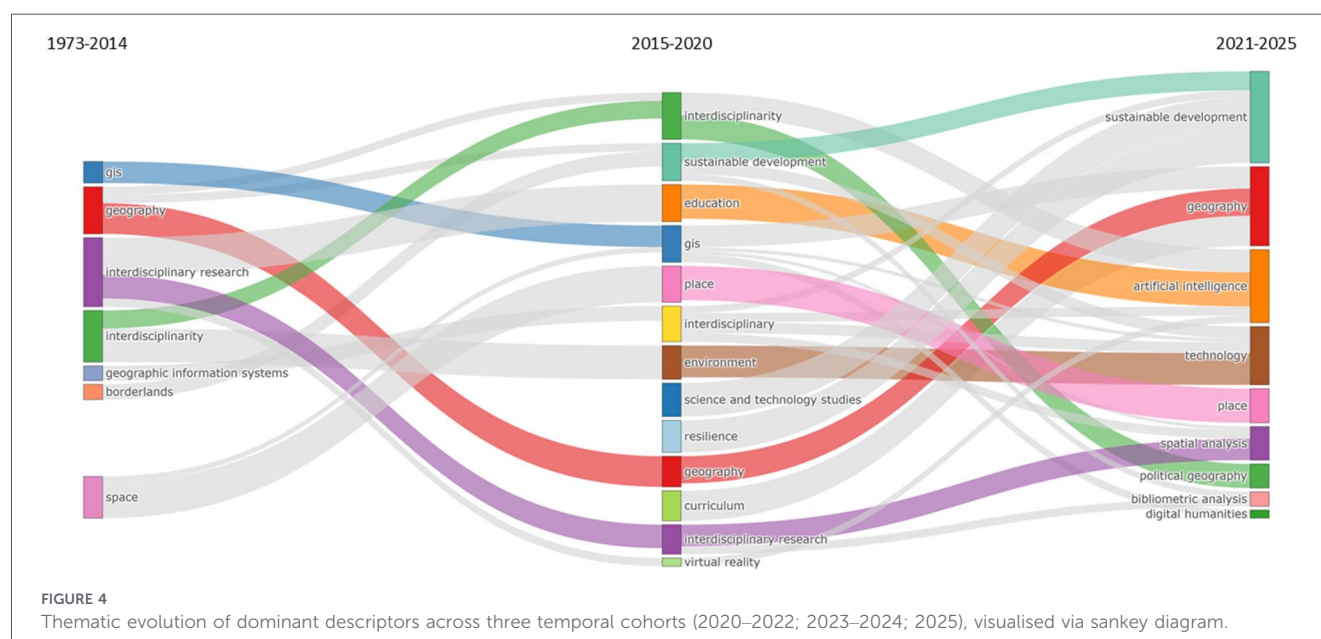
These clusters bear directly on RQ1 and RQ2. The red (curriculum/framework) and blue (systematic review/PRISMA) clusters jointly show that the field already possesses a mature methodological and conceptual infrastructure for evaluating digital and mobile learning models against curricular aims—evidence used in Section 4 to answer RQ1. The relative peripherality of civic- and

assessment-oriented terms, compared with the centrality of technology- and framework-oriented terms, foreshadows the “policy–competency gap” formalized in response to RQ2: the network structure itself indicates that curriculum-alignment and assessment-validation research is comparatively underdeveloped relative to technology-implementation research.

3.3 Thematic evolution of the research field (2020–2025)

The Sankey diagram presented in Figure 4 visualizes the temporal evolution of the dominant thematic descriptors across three cohorts spanning the broader disciplinary literature from which this review’s search terms were drawn: 1973–2015, 2016–2020, and 2021–2026. This diagram allows for a systematic analysis of how thematic emphases within interdisciplinary geography scholarship have shifted over five decades, from foundational, technology- and borderland-oriented framings toward sustainability-, education-, and artificial-intelligence-oriented framings.

The earliest cohort (1973–2015) is dominated by the descriptors gis, geography, interdisciplinary research, interdisciplinarity, geographic information systems, borderlands, and space, reflecting the field’s roots in geographic information science alongside early interdisciplinary and borderlands scholarship. In the second cohort (2016–2020), the thematic space broadens considerably to include interdisciplinarity, sustainable development, education, gis, place, interdisciplinary, environment, science and technology studies, resilience, geography, curriculum, interdisciplinary research, and virtual reality, marking a shift toward education-focused, sustainability-oriented, and technology-integrated framings. By the most recent cohort (2021–2025), the space consolidates around sustainable development, geography, artificial intelligence, technology, place, spatial analysis, political geography, bibliometric analysis, and digital humanities.



Several individual flows are informative. The descriptor interdisciplinarity traces a path from the first cohort through interdisciplinarity in the second cohort into sustainable development in the third, indicating that a generic interdisciplinarity discourse has become increasingly consolidated within a sustainability framing over time. Geography itself persists as a stable anchor across all three cohorts, indicating disciplinary continuity even as the surrounding thematic emphases shift. GIS follows a related trajectory, flowing from the first into the second cohort and then converging with geography in the third, suggesting that GIS has been progressively absorbed into the broader disciplinary identity rather than persisting as a separate descriptor. Education, prominent in the second cohort, flows predominantly into artificial intelligence in the third, signaling a recent pivot toward AI-integrated pedagogical research. Environment and science and technology studies, both present in the second cohort, converge on technology in the third. Interdisciplinary research, present in both the first and second cohorts, diverges by the third cohort into spatial analysis and political geography. Virtual reality, a comparatively small descriptor in the second cohort, feeds into bibliometric analysis and digital humanities, the two smallest descriptors in the final cohort, indicating that VR-specific scholarship remains an emerging rather than an established thread relative to the field's other technological priorities.

A coherent thematic thread linking the evolution of the research field is evident across all three phases: a gradual shift from conceptual and contextual justification to empirically validated, technologically-infused, and scalable models for developing interdisciplinary competencies. This evolutionary trajectory reflects broader trends in educational research and aligns with the bibliometric data discussed in Section 3.2.

This temporal evolution informs RQ1 and RQ3 directly. For RQ1, the diachronic trajectory—from foundational, GIS- and borderlands-oriented work (1973–2015), through education- and technology-integrated framings (2016–2020), to the consolidation of artificial intelligence and technology descriptors (2021–2026)—identifies GIS and AI-based tools as the digital and mobile learning models with the longest and most consolidated evidence trajectories, and therefore strong candidates for the effectiveness conditions sought in RQ1. For RQ3, the comparatively minor role of virtual reality in the 2016–2020 cohort, feeding forward only into the smallest descriptors of the final cohort (bibliometric analysis, digital humanities) rather than into mainstream technology or geography nodes, signals that VR-specific and digital-humanities-oriented interdisciplinary research remain nascent, underrepresented strands—a knowledge gap that directly informs the future-research priorities identified in response to RQ3.

3.4 Methodological landscape: research designs, analytical approaches, and technology integration

The 91 included studies are characterized by considerable methodological diversity, reflecting the breadth of the research field and the various epistemological traditions on which it draws (Table 3).

A comprehensive classification of methods identifies five main research designs: qualitative research (including case studies, content analysis, narrative research, and focus groups), quantitative research (surveys, experimental and quasi-experimental designs, as well as secondary data analysis), mixed methods, systematic and review literature analyses, as well as conceptual or theoretical studies. No single design is dominant; however, qualitative and mixed methods constitute the largest share, which is consistent with the interpretive, practice-oriented tradition in geography education research and the need for context-dependent, multifaceted data in competency assessment.

Qualitative methodologies are represented in approximately 28 studies. Qualitative content analysis, often conducted within a theory-oriented framework based on Mayring (2015) or Kuckartz (2014), is widely used in studies examining issues of argumentation, perspective taking, and curriculum design (Gebele et al., 2022; Morawski and Budke, 2025; Steingrübli and Budke, 2024; Vasiljuk and Budke, 2021). Ethnographic and communicative approaches are also used, as in the work of Hammond (2022). Interpretative phenomenological analysis (IPA) was used by Střechová et al. (2025) to investigate students' experiential reception of collaborative immersive VR environments. Kolmos et al. (2024) applied it in developing a typology of interdisciplinary projects, and Ponomariovienė et al. (2025) applied action research designs to study competency-based assessment through digital monitoring tools demonstrate the field's interest in reflective, practitioner-led research approaches.

Quantitative research designs are found in approximately 18 studies and span the range from large-scale survey analyses to experimental and quasi-experimental interventions. hierarchical linear modeling based on NAEP data (Solem, 2023; Solem and Vaughan, 2023), logistic regression on longitudinal datasets (Playford et al., 2023), and structural equation modeling (Chiu et al., 2024; Schijf et al., 2023) represent the most complex types of quantitative methods. Quasi-experimental “pre-test–post-test” designs with control groups were used by Yesnazar et al. (2025), who assessed the development of STEM-integrated interdisciplinary competencies in primary schools in Kazakhstan using Mann–Whitney U statistical analysis; a similar design examined the impact of a project-based learning course aimed at sustainable development (Braßler and Sprenger, 2021). The use of gamification-based digital tools—including the validated scales of the TMMS-24 for measuring emotional intelligence and learning strategies—was demonstrated in Redondo-Rodríguez et al. (2022), while Bendowska and Baum (2023) used the validated ATHCT survey to study attitudes toward interdisciplinary collaboration among 1,266 medical students.

Mixed methods, which combine quantitative and qualitative components within a single study, have been used in approximately 22 studies and are particularly prevalent in geography education literature. Serial explanatory designs (Cheuk and Lam, 2025; Chiu et al., 2024), and mixed-methods case studies (Kolvoord and Peterson, 2024; Morawski and Georgakaki, 2024), as well as comparative content analyses combining quantitative and qualitative coding (Czimre et al., 2024; Sun et al., 2024) demonstrate the methodological complexity of this group. Systematic and scoping reviews—a total of 18 studies—followed PRISMA guidelines (Deroncel-Acosta

TABLE 3 Summary of included studies: developing interdisciplinary and meta-subject competencies in school geography.

No.	Author(s)/year	Method	Technology	Journal
1	Laasch et al. (2023)	Systematic Review	Digital learning approaches	Journal of Business Ethics
2	Horn et al. (2022)	Systematic Literature Review (PRISMA 2020)	–	Sustainability Science
3	Bassachs et al. (2020)	Mixed-Methods Study	Cooperative digital tools	Sustainability
4	Drake and Reid (2020)	Conceptual/Historical Literature Review	–	Frontiers in Education
5	Kolmos et al. (2024)	Action Research (PBL)	–	European Journal of Engineering Education
6	Pellaud et al. (2021)	Qualitative Study/Focus Groups	–	Frontiers in Education
7	Redondo-Rodríguez et al. (2022)	Quantitative Study	Gamification	International Journal of Environmental Research and Public Health
8	Braßler and Sprenger (2021)	Quasi-Experimental Pre–Post Study	Project-based digital learning	Sustainability
9	Schijf, J. E. et al. (2023)	Quantitative Study (CFA)	–	European Journal of Higher Education
10	George (2023)	Conceptual Literature Review	Artificial Intelligence (AI)	Partners Universal Innovative Research Publication
11	Bendowska and Baum (2023)	Cross-Sectional Quantitative Survey	–	International Journal of Environmental Research and Public Health
12	Podgórska and Zdonek (2024)	Mixed-Methods Study	Digital collaborative tools	Sustainable Development
13	Ye and Xu (2023)	Qualitative Case Study	Digital learning tools	Frontiers in Psychology
14	Sommier et al. (2025)	Qualitative Case Study (Thematic Analysis)	–	Environment, Development and Sustainability
15	Goos et al. (2023)	Narrative Literature Review	Computational thinking tools	ZDM–Mathematics Education
16	Rehman et al. (2025)	Systematic Literature Review (PRISMA)	STEM digital tools	Humanities and Social Sciences Communications
17	Schleiss et al. (2023)	Design-Based Research (DBR)	AI education tools	Education Sciences
18	Garnett et al. (2023)	Quantitative Instrument Development (ESEM)	–	Journal of the Scholarship of Teaching and Learning
19	Oudenampsen et al. (2023)	Qualitative Focus Group Study	–	BMC Medical Education
20	Falloon (2020)	Conceptual Framework/Scoping Review	Digital tools, TPACK, SAMR	Educational Technology Research and Development
21	Chiu et al. (2024)	Sequential Explanatory Mixed-Methods (SEM)	AI, digital learning platforms	Computers & Education
22	Markauskaite et al. (2024)	Conceptual Theoretical Study	Digital collaborative learning	Journal of the Learning Sciences
23	Huang et al. (2020)	Conceptual Theoretical Study	Design-based learning tools	Sustainability
24	Berasategi et al. (2020)	Quasi-Experimental Pre–Post Study	Case study methodology tools	Sustainability
25	Foadi and Varghese (2022)	Conceptual Viewpoint Study	Digital health tools, AI	Journal of European CME
26	Membrillo-Hernández et al. (2021)	Retrospective Case Study (CBL)	Challenge-based learning tools	Sustainability
27	Anderson-Levitt and Gardinier (2021)	Conceptual Comparative Policy Analysis	–	Comparative Education
28	Mostert et al. (2025)	Descriptive Exploratory Study (Pre–Post)	–	Frontiers in Education
29	Lu et al. (2022)	Single-Case Experimental Design (A–B–M)	Micro:bit, mobile/digital tools	Sustainability
30	Yesnazar et al. (2025)	Quasi-Experimental (Pre–Post, Control Group)	STEM digital tools	Frontiers in Education
31	Meadows (2020)	Conceptual Perspective Paper	–	Geography and Sustainability
32	Sun et al. (2024)	Comparative Content Analysis (Mixed-Methods)	Analysis of digital textbooks	Sustainability

(Continued)

TABLE 3 Continued

No.	Author(s)/year	Method	Technology	Journal
33	Bagoly-Simó et al. (2020)	Qualitative Exploratory Study (Interviews)	–	Journal of Economic and Social Geography
34	Morawski and Georgakaki (2024)	Mixed-Methods Exploratory Case Study	Language-aware digital materials	European Journal of Geography
35	Mitchell (2023)	Conceptual Analytical Study	–	Education Sciences
36	Solem and Vaughan (2023)	Hierarchical Linear Modelling (HLM)	–	Educational Sciences
37	De Pascale (2023)	Qualitative Case Study (Ethnographic)	–	Sustainability
38	Miao et al. (2022)	Mixed-Methods Content Analysis	Digital curriculum tools	Sustainability
39	Kolvoord and Peterson (2024)	Mixed-Methods Quasi-Experimental	GIS, geospatial technology	Journal of Geography in Higher Education
40	Yemini et al. (2025)	Systematic Literature Review (SLR)	–	Educational Review
41	Golightly and Sprenger (2024)	Quantitative Case Study and Survey	–	Journal of Geography
42	Remmen and Iversen (2023)	Scoping Review	–	Journal of Adventure Education and Outdoor Learning
43	Smit et al. (2024)	Mixed-Methods (PCK Survey+CoRe)	–	Int. Research in Geographical and Environmental Education
44	Duindam et al. (2025)	Qualitative Content Analysis	–	Int. Research in Geographical and Environmental Education
45	Cheuk and Lam (2025)	Mixed-Methods Empirical Study (Survey)	STEM/STEAM tools	Education Sciences
46	Skarstein and Wolff (2020)	Conceptual/Perspective Study	Digital tools, dialogic teaching	Education Sciences
47	Brookfield (2022)	Narrative Literature Review	–	Journal of Geography in Higher Education
48	Schmidt and Stumpe (2025)	Systematic Review (PRISMA + Thematic)	Mobile Augmented Reality (AR)	Review of Education
49	Golightly (2025)	Conceptual Study (Literature Analysis)	Technology in education (general)	South African Geographical Journal
50	van der Vaart et al. (2025)	Qualitative Case Study (Thematic)	Deep mapping tools	Journal of Geography in Higher Education
51	Steingröbl and Budke (2024)	Qualitative Exploratory (Interviews + Content Analysis)	–	Education Sciences
52	Granados-Sánchez (2022)	Qualitative Theoretical Model (Expert Interviews)	–	Sustainability
53	Zhu et al. (2023)	Case Study + Mixed-Methods	SPOC, online learning platform	Sustainability
54	Donmez Bayrakci (2025)	Mixed-Method Quasi-Experimental	Artificial Intelligence (AI)	Sustainability
55	Wolff-Seidel and Budke (2022)	Mixed-Method Sequential (Survey + Interviews)	Digital geomedias, OER	European Journal of Investigation in Health, Psychology and Education
56	Gielstra et al. (2024)	Design-Based Study	Virtual field trip, GIS tools	Education Sciences
57	Gebele et al. (2022)	Qualitative (Think-Aloud + Text Analysis)	–	European Journal of Investigation in Health, Psychology and Education
58	Eberth et al. (2025)	Mixed-Method (Participatory Mapping)	Digital participation platform, geospatial tools	KN Journal of Cartography and Geographic Information
59	Vasiljuk, and Budke (2021)	Qualitative Content Analysis	–	European Journal of Investigation in Health, Psychology and Education
60	Střechová et al. (2025)	Qualitative UX Case Study (IPA)	Collaborative Immersive VR (eDIVE)	ISPRS Int. Journal of Geo-Information
61	Czimre et al. (2024)	Systematic Mixed-Method Review (Bibliometric)	Virtual Reality (VR)	ISPRS Int. Journal of Geo-Information
62	Virranmäki et al. (2021)	Qualitative Theory-Driven Content Analysis	–	Journal of Geography

(Continued)

TABLE 3 Continued

No.	Author(s)/year	Method	Technology	Journal
63	Morawski and Budke (2025)	Qualitative Content Analysis (Multimodal)	Digital games, map-based learning	KN Journal of Cartography and Geographic Information
64	Healy and Hammond (2025)	Mixed-Method Survey (Thematic Analysis)	–	Journal of Geography in Higher Education
65	Solem (2023)	Quantitative Analysis (NAEP datasets)	–	The Professional Geographer
66	Hammond (2022)	Qualitative Case Study (Participatory)	–	Children's Geographies
67	Hammond et al. (2025)	Comparative Qualitative Curriculum Analysis	–	Journal of Curriculum Studies
68	Gubevu and Mncube (2024)	Qualitative Case Study (Triangulation)	Mobile smartphones, tablets, Google Earth	Education Sciences
69	Baßeng and Budke (2025)	Design-Based Research (DBR)	Digital game-based learning	Education Sciences
70	Chang and Kidman (2021)	Conceptual Theoretical Analysis	–	International Research in Geographical and Environmental Education
71	Bagoly-Simó (2023)	Conceptual-Critical Analysis	–	Int. Research in Geographical and Environmental Education
72	Day et al. (2021)	Survey Study	Online teaching platforms	The Professional Geographer
73	Sund and Gericke (2020)	Comparative Qualitative Study	–	Environmental Education Research
74	Jekel et al. (2025)	Conceptual Theoretical Model Development	Geomedia, social geomedia tools	Journal of Geography
75	Jazdzewska et al. (2022)	GIS-Based Empirical Study	GIS, spatial database	ISPRS Int. Journal of Geo-Information
76	Adarkwah (2021)	Qualitative Narrative Inquiry (NVivo)	ICT, e-learning platforms	Education and Information Technologies
77	Chistyakov et al. (2023)	Systematic Mini-Review (ERIC database)	STEAM digital tools	Eurasia Journal of Mathematics, Science and Technology Education
78	Hallinger and Nguyen (2020)	Bibliometric Systematic Review (VOSviewer)	–	Sustainability
79	Playford et al. (2023)	Longitudinal Quantitative Analysis (Logistic Regression)	–	Social Sciences
80	Ponomariovienė et al. (2025)	Qualitative Action Research	Digital monitoring tools	Education Sciences
81	Sisternans (2020)	Qualitative (Literature + Expert Interviews)	Online learning platforms	Asia Pacific Education Review
82	Marcotte and Gruppen (2022)	Conceptual (Theoretical Analysis)	–	Education Sciences
83	Wittenberg et al. (2025)	Mixed-Methods (Survey + Quasi-Experimental)	–	Journal of Professional Nursing
84	Marcellis et al. (2024)	Conceptual (Design Model Development)	Blended learning platforms	Learning Environments Research
85	García-Álvarez et al. (2022)	Systematic Review (PRISMA)	–	Education Sciences
86	Rubene et al. (2024)	Cross-Sectional Survey (Network Analysis)	–	Education Sciences
87	Belchior-Rocha et al. (2022)	Quantitative Exploratory Survey	–	Education Sciences
88	Devika et al. (2020)	Qualitative (Semi-Structured Interviews, MAXQDA)	Learning factory tools	Procedia Manufacturing
89	Deroncele-Acosta et al. (2025)	Systematic Literature Review (PRISMA + Bibliometric)	Generative AI (ChatGPT)	Applied System Innovation
90	Veiga (2022)	Qualitative Narrative Study	Sociodrama methodology	Education Sciences
91	Shakhila et al. (2025)	Mixed-Methods (Curriculum Analysis + Teacher Survey)	GIS, mobile GIS applications, geospatial technologies	International Research in Geographical and Environmental Education

et al. 2025; García-Álvarez et al., 2022; Horn et al., 2022; Rehman et al., 2025; Schmidt and Stumpe, 2025), VOSviewer bibliometric analysis (Czimre et al., 2024; Hallinger and Nguyen, 2020) and narrative synthesis (Brookfield, 2022; Goos et al., 2023) at various levels, contributing to the development of a consolidated evidence base for competence-oriented geography pedagogy. Conceptual and theoretical studies, comprising approximately 15 works, provide the normative, analytical, and structural functions important for any emerging field (Bagoly-Simó, 2023; Chang and Kidman, 2021; Drake and Reid, 2020; Falloon, 2020; Markauskaite et al., 2024; Meadows, 2020).

In terms of educational technology integration, the body of research indicates four main categories of digital tools used to develop interdisciplinary and transdisciplinary competencies: geospatial and GIS technologies; immersive and simulation-based tools; artificial intelligence and computational tools; as well as digital collaborative platforms and geomedias.

Geospatial technologies-including ArcGIS, ESRI StoryMaps, Google Earth, mobile GIS applications, and participatory GIS platforms-constitute the most consistently represented technological cluster across the body of research. Kolvoord and Peterson (2024), within the Geospatial Semester program, demonstrate through neuroimaging data that sustained work with GIS improves spatial thinking and activates neural regions associated with abstract thinking. Jazdzewska et al. (2022) demonstrate that analyzing GIS-based geographical education directions contributes to developing spatial thinking and systems analysis as interdisciplinary competencies. Eberth et al. (2025) used the PUBinPLAN digital participatory platform to develop critical-reflexive mapping skills, while Gielstra et al. (2024) integrated LiDAR scanning and 360° spherical photographs via Polycam into virtual field studies, making physical geography processes accessible for study. Schmidt and Stumpe (2025) synthesized 18 empirical studies on mobile augmented reality in geography education, they identified that the three-dimensional visualization of invisible geographical phenomena-such as air pollution gradients, topography, and ecosystems-is a unique capability of mobile AR and directly contributes to the development of spatial meta-competencies.

Immersive and simulation-based tools-virtual reality (VR), collaborative immersive virtual environments (CIVEs), digital games, and virtual field studies-represent the fastest-growing technological category in the body of research. Synthesizing the results of 47 VR studies, Czimre et al. (2024) confirmed that immersive environments enhance spatial understanding, engagement, and collaborative problem-solving in the context of geography, while also identifying infrastructural inequity and insufficient integration into the curriculum as key barriers to implementation. Střechová et al. (2025) demonstrated through qualitative UX data that CIVE environments using the Biomes platform on Meta Quest 2 devices contribute to developing spatial thinking, emotional engagement, and hands-on cognition in middle school students studying climatic zones. Nikhanbayeva et al. (2026) investigated immersive VR instruction in the context of interdisciplinary higher education and identified significant progress in collaborative knowledge construction. In the field of game-based learning, Baßeng and Budke (2025) a design-based study using the commercial city-building game PocketCity demonstrated that the educational

value of digital games is shaped not only by the gameplay process but also by structured group reflection and written reflection journals, transforming this gaming experience into metacognitive and meta-subject learning outcomes. Morawski and Budke (2025), through a multimodal content analysis of 18 commercial digital games, show that the cartographic systems inherent in games (ludic cartographies) contribute to the development of spatial thinking, critical cartographic literacy, and reflective thinking as transferable competencies.

Artificial intelligence and computational tools constitute an emerging but rapidly developing technological cluster. In their conceptual review, George (2023) considered AI-based personalized learning environments as a transformative tool for developing 21st-century competencies such as computational thinking, data literacy, and self-regulation. Deroncelle-Acosta et al. (2025) In a PRISMA-based systematic review of 35 studies, identified fifteen transversal competencies-including AI literacy, critical thinking, and autonomous learning-that are developed through working with generative AI tools like ChatGPT. Through a design-based study, Schleiss et al. (2023) developed and validated the AI Course Design Planning Framework (AI CDPF), achieving a System Usability Scale score of 81.2. (very high) result, demonstrating it is a replicable tool for developing interdisciplinary AI courses that can also be adapted for geography education. Donmez Bayrakci (2025) conducted one of the few quasi-experimental studies that directly examined the impact of AI on geography competencies in a school setting. Chiu et al. (2024) empirically demonstrated that AI-based digital platforms, when implemented in a school environment that satisfies teachers' needs for autonomy, competence, and relatedness, significantly predict the development of personal-ethical and personal-professional digital competence.

Digital collaborative tools and geomedias-including digital geomedias, Web 2.0 platforms, open educational resources (OER), digital participatory cartography, and online collaborative learning environments-constitute the fourth technological cluster. Wolff-Seidel and Budke (2022) empirically demonstrated that digital geomedias, including satellite images and Web 2.0 platforms, enhances multiperspectivity, authenticity, and argumentation in geography education, while also identifying information overload and insufficient critical media literacy as pedagogical challenges. Jekel et al. (2025) proposed an emancipatory geomedias competence framework based on the DiGEO open educational resources project, oriented toward reflection, argumentation, and participatory citizenship. Gubevu and Mncube (2024), in a qualitative case study from South Africa, showed that mobile smartphones transformed a location-sensitive, technology-enhanced learning environment into a space for spatial analysis, digital cartography, and self-regulation competence. Lu et al. (2022) used Micro: bit-based mobile tools in a single-case experimental design to develop STEM geography integration competencies at the school level.

A common conclusion is clearly evident across all four technological categories: Digital and mobile tools in geography education are effective only when they are integrated into concrete competence frameworks, supported by teacher professional development, and used alongside structured reflection, rather than as standalone resources (Baßeng and

Budke 2025.; Chiu et al., 2024; Falloon, 2020; Schmidt and Stumpe, 2025). The quality of pedagogical design consistently emerges as the primary determining factor for the success of digital tools in fostering genuine interdisciplinary and transdisciplinary competencies in the context of geography education, more so than the complexity level of the technology.

4 Discussion

4.1 Synthesis evolution of principal results

This systematic review identifies 12 key contradictions that structure the current scholarly debates regarding the development of interdisciplinary and meta-subject competencies in school geography, based on 91 scientific articles. These contradictions are grouped into three main dimensions. The first strand is the epistemological tension between knowledge-oriented and competency-based pedagogical paradigms, i.e., whether the introduction of interdisciplinary and higher-order competencies enriches the content of the geography discipline, or does it dilute it? The second strand concerns the controversial role of digital and mobile technologies, including virtual reality, augmented reality, GIS, geomedia, and commercial games, in shaping geographical learning outcomes. The third line of inquiry concerns the persistent gap between the normative goals set out in curricula in various national contexts and their implementation in the actual classroom. Importantly, this review shows that many of the apparent disagreements among researchers are not empirical evidence that directly contradicts one another; Rather, they are based on methodological asymmetries, differences in units of analysis, particularities of national educational traditions, and the gap between planned (normative) models and actual practice. Thus, uncovering this complex and multifaceted image of the scientific field in a state of “productive contradiction” is the main analytical contribution of this study.

The first and most fundamental contradiction concerns the question of whether the current shift to competency-based curricula enriches or, on the contrary, weakens geographical education. Bagoly-Simó (2023) argues that the marginalization of physical geography and the introduction of value-oriented moral content in place of evidence-based scientific thinking represents a qualitative loss for the discipline; this view is partially empirically supported by Virranmäki et al. (2021), where 39% of the objectives in Finland’s upper secondary curriculum are formally directed toward higher-order thinking skills (HOTS), it is shown that in traditional teaching, students do not systematically achieve assessment and creative competencies, and that metacognitive knowledge is completely absent from both the curriculum and actual outcomes. Overall, these results demonstrate that the inclusion of ambitious competency goals in official documents does not lead to their automatic implementation, a conclusion that resonates with the broader international argument proposed by Anderson-Levitt and Gardinier (2021), i.e., competency-based education is polysemous in nature, allowing for its varied and sometimes superficial reinterpretation across different national contexts, with the result that while the discourse on 21st-century skills is

maintained, their specific pedagogical content may not be fully realized (Table 4).

4.2 Comparison with existing literature

In contrast to this skeptical stance, Ye and Xu (2023) and Yesnazar et al. (2025) offer quasi-experimental evidence, whose results suggest that well-designed interdisciplinary, project-based learning (PBL) environment provides statistically significant improvements ($p < 0.05$) in the four core components of 21st-century competencies-critical thinking, communication, collaboration, and creativity-without compromising the quality of subject knowledge. Drake and Reid (2020) provide a theoretical basis for these empirical findings. Similarly, Chistyakov et al. (2023), in their review of project-based learning in STEM and STEAM contexts, identify real-life tasks as the key mechanism that effectively engages metacognitive processes, including critical thinking, creativity, collaboration, and self-directed learning. The contradiction between these optimistic empirical results and the skeptical curriculum analyses proposed by Bagoly-Simó (2023) and Virranmäki et al. (2021) is not substantive but primarily methodological: the former studies measure learning outcomes from specifically organized interventions, while the latter assess the structural features of national education curricula and outcomes in natural learning settings. Thus, both claims are grounded within their respective analytical frameworks, and this interpretive precision-the need to interpret results according to their methodology and context-is one of the main focal points of this systematic review.

A second line of argument concerns the effectiveness of digital technologies in geography education. Research by Czimre et al. (2024), Kolvoord and Peterson (2024), and Schmidt and Stumpe (2025) on VR environments, AR-augmented fieldwork and GIS integration enhance spatial thinking and learning motivation, while GIS is associated with neurocognitive changes linked to higher-level abstract thinking. These findings align with the extensive evidence reviewed by Gubevu and Mncube (2024), where Google Earth, Mobile smartphone tools, such as GPS applications and virtual reality interfaces, are described as a catalyst for developing interdisciplinary competencies that integrate geography with data literacy, ecological analysis, and systems thinking. However, a design-based study by Baßeng and Budke (2025) shows that the commercial mobile city simulation game PocketCity only elicits pedagogically meaningful reflection when accompanied by structured debriefing and peer coaching, indicating that the game’s educational value stems not from the game itself, but from its pedagogical organization. Furthermore, Bagoly-Simó et al. (2020) and Day et al. (2021) find that during remote learning during the pandemic, traditional textbook-based approaches were maintained despite teachers’ access to geospatial tools, a finding that aligns with Golightly and Sprenger’s (2024) conclusion that structural factors in resource-limited classrooms in South Africa inhibit student-centered innovations, despite the availability of technology.

The simultaneous validity of optimistic and cautious stances toward technology is explained by the difference between idealized intervention scenarios and ecologically valid classroom contexts-a difference that Chiu et al. (2024), through structural

TABLE 4 Systematic review on the topic: developing interdisciplinary and meta-subject competencies in school geography.

No.	Topic of the contradiction	Position A	Position B	Why they disagree
1	Are competencies replacing knowledge?	YES—the competency-based approach impoverishes geography The shift toward competencies marginalizes physical geography, replacing evidence-based thinking with moral judgment. Bagoly-Simó (2023) ; Bagoly-Simó et al. (2020)	NO—Competencies and knowledge are compatible; PBL improves both Interdisciplinary thematic learning enhances 4C skills and knowledge simultaneously; statistically significant improvements across all competencies ($p < 0.05$). Ye and Xu (2023) ; Yesnazar et al. (2025)	Methodology: bagoly-simó—critical analysis of programs (no student data). Ye and Xu—quasi-experiment pre/post $n = 32$. Context: Germany vs. China. Different units of analysis: curriculum vs. classroom outcomes.
2	Is technology alone sufficient?	YES—VR/AR/GIS significantly improve cognitive outcomes 47 studies confirm: VR enhances spatial thinking and motivation; GIS programs produce neurocognitive changes. Czimre et al. (2024) ; Kolvoord and Peterson (2024) ; Schmidt and Stumpe (2025)	NO—without pedagogy, technology is useless Digital games are effective only through structured debriefing. Teachers during the pandemic had GIS but used textbooks. Baßeng and Budke (2025) ; Bagoly-Simó et al. (2020) ; Day et al. (2021)	Reviews aggregate the results of specially designed interventions (selection bias). Baßeng and Budke—DBR in a real classroom with a commercial game. Difference: ideal conditions vs. ecological validity.
3	Digital vs. natural learning	Digital/immersive environments—the main driver of competencies VR, AR, and mobile apps foster spatial and systems thinking better than traditional approaches. Czimre et al. (2024) ; Gubevu and Mncube (2024) ; Nikhanbayeva et al. (2026)	The natural environment is no less effective but has been studied less Outdoor learning has a positive impact on cognition (ART/SRT); digital resources are chronically underrepresented in scoping reviews. Brookfield (2022) ; Remmen and Iversen (2023)	Disciplinary origins: edTech paradigm vs. eco-pedagogy. Different databases, different keywords, virtually zero citation of each other. Both are valid within their respective fields.
4	Does ESD enrich or simplify geography?	ESD—impoverishment: science is being supplanted by moralizing Expanding the curriculum to include ESD leads to the “impoverishment” of knowledge; physical geography is reduced to a tool for instilling values. Bagoly-Simó (2023)	ESD integrates and enriches: GIS + systems thinking ESD, through geospatial technologies, enhances geocompetence and critical thinking without replacing scientific knowledge. Meadows (2020) ; Miao et al. (2022) ; Mitchell (2023)	National context: bagoly-simó analyzes the German curriculum (FÖSB). Meadows and Miao examine international/American/Chinese standards. Different operationalizations of ESD: normative (Germany) vs. spatially-analytical (IGU).
5	Affective goals: hidden values or cognitive neutrality?	Curricula must contain explicit affective and value-based goals (Spain) “Hidden values” guide students toward environmentally responsible behavior; affective goals are an integral part of ESD. Duindam et al. (2025) — <i>Spanish case</i>	Curricula should be cognitive, without r prescriptive values (Netherlands) The Dutch curriculum is analytically neutral, allowing students to draw their own conclusions without prescribing behavioral norms. Duindam et al. (2025) — <i>Dutch case</i> ; Bagoly-Simó (2023)	One article (duindam) describes two polar national approaches. The difference is explained by political culture: the Spanish tradition is value-integrated education; the Dutch tradition is liberal neutralism. This is not a methodological divergence, but a normative-political one.
6	HOTS: Are they included in the curricula or not?	HOTS are stated in the curricula, but students do not achieve them 39% of the Finnish curriculum’s goals are HOTS, but students struggle with evaluative and creative tasks; metacognition is completely absent. Virranmäki et al. (2021)	Interdisciplinary PBL significantly improves HOTS ($p < 0.05$) 32 students in a quasi-experiment showed significant improvements in critical thinking, creativity, and collaboration. Ye and Xu (2023) ; Yesnazar et al. (2025)	Virranmäki measures current achievements in a traditional context (system audit). Ye & Xu measure gains following a specially designed intervention (proof of concept). Both are correct, but they answer different questions.
7	Is the teacher the key factor, or is the structure more important?	The teacher is the key variable; professional development is crucial Training workshops reduce teachers’	Structural barriers overshadow the teacher’s influence In South Africa, teachers do not use	Cheuk & Lam examine changes in intentions (the short-term effect of training, $n = 49$). Golightly & Sprenger examine

(Continued)

TABLE 4 Continued

No.	Topic of the contradiction	Position A	Position B	Why they disagree
		anxiety about integrating STEM; professional development is a necessary condition. Cheuk and Lam (2025) ; Golightly (2025)	learner-centered strategies due to class size and exam pressure-and this remains consistent regardless of training. Golightly and Sprenger (2024) ; Solem (2023)	actual classroom practice ($n = 130$). Context: Hong Kong (affluent) vs. South Africa (North West Province).
8	Does affect predict outcomes?	YES—affective dispositions positively correlate with achievement Enjoyment of challenging tasks, interest in geography, and academic self-discipline significantly predict success on the NAEP ($n = 12,900$). Solem and Vaughan (2024)	Online learning does not foster affective engagement for HOTS In a SPOC environment, higher-order cognitive engagement (evaluate/create) is limited; students are predominantly at the analysis level. Zhu et al. (2023)	Not a direct contradiction, but different levels of analysis: solem & vaughan measure existing dispositions as predictors (cross-sectional). Zhu et al. examine the extent to which a specific environment fosters these dispositions (interventional).
9	Multiperspectivity: implicit or explicit?	Implemented implicitly and without metareflection Analysis of 28 articles: perspectivity is present, but deconstruction and re metareflection are the rarest dimensions. Vasiljuk and Budke (2021)	Cognitive program objectives cover HOTS, including evaluation In the 2015 Finnish curriculum, 39% of the objectives are oriented toward HOTS; a Bloom analysis shows the presence of evaluation objectives. Virranmäki et al. (2021)	Different analytical objects: vasiljuk & budke-specifically multiperspectivity in German-language literature. Virranmäki-general HOTS in the Finnish curriculum. Different national systems and constructs.
10	Games: potential for learning or a simplification of reality?	Commercial games intentionally simplify geographical topics Game designers consciously sacrifice accuracy for the sake of engagement; socio-environmental topics are simplified into game abstractions. Lux, Budke and Guardiola (2021)	Maps in games foster cartographic literacy "Human-centered cartographies" in strategy, open-world, and shooter games develop analytical thinking, spatial orientation, and situational awareness. Morawski and Budke (2025)	One research group (budke), different objects of analysis: Lux-content accuracy and environmental issues; morawski-the cartographic/spatial function of maps. The game simultaneously simplifies the subject matter AND forms spatial schemas.
11	Geography as the "science of sustainability": potential vs. reality	YES—Geography uniquely integrates natural and social GIS, remote sensing, and the IYGU framework make geography a core subject of ESD; international IGU consensus. Meadows (2020) ; Mitchell (2023)	The potential exists, but is poorly realized: normative narrative instead of science German curricula reduce knowledge; South African teachers do not utilize opportunities; in Italy, students learn about climate from the media, not from science. Bagoly-Simó (2023) ; Golightly and Sprenger (2024) ; De Pascale (2023)	Level of analysis: meadows and mitchell—normative-political (how it should be). Bagoly-Simó et al.—empirical-critical (what it is in practice). The gap between aspiration and implementation is the central unresolved contradiction in the field.
12	Civic competence: is it developing or lagging behind?	Civic competence is the weakest in the network Network LASSO analysis of 24 nodes: civic competence is the lowest of all; community involvement is systematically underestimated by students. Rubene et al. (2024)	Geomedia and participation-the foundation of civic competence A three-component model (reflection–argumentation–participation) suggests that participation through geomedia fosters civic engagement. Jekel et al. (2025)	Empirical vs. normative: Rubene measures students' self-assessment (a snapshot of the current state) Jekel constructs a normative model for teacher education (the desired state). Different populations and methods.

equation modeling conducted on 370 teachers, clearly demonstrates: academic support at school and the satisfaction of teachers' basic psychological needs (autonomy, competence, relatedness) fully mediate the relationship between technology availability and teachers' personal-ethical and professional digital competence. This finding reframes the technology issue: what

matters is not the availability of digital tools, but the creation of motivational and cultural conditions that allow for their mindful pedagogical use. The Teacher Digital Competency (TDC) model proposed by [Falloon \(2020\)](#) theoretically grounds this assertion, viewing digital competence as a comprehensive concept that includes components such as critical thinking, digital

citizenship, ethical awareness, and interdisciplinary integration; These competencies are developed not from the technology itself, but through purposeful pedagogical design.

The intersection of outdoor, nature-based learning and digital learning formats constitutes a third important strand of the discussion. Brookfield (2022), synthesizing interdisciplinary research from ecological psychology and education, shows how Attention Restoration Theory (ART) and Stress Reduction Theory (SRT) mechanisms positively affect cognitive functions and the development of metacognitive skills such as critical thinking, problem-solving, and reflection. In their review of 52 empirical studies from Northern European countries, Remmen and Iversen (2023) confirm that the overall cognitive outcomes of outdoor learning are positive, and also notes that digital tools have been systematically underrepresented in this line of research: only two of the works considered included mobile applications, which is particularly noteworthy given the high level of digitalization in schools, especially in Northern countries. The near-absence of cross-references between the EdTech and eco-pedagogy scholarly communities, identified by this review, indicates that the main reason for the observed differences is not empirical inconsistency but rather disciplinary isolation. Skarstein and Wolff (2020) show that digital tools—time-lapse footage, drone-captured video, interactive simulations, and geospatial platforms—can serve as a cognitive scaffold, allowing students to overcome the perceptual limitations of direct experience, enabling them to understand environmental processes on spatial and temporal scales previously inaccessible in the classroom. This demonstrates that there is a productive theoretical space in which these two approaches can be integrated within a multimodal concept of developing geographical competencies.

Issues of integrating Education for Sustainable Development (ESD) into geography curricula constitute a fourth important line of scholarly debate. Bagoly-Simó (2023) describes ESD as a normative-moral instrument within the German curriculum context that displaces scientific content and marginalizes physical geography as a strict epistemological foundation. In response to this critique, Meadows (2020) and Mitchell (2023), examining ESD implemented through geospatial technologies—GIS, remote sensing, ArcGIS Story Maps, and the Geo-Inquiry Process—in international and North American contexts, demonstrate that these tools enhance geocompetence, critical thinking, and spatial thinking without replacing scientific knowledge. Miao et al. (2022) extend this conclusion to the Chinese context as well. Duindam et al. (2025) highlight this national difference through a comparative analysis of the curricula of Spain and the Netherlands: the presence or absence of affective and value-oriented goals in geography curricula is more dependent on political culture than on pedagogical evidence, with the Spanish tradition being value-integrated, while the Dutch tradition is analytically neutral. This result aligns with the argument proposed by Pellaud et al. (2021), based on focus groups with 89 prospective and experienced teachers, which shows that effective competency development for sustainable development requires an integrative tripartite structure composed of cognitive, social-emotional, and metacognitive components, and that none of these components can be considered in isolation.

The interplay between teacher role and structural constraints constitutes the fifth and most significant set of contradictions. Cheuk and Lam (2025), in a mixed-methods study involving 49 prospective and experienced geography teachers in Hong Kong, found that professional development workshops based on geospatial technologies such as Google Earth and 3D modeling tools significantly reduced teachers' anxiety about integrating STEM, even redirecting their teaching intentions toward inquiry-based practice. Golightly (2025) also identifies professional development as a necessary condition for teaching geography oriented toward competence. However, Golightly and Sprenger (2024), based on a survey of 130 teachers in South Africa's North West Province, indicates that despite the official support for student-centered methods in the curriculum, teacher-centered approaches predominate in classrooms; structural factors such as large class sizes, test pressure, and language barriers contribute to this, inhibiting pedagogical innovations even when pre-training is provided. Solem (2023), analyzing large-scale NAEP data, finds that the primary constraints on developing higher-order geographic thinking are systemic inequities. A closer examination of the apparent contradiction between these positions reveals that it stems primarily from methodological differences: While Cheuk and Lam's study measures short-term attitudinal changes in a relatively small and favorable setting, Golightly and Sprenger's study analyzes long-term, authentic learning experiences in resource-limited contexts. Therefore, these findings are not mutually exclusive but rather indicate that the effectiveness of professional development interventions is context-dependent and that structural conditions must be considered alongside teacher preparation.

The sixth line of contradiction involves the relationship between affective dispositions and learning outcomes. Solem and Vaughan (2024) conducted hierarchical linear modeling on NAEP data from 12,900 eighth-grade students, finding that interest in complex tasks, academic self-discipline and interest in geography are statistically significantly and positively correlated with higher academic achievement, and also show a positive correlation with several affective indicators of process-oriented computer-based activities. However, this study warns that excessive reliance on technology in the absence of fully developed content-based geographic knowledge may lead to decreased academic achievement, highlighting the importance of pedagogical balance. Zhu et al. (2023), based on an analysis of online SPOC environments, indicate that higher-order cognitive activity corresponding to the evaluation and creation levels of Bloom's taxonomy is limited, with most students remaining at the analysis level. These results are not in direct contradiction but indicate different analytical levels: While Solem and Vaughan consider existing affective dispositions as cross-sectional predictor factors, Zhu and colleagues examine the extent to which a specific technological environment shapes these dispositions.

The question of whether civic competence is developing or, conversely, falling behind represents the final key contradiction identified by this review. Rubene et al. (2024), in a study of 1,575 students in Latvia, conducted a LASSO network analysis of 24 transversal competence components and found that civic competence was the least developed among all dimensions,

while participation in society is often systematically underestimated. This empirical finding aligns with [Jekel et al. \(2025\)](#) proposed normative model, in which the triad of reflection–argumentation–participation in geomeia-based learning is regarded as an accessible and foundational outcome of civic engagement. The gap between Rubene and colleagues' empirical picture of the “current situation” and Jekel and colleagues' “desired” model represents a concrete manifestation of the aspiration–implementation gap identified by this review, a conclusion supported by [Vasiljuk and Budke's \(2021\)](#) study, which shows that the multi-perspectivity that is a prerequisite for civic thinking is often only indirectly implemented in geography lessons, while critical metareflection is the least frequently and systematically developed component.

4.3 In-depth analysis: mechanisms and theoretical implications

Overall, the contradictions identified in this review are not the result of random scientific disagreements but are manifestations of three specific structural mechanisms. The first is methodological asymmetry. The bulk of the contradictions are analytical studies at the curriculum level—which assess the formal characteristics of educational programs—and classroom-level experimental studies—which measure learning outcomes in controlled intervention settings—arise from treating them as parallel. Essentially, these studies answer different questions. [Virranmäki et al. \(2021\)](#) analysis of curriculum goals and [Ye and Xu \(2023\)](#) experimental intervention with 32 students clearly illustrates this asymmetry: while each is correct within its own analytical framework, together they describe a system with ambitious goals that have not been fully realized. The failure to sufficiently specify the unit of analysis in the research domain has led to spurious debates and the inefficient allocation of scientific resources. Therefore, future systematic reviews should consider it a methodological requirement to classify results according to this criterion.

The second mechanism is contextual non-transferability. A common pattern observed in almost all twelve contradictions is that the results are deeply dependent on national, institutional, and socio-economic contexts, yet this dependency is often not sufficiently theorized. The contrast between professionally advantaged teachers in Hong Kong ([Cheuk and Lam, 2025](#)) and educators facing structural constraints in South Africa ([Golightly and Sprenger, 2024](#)), as well as the gap between Germany's ESD implementation ([Bagoly-Simó, 2023](#)) and the International Geographical Union's coherent international models ([Meadows, 2020](#)), clearly demonstrates this. [Markauskaite et al. \(2024\)](#) proposed an ecological approach to interdisciplinary teaching that views competency development as a heterogeneous, distributed, and multi-layered process occurring at the micro, meso, and macro levels of the educational ecosystem, providing a robust theoretical foundation for explaining this contextual dependency. Within this ecological logic, digital artifacts and mobile technologies mediate the formation of competencies as non-human actors, and this process is inseparable from the institutional and cultural environment in which they are used, a conclusion empirically

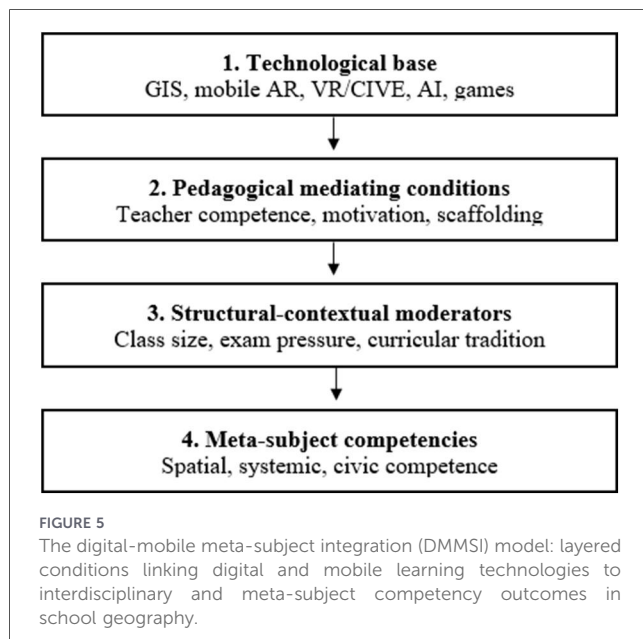
supported by [Chiu et al. \(2024\)](#), who demonstrate that school culture mediates the relationship between technology access and teachers' digital competence.

The third mechanism is the “goal–implementation” gap, which is considered the most important theoretical issue in the field according to this review. [Solem \(2023\)](#), [De Pascale \(2023\)](#), and [Bagoly-Simó et al. \(2020\)](#) show that structural factors such as class size, the exam system, resource constraints, and teacher training systematically hinder the translation of ambitious curriculum goals into actual practice at various empirical levels. This gap is evident not only at the structural level but also at the epistemological level: [Klescheva et al. \(2020\)](#), who consider the Physical World Image (PWI) concept as a unifying basis in the theory of designing interdisciplinary courses, argue that effective competency development requires a deep philosophical structure that considers the methodology of scientific cognition as the primary object of instruction, yet such an approach is often absent in the curricula reviewed in this overview. Furthermore, [Marcellis et al. \(2024\)](#) argue in their design-based model for designing blended learning environments that the effectiveness of digital and mobile learning is not due to the presence of technology, but rather depends on its alignment with learner-centered pedagogical principles, which align with the foundations of Self-Determination Theory, aimed at supporting three core psychological needs: autonomy, competence, and relatedness.

4.4 A conceptual model: conditions for digital- and mobile-mediated meta-subject competency development

Building on the mechanisms identified in Section 4.3 and the technological and thematic structure identified in Section 3.2, this review proposes the Digital-Mobile Meta-Subject Integration (DMMSI) model ([Figure 5](#)), which formalizes the conditions under which digital and mobile learning (DML) technologies translate into interdisciplinary and meta-subject competency gains in school geography. The model comprises four layers and one central dynamic.

- (1) The technological base layer comprises the empirically validated DML modalities identified through the bibliometric analysis in Section 3.2—geospatial information systems (GIS), mobile augmented reality (AR), immersive and collaborative virtual environments (VR/CIVE), artificial-intelligence tools, and digital games. Consistent with the review's central finding, access to these technologies is a necessary but not sufficient condition for competency development ([Chiu et al., 2024](#); [Golightly and Sprenger, 2024](#)).
- (2) The pedagogical mediating layer specifies the conditions under which technological access translates into learning gains: teacher digital competence across [Falloon's \(2020\)](#) five TDC dimensions (technical skill, critical thinking, digital citizenship, ethical responsibility, and interdisciplinary synthesis); institutional support for teachers' autonomy, competence, and relatedness needs, which fully



mediates the technology-competency relationship (Chiu et al., 2024); and structured pedagogical scaffolding such as peer coaching and reflective debriefing, without which technology use remains pedagogically inert (Baßeng and Budke, 2025).

- (3) The structural-contextual layer, grounded in the ecological framing proposed by Markauskaite et al. (2024), situates competency development within micro- (classroom), meso- (school/institutional), and macro-level (national curricular tradition) conditions-class size, examination pressure, resource availability, and the prevailing competency discourse (e.g., the post-Soviet meta-subject tradition versus Western transversal/21st-century-skills framings; see Section 2). This layer explains the contextual non-transferability mechanism identified in Section 4.3: identical technologies and pedagogies yield divergent outcomes across national contexts because these structural conditions vary systematically.
- (4) The outcome layer comprises the interdisciplinary and meta-subject competencies targeted by this review: spatial thinking, systemic reasoning, metacognitive regulation, critical argumentation, and civic competence, operationalized through the reflection-argumentation-participation triad proposed by Jekel et al. (2025). Civic competence emerged as the least-developed of these outcomes across the reviewed literature (Rubene et al., 2024), marking it as a priority target for future intervention design.

The central dynamic is the goal-implementation (“policy-competency”) gap formalized in Section 4.3: this gap opens whenever the technological layer is present but the pedagogical and structural layers are weak or misaligned, and it is this misalignment-rather than technology itself-that generates the “productive contradictions” catalogued in Table 3. Closing the gap therefore requires coordinated intervention across all three

upper layers, not investment in technology alone. The practical, curricular, and research implications of each model component are elaborated in Section 4.6.

4.5 Advantages and limitations

The main advantage of this review is its systematic identification of contradictions and structural analysis within a broad and geographically diverse corpus of literature ($n = 91$ articles). By moving beyond traditional descriptive synthesis and analyzing the structural causes of scientific disagreements, this study shows that in many cases apparent contradictions are not genuine empirical inconsistencies, contributing to methodological clarity by showing that apparent contradictions are often the result of different analytical approaches rather than genuine empirical inconsistencies. Integrating a specific table of contradictions with the thematic interconnections throughout the full literature review provides a replicable analytical approach that allows future researchers to observe how these debates evolve as new evidence emerges. A precise systematization of twelve types of contradictions, encompassing epistemological, technological, affective, and structural dimensions, establishes a coherent conceptual architecture that deepens theoretical understanding in the field.

Several limitations should be noted. First, a focus on English-language, peer-reviewed journal publications may lead to the systematic exclusion of important data from national and linguistic contexts that are insufficiently represented, especially considering that the majority of the literature reviewed is from Europe and East Asia. Second, the lack of meta-analytic procedures prevents this review from comparing effect sizes between opposing conclusions, thereby limiting a clear empirical determination of which is dominant. Third, the methodological heterogeneity of the included studies-ranging from a single-classroom quasi-experiment with $n = 32$ by Ye and Xu (2023) to national-level studies with $n = 12,900$ participants (Solem and Vaughan, 2024)-making formal comparison impossible and necessitating the interpretive reasoning characteristic of qualitative syntheses. Therefore, the proposed conclusions should be viewed not as definitive results, but as theoretically grounded propositions that may be refined through future empirical research, especially given the rapidly changing technological landscape in geography education.

4.6 Practical implications and future research directions

The findings of this review offer a number of important implications for educational policy, curriculum design, and professional practice. Curriculum developers aiming to integrate interdisciplinary and transdisciplinary competencies into the geography curriculum should abandon the view of competency models as a “self-actualizing” system. As the data reviewed indicate, formal learning objectives remain insufficient when not aligned with pedagogical support structures, teacher professional development, and assessment systems that evaluate high-level outcomes (Golightly and Sprenger, 2024; Virranmäki et al.,

2021). Virranmäki et al.'s, (2021) finding that metacognitive knowledge is not addressed at all in Finland's national curriculum-despite the country's education system being recognized as progressive-clearly highlights the relevance of intentionally incorporating metacognitive components into geography curricula. Furthermore, the findings of Wolff-Seidel and Budke (2022) and Gebele et al. (2022) indicate that teaching argumentation and metacognitive strategies are key mechanisms for fostering reflective and evidence-based geographical thinking, though these strategies are currently implemented mostly indirectly and without systematic support, which in turn limits the full development of the higher-order competencies required by ESD and interdisciplinary teaching.

In the context of technology integration, this review warns against the uncritical introduction of digital and mobile tools based on aggregate efficacy evidence from controlled interventions. It has been systematically shown that pedagogical application in real classroom settings is limited (Baßeng and Budke, 2025; Golightly and Sprenger, 2024), indicating that professional development programs must address not only technical skills but also motivational and institutional conditions. The AI Course Design Planning Framework proposed by Schleiss et al. (2023) and the TDC model developed by Falloon (2020) offer universal design logics for structuring such interdisciplinary and context-adaptive teacher preparation. Furthermore, as Brookfield (2022) and Remmen and Iversen (2023) show, a synthesis of open-environment learning and digital technology integration, which has not yet been fully realized due to disciplinary silos between the EdTech and ecopedagogy research communities, represents a highly promising direction for curriculum renewal; in this regard, mobile learning technologies offer a unique opportunity to bridge the gap between formal and informal learning through spatially and context-adaptive platforms.

Regarding the development of civic competence—Rubene et al. (2024) identified as the least developed component—this review justifies prioritizing pedagogies focused on participation in the preparation of future and in-service geography teachers. The geomedia-based tripartite model (reflection—argumentation—participation) proposed by Jekel et al. (2025) is a theoretically grounded and practically implementable effective tool for achieving this goal, and its alignment with the tradition of spatial citizenship provides a productive foundation for integrating digital technologies with the aims of civic education. Furthermore, a systematic review of employer requirements conducted by García-Álvarez et al. (2022) identified ICT literacy and critical thinking as two of the most highly valued transversal competencies in the global labor market, thereby reinforcing the importance of educational initiatives designed to develop digital competencies within geography education.

Several priority directions are identified for the research community. Future research should systematically and explicitly specify the unit of analysis and describe contextual moderators such as class size, resource availability, the national examination system, and school culture in sufficient detail to allow comparison across studies. Longitudinal research designs are also needed: the long-term retention of competencies developed through PBL (Ye and Xu, 2023; Yesnazar et al., 2025), as well as the cumulative effect of affective factors highlighted by Solem

and Vaughan (2024), remains under-researched. Validated instruments for measuring interdisciplinary and transdisciplinary competencies—such as the Collaborative Knowledge Practices questionnaire developed by Muukkonen et al. (2020) and the Interdisciplinary Understanding Questionnaire proposed by Schijf et al. (2023)—both of which need to be adapted to the context of school geography and applied systematically, as psychometrically reliable instruments are still lacking in this field. The “goal–implementation” gap identified across various national contexts calls for research using targeted mixed-methods designs that explore in depth how structural factors mediate the link between curricular goals and actual teaching practice. If such a research program is conducted in line with the ecological approach proposed by Markauskaite et al. (2024), it will generate accumulated scientific knowledge and enable the grounding of genuine transformative educational reforms.

6 Conclusion

This systematic review synthesizes the evidence base from 91 empirical and conceptual studies published between 2020 and 2025, in the subject of school geography, how Digital and Mobile Learning (DML) approaches contribute to the development of interdisciplinary and meta-subject competencies. The main conclusion of the review is clear: purposefully designed DML environments—including geographic information systems (GIS), augmented and virtual reality (AR/VR), mobile applications, game-based platforms, and blended learning architectures—are more than just technological supplements to geography education. Rather, they serve as conditions that structurally enable the development of competencies that cross disciplinary boundaries. A body of research, conducted in diverse national and institutional contexts, arrives at a common conclusion: digital geospatial tools, interactive simulations, and collaborative mobile environments consistently foster spatial thinking, systems thinking, critical analysis, and communicative competence. In the terminology of the Russian-language and post-Soviet educational tradition, these abilities constitute the core of meta-disciplinary teaching (Klescheva et al., 2020; Yesnazar et al., 2025). Overall, these findings do not position DML as a marginal educational innovation; rather, they establish it as a pedagogical imperative for fostering 21st-century transferable competencies and advancing geography education in alignment with the requirements of Industry 4.0 and sustainable development.

One of the methodological gaps in school geography, widely documented in the literature, is the predominance of teacher-led instructional practices over learner-initiated inquiry, which persists despite well-documented limitations on opportunities for collaborative problem-solving and authentic data work. Golightly and Sprenger (2024) based on a large-scale survey of 130 geography teachers in South Africa, found that the lecture format and the question-and-answer method clearly dominate classroom practice, while field research, modeling, and project-based learning strategies remained marginal; This structural trend is explained by exam-oriented curricula, class sizes, and an insufficient pedagogical preparation for inquiry-based teaching.

Similarly, [Smit, Tuithof, and Bénéker \(2024\)](#) showed that future geography teachers in the Netherlands rely mainly on visual presentations and classroom discussions, while student activities remain at a low cognitive level, limiting opportunities to develop higher-order metacognitive skills such as systems thinking and critical analysis. These findings clearly illustrate a systemic mismatch between the interdisciplinary goals of current geography curricula and the teaching repertoire available to teachers.

Digital and mobile learning offers an opportunity to address this gap, as it shifts the focus of geographical cognition from passive reception to active, productive, and autonomous student engagement with real-world problems. [Gubevu and Mncube \(2024\)](#) showed that when mobile smartphones are used as a pedagogical tool, geography classes become a flexible, technologically enhanced environment; In such an environment, learners conduct spatial analysis, create digital maps, and collect real-time data using tools like Google Earth, GPS platforms, a WhatsApp-based collaborative environment, and virtual reality applications. The shift from reproductive learning to productive, inquiry-based learning aligns directly with the demands of Industry 4.0, as digital literacy, data literacy, and interdisciplinary problem-solving are considered foundational for civic and professional engagement ([Foadi and Varghese, 2022](#); [George, 2023](#)). Furthermore, [Drake and Reid \(2020\)](#) demonstrated that integrated interdisciplinary curricula, implemented through project-based, inquiry-based, and phenomenon-based learning models supported by digital tools, do not diminish academic outcomes compared to traditional models, and instead enhance student engagement in the learning process and the development of their complex competencies. The body of evidence reviewed in this study clearly demonstrates that DML provides a methodologically coherent and empirically grounded response to the structural limitations of traditional geography instruction.

One of the most reliably proven features of digital and mobile learning (DML) in school geography is its effectiveness in organizing and progressively supporting students' exploratory and inquiry-based activities through geospatial and immersive tools. [Kolvoord and Peterson \(2024\)](#), documenting the impact of the Geospatial Semester program, found that long-term work with the ArcGIS Online and StoryMaps platforms enabled high school students to explore real-world civic and environmental issues, such as urban heat islands and food deserts. The study identified a neurobiologically measurable improvement in spatial thinking skills, evidence-based reasoning, and the performance of verbal tasks that rely on spatial visualization as a result of the program. Furthermore, the study, using neuroimaging data, demonstrated that participants in the program activated brain regions responsible for higher-, level abstract thinking more effectively than students in the control group. This indicates that geospatial digital tools not only supplement content delivery but also reorganize cognitive structures. [Mitchell \(2023\)](#), in a study analyzing the Geo-Inquiry Process model developed by the National Geographic Society, demonstrated that using ArcGIS Story Maps, digital cartography, and Google Earth tools enhances the critical thinking and evidence-based argumentation of middle school students analyzing the complex, multifaceted issue of climate change.

Mobile augmented reality (AR) is considered a particularly promising tool for the inquiry-based practices characteristic of geography. Synthesizing 18 empirical studies conducted between 2015 and 2023, [Schmidt and Stumpe \(2025\)](#) found that mobile AR significantly improves students' conceptual understanding, long-term knowledge retention, and spatial reasoning by visualizing abstract or otherwise unobservable geographic processes, such as air pollution dynamics, landform development, and ecosystem processes. Mobile AR's platform-independent capabilities—three-dimensional visualization, context-based collaborative learning, and the integration of formal and informal learning environments—make it particularly suitable for location-dependent research tasks that require linking field observations with theoretical models.

Virtual reality (VR) further expands this research potential. [Gielstra et al. \(2024\)](#), describing a virtual field trip to the glacial landscapes of Glacier National Park (Montana) using 360° spherical photographs and LiDAR-based 3D digital twins created with the Polycam app and the GeoEPIC platform, demonstrated that students can measure, rotate, and analyze geomorphological features with scientific precision. This approach fostered the development of spatial reasoning, ecosystemic thinking, and scientific inquiry skills that transcend disciplinary boundaries. [Czimre et al. \(2024\)](#), analyzing the use of VR in geography education based on a systematic bibliometric and content review, found that VR is often implemented through immersive virtual field trips and interactive simulations, and that these technologies, when integrated with constructivist and collaborative pedagogical strategies, consistently improve learning outcomes, motivation, spatial understanding, and engagement. The collaborative aspect of immersive environments was explored in greater depth in the study by [Střechová et al. \(2025\)](#). The qualitative case study results on Collaborative Immersive Virtual Environments (CIVEs) revealed that using Meta Quest 2 headsets and the Biomes CIVE platform with students aged 12–15 resulted in high levels of engagement, learning, and spatial conceptualization.

The reviewed literature on digital and mobile learning in school geography (DML) clearly and consistently demonstrates that digital mobile learning systematically develops specific interdisciplinary competencies that transcend the boundaries between geography, the natural sciences, technology, the social sciences, the arts, and mathematics. Among these competencies, spatial thinking is the foundational ability most consistently linked with digital geospatial tools. [Meadows \(2020\)](#) considers geographic information systems (GIS) and remote sensing technologies as tools that enable the analytical management of global environmental issues that are inherently spatial, simultaneously fostering spatial reasoning, interpretation of data, systems thinking, and evidence-based argumentation. [Chang and Kidman \(2021\)](#) further advance this argument by demonstrating that digital cartography and satellite-based technologies enable students to investigate geographical and ecological phenomena across multiple spatial scales previously inaccessible within traditional classroom environments, thereby enhancing multi-scalar analytical competencies and metacognitive capacities.

[Kolvoord and Peterson \(2024\)](#) further confirm that documented gains in spatial reasoning through GIS-based

instruction foster a way of thinking that bridges the fields of environmental science, social studies, public health, and mathematics in digital geospatial environments.

Separate from spatial competencies, integrating digital tools with structured pedagogical models has been proven to foster critical thinking, metacognitive reflection, and evidence-based argumentation. Wolff-Seidel and Budke (2022) demonstrated that digital geomedium, including satellite imagery, Web 2.0 platforms, and digital maps, enhances multiperspectivity, a sense of reality, and real-time interactivity. In such an environment, learners analyze spatial conflicts from various perspectives, construct evidence-based arguments, and develop media literacy skills that are crucial for navigating the information space. Jekel et al., (2025) demonstrated that emancipatory interaction with geomedia-which includes social networks, digital maps, and location-based platforms-forms a tripartite competency architecture consisting of elements of reflection, argumentation, and participation; this allows for the description of these digital spatial tools as a mechanism for civic and epistemological empowerment. Gebele et al. (2022) empirically demonstrated that working with maps, graphs, and texts simultaneously in a digital environment develops students' metacognitive strategies, such as planning, monitoring, and evaluation; These strategies significantly impact their argumentative writing quality, confirming the contribution of digital multimodal learning to the development of higher-order metacognitive skills.

Digital game-based learning fosters a unique set of interdisciplinary competencies focused on systems thinking and reflective reasoning. Baßeng and Budke (2025) combine the commercial mobile city-building game PocketCity with peer reflection coaching and structured reflection journals within a design-based research framework, enabling students to compare virtual and real-world systems, critical evaluation of spatial solutions, as well as engaging in complex cognitive processes such as self-analysis of their own learning strategies. These abilities form the core of metacognitive and interdisciplinary meta-subject competence development. The collaborative reflection format also enhanced communication, argumentation, and self-regulation skills through guided questions and peer feedback. Ye and Xu (2023) confirmed these results in a study on interdisciplinary thematic teaching that integrated geography, biology, information technology, and art: the use of 3D modeling, visual data analysis, and virtual and augmented reality environments produced statistically significant improvements across all four dimensions of the 4C competency framework (critical thinking, communication, collaboration, creativity), particularly with a marked increase in communication and collaboration scores among middle school students. Integrating STEM-focused instructional approaches further strengthened this competency architecture: Yesnazar et al., (2025) reported that project-based STEM instruction-including engineering design, scientific research, and modeling tasks-significantly strengthened elementary school students' metacognitive competencies in the cognitive, regulatory, communicative, and personal domains.

The findings of this review have significant implications for the design of geography teaching environments. Marcellis et al. (2024) demonstrated that blended learning architectures-which

integrate online and offline learning formats flexibly, provide adaptive feedback, and foster peer collaboration-enhance the development of metacognitive skills by simultaneously supporting learner autonomy, competence, and social interaction. Drawing on self-determination theory, a blended learning environment that includes flexible participation options, adaptive feedback, and peer collaboration was shown to significantly enhance students' self-regulation, problem-solving abilities, and flexible learning skills; however, this effect is only observed when the digital design is explicitly aligned with student-centered pedagogical principles. The core of this conclusion-that the effectiveness of digital learning depends not on the technology itself, but on its alignment with psychological and pedagogical conditions-was also confirmed in the study by Chiu et al. (2024): they found that the successful integration of digital tools into interdisciplinary curricula depends on the school's motivational and cultural environment, which enables teachers to make conscious pedagogical judgments beyond subject boundaries.

Project-based learning, when supported by digital infrastructure, serves as a particularly effective mechanism for developing interdisciplinary and transdisciplinary competencies in geography. In their thematic review of 36 studies on project-based learning in natural science and STEAM education, Chistyakov et al., (2023) found that a project-based environment supported by digital tools systematically enhances student engagement, problem-solving, systems thinking, critical thinking, creativity, collaboration, communication, and self-directed learning. These results were particularly evident when using e-portfolios, ICT-based collaborative tools, and online learning systems to carry out real-life tasks. Mostert, van Wyk, and Wessels (2025) confirmed these findings in a mixed-methods study on interdisciplinary case-based learning: Group projects that integrated digital tools for research and presentation led to statistically significant improvements in critical thinking, problem-solving, teamwork, and communication. The consistent evidence from these studies allows for project-based digital learning to be described as a structural mechanism that integrates subject knowledge with transferable professional competencies; which in turn directly enhances students' readiness for civic, academic, and professional environments.

The motivational aspect of integrating digital and mobile learning (DML) requires special attention. Solem and Vaughan (2024), analyzing 2018 National Assessment of Educational Progress data from 12,900 eighth-grade students, found that computer-based process-oriented learning activities-conducting digital investigations, including technological tasks such as conducting digital research and creating multimedia products-were positively correlated with academic self-discipline, perseverance, and interest in complex problems. These qualities are the necessary affective prerequisites for the development of metacognitive competencies. Redondo-Rodríguez et al. (2023) showed that combining gamification with cooperative interdisciplinary team structures leads to statistically significant improvements in emotional intelligence, study strategies, and motivational life goals among university students. This demonstrates that the pedagogical synergy of digital game mechanics and collaborative learning structures is crucial for

achieving transformative educational outcomes. Overall, these findings indicate that the integration of digital and mobile tools in geography education, based on evidence-based pedagogical design, enhances not only cognitive aspects but also the motivational and emotional dimensions of competency development. These dimensions are increasingly recognized as an integral part of fostering interdisciplinary and self-regulated learners prepared for the demands of a complex, technology-saturated world.

Despite the substantial and consistent evidence analyzed in this study, a number of significant limitations and unresolved issues remain in the field, which will shape the future research agenda. The most fundamental issue is the lack of an integrated, theoretically coherent didactic model. Czimre et al. (2024) identified insufficient integration of instructional design and the lack of pedagogical frameworks as key factors hindering the effective use of virtual reality (VR) in geography education. Schmidt and Stumpe (2025) indicated that the lack of systematic alignment of mobile augmented reality (AR) applications with established pedagogical models, such as TPACK, limits their potential to fully realize their educational impact. Furthermore, Virranmäki, Valta-Hulkkonen, and Pellikka (2021) demonstrated that the presence of higher-order thinking objectives in geography curricula does not guarantee their genuine adoption in practice; This indicates a structural mismatch between curricular intentions and actual learning outcomes. Such a gap cannot be addressed by simply introducing a digital environment; it requires a systematic reorientation of teaching strategies and assessment practices.

These limitations are further exacerbated by structural inequalities in access. Czimre et al. (2024) identified hardware levels, device technical performance, and infrastructural inequities as significant factors hindering the widespread adoption of virtual reality (VR). Solem (2023), analyzing NAEP data across various demographic groups, showed that insufficient access to technology-enabled geographic learning opportunities disproportionately limits the development of competencies among underrepresented and underrepresented student groups. This suggests that applying DML without equity-based implementation mechanisms may deepen, rather than reduce, educational inequities. Carter-White and Roelofsen (2025) raised similar issues regarding VR-based learning, arguing that immersive environments are based on implicit assumptions about the “ideal user body,” thereby limiting the participation of learners with physical or sensory differences. Therefore, any coherent didactic model for DML in geography education must regard equity-oriented design principles not as an additional element but as a foundational basis.

Future research should prioritize several interconnected strategic directions. First, it is necessary to develop theoretically grounded and empirically validated integrated didactic models that link digital and mobile learning (DML) tools with specific competency trajectories in school curricula. Examples of such models include the Teacher Digital Competency framework proposed by Falloon (2020) and the AI Course Design Planning Framework developed by Schleiss et al. (2023). These frameworks enable practitioners to make evidence-based decisions regarding technology selection, planning pedagogical sequencing, and assessing competencies. Secondly, researchers

should systematically focus on developing and validating valid and reliable instruments that can measure the development of interdisciplinary and metacognitive competencies in digital learning environments. In this regard, the Interdisciplinary Understanding Questionnaire proposed by Schijf, van der Werf, and Jansen (2023) can serve as a methodological guide, as it demonstrated the feasibility of reliably assessing interdisciplinary competencies across different disciplinary contexts. Third, Remmen and Iversen (2023), in their review of field-based learning practices in Scandinavian countries, found that mobile learning based on the external environment and location remains insufficiently researched—only two of the 52 studies reviewed used digital resources. This area calls for targeted empirical research, building on the work of Yemini, Engel, and Ben Simon (2025). Fourth, the issue of integrating generative artificial intelligence and AI-based platforms into geography education, described by Hanus and Lee (2025) as a transformative process, requires proactive curriculum research. These studies should comprehensively analyze the impact of AI-mediated instruction on competency development, ethical reasoning, and teacher professional agency—considering both its opportunities and risks.

Ultimately, the epistemological foundations of geography education must not be overshadowed by technological optimism. Bagoly-Simó (2023) shows that when curricula place excessive emphasis on normative values and competency-based indicators at the expense of foundational disciplinary knowledge, students’ critical and evidence-based reasoning skills are weakened—the very skills that DML is meant to develop. According to the interdisciplinary ecological framework proposed by Markauskaite et al., (2024), the development of authentic transdisciplinary competencies through DML is not limited to the introduction of digital tools; it must be grounded in carefully designed learning ecosystems that develop epistemic resources—including values, dispositions, and affective orientations—coherently across the micro (classroom), meso (school), and macro (education system) levels. Therefore, promoting DML in school geography must first be based on the professional development of teachers, systematic alignment of curricula, and sustained investment in theoretically grounded, empirically rigorous research that aims to synthesize and advance this systematic review.

Data availability statement

The datasets presented in this article are not readily available because no. Requests to access the datasets should be directed to Yerlan Issakov, erlan.issakov@gmail.com.

Author contributions

AS: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. NU: Conceptualization, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. BA: Formal analysis, Methodology, Writing – original draft. MK: Data curation, Investigation, Writing – original draft. KM: Formal

analysis, Methodology, Validation, Writing – original draft. RK: Data curation, Software, Writing – original draft. SK: Data curation, Formal analysis, Investigation, Writing – original draft. YI: Conceptualization, Formal analysis, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing. LD: Conceptualization, Formal analysis, Funding acquisition, Project administration, Visualization, Writing – original draft, Writing – review & editing.

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Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. During the preparation of this manuscript, ChatGPT was used exclusively as a language support and translation tool to assist with the translation of the manuscript from Kazakh into English and to ensure the accurate rendering of scientific and technical terminology. All scientific content, including research ideas, methodology, data analysis, interpretation of results, conclusions, figures and tables, was developed and prepared by the authors. The authors have reviewed, verified and edited the entire manuscript and bear full responsibility for its content.

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